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Construction with Materials Derived from Locally Available Natural and Biological Resources

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Yask Kulshreshtha

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by

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To

My family and friends

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Summary

The government of India has identified a need for 29.5 million houses for low-income rural households by 2022. With 16.6 million claimed to be built by December 2021, the implementation is far from the announced goal. Thus, there is a huge demand for low-cost rural housing that needs to be catered for within a short time. While construction with conventional materials such as concrete and fired bricks is often feasible due to their wide availability and standardisation in use, these materials are unaffordable for low-income rural households. Hence, there is a need for alternative building materials that are cheap, readily available and ecological. One of such economical and environmentally friendly building materials is 'earth'.

Building with unfired earth (mud) is an over 10 000 years old practice that is regaining its popularity due to the rising concern of the construction sector on the climate. As a construction material, 'earth' offers several advantages such as improved indoor thermal comfort, reduced operational and embodied energy use and potential to be reused. The raw material for earthen construction, 'soil', is generally excavated from the building site, but may not always be suitable for construction. Hence, the soil is stabilised physically (by adding extra clay or sand), mechanically (by compaction), and/or chemically (by addition of a binder such as cement or hydraulic lime) to improve its strength and durability characteristics. While the strength of earthen material is primarily adequate to construct low-rise buildings, its deterioration is often due to low durability, especially its sensitivity to water ingress. The poor water resistance along with prevalent myths and prejudice surrounding earthen materials limit the widespread application of earthen construction globally.

Although building houses with earthen materials is a practical choice for low-income households living in rural areas, earthen houses are consistently declining over the past few decades in India. Thus, it becomes necessary to evaluate if earth can make a valuable contribution to contemporary housing shortage. Hence, a field survey was conducted in India to understand factors favouring or limiting construction and daily use of earthen houses. As an outcome of the survey, the low image of earth was identified as the key barrier towards the acceptance of earth as a building material for low-income rural households. The image is strongly linked to poverty and it is significantly influenced by the poor performance of earthen materials (in terms of poor water and weather resistance and termite infestation), frequent maintenance and governmental policies that give a negative reputation to earth. Hence, to improve the acceptance and wider adoption for rural housing in India, it is necessary that earthen buildings are affordable (to low-income households), durable (good water resistance, limited required maintenance) and most importantly, desirable (good aesthetics of both the material and structure, good technical performance). In this regard, modern earthen construction techniques such as compressed earth blocks (CEB) can be viable due to the good quality of the finished product and the wide availability of low-cost CEB making presses/machines in India.

The use of unstabilised (without an added binder) compressed earthen blocks (CEBs) in construction is often restricted by their water resistance performance. Hence, enhancing its water resistance can improve the acceptability. An experimental study was conducted to understand the influence of soil composition, compaction and water content on water resistance and compressive strength of unstabilised CEBs. It was found that in CEBs of similar dry density, strength and soil composition, a higher compaction water content (water content in the earthen block immediately after compaction) results in better water resistance. An increase in compaction water content by 3% resulted in up to 70% reduction in water-driven erosion, whereas doubling the compaction pressure decreased the erosion by up to 60%. CEBs with a high pre-wetting water content (water content in earthen block just prior to the water resistance test or during strength test) of 12.6% resisted 6 times more erosion than CEBs with low pre-wetting water content (<6%), indicating the role of water saturation in decreasing the water-driven erosion of unstabilised walls. The CEB prepared with bentonite rich soil survived 5 days in immersion, more than other CEBs that disintegrate within 30 min, indicating the dominant effect of clay mineralogy on the water ingress and water resistance. Based on the investigation, selection of appropriate soil, preparation of CEBs with a higher compaction water content and if feasible, a high compaction force are essential steps towards improved water resistance of unstabilised earthen houses.

The water resistance of CEBs can be improved further by adding a binder (also referred to as stabiliser) such as Portland cement or hydraulic lime. However, the high cost of these binders and wider debate around the negative environmental impact of them has led to growing interest in biological stabilisers. While the strengthening mechanism of biological stabilisers is widely covered in scientific studies, information regarding their water-resistance performance is limited. Therefore, a review of a wide range of biological stabilisers (cow-dung, casein, chitosan, starch, guar gum, cactus mucilage, lignin, tannin and linseed oil, alginate, agar, carrageenan, xanthan gum and gellan gum) was conducted to understand the water resistance behaviour of biologically stabilised earthen materials. A biological stabiliser can modify the pore structure by pore-filling (such as in cactus, lignin), or by altering the physico-chemical properties of soil surface through forming ionic bond with clays (as reported in chitosan, casein, lignin) or by imparting hydrophobicity (observed in chitosan, linseed oil, carrageenan). Stabiliser can also be transformed into a water-stable form by heating (in casein, starch, agar gum and gellan gum) and/or by addition of cation (effective in casein, alginate and gellan gum), improving the overall stability of stabilised earthen material under wet conditions. A technical assessment of biological stabilisers reveals that they do not perform well in comparison with chemical stabilisers in water resistance tests. Moreover, the costs of industrially produced biological stabilisers are significantly higher than cement and hydraulic lime, even though lower quantities are required for stabilisation. In this regard, traditional stabilisers such as cow-dung, cactus juice and tannins could be cost-effective if sourced and processed locally. Based on the assessment of biological stabilisers, cow-dung was found to be an economic and ecological stabiliser that is relevant for rural housing in India due to its known water resistance characteristics, wide availability and wide acceptability.

Although cow-dung is known to improve the water resistance characteristic of stabilised earthen materials, no scientific study so far provided a strong insight or evidence of this characteristic. Therefore, the water-resistance behaviour of cow-dung stabilised compressed earthen blocks (CD-CEBs) was investigated through an extensive experimental programme to evaluate the influence of various choices involved in their manufacturing and to identify and characterise the components of cow-dung responsible for its water resistance. The addition of cow-dung improves the water resistance of stabilised earthen block by (up to) over 500 times. This improvement was found to be linked to small-sized microbial aggregates (SSMAs), which constitute approximately one-third of the solid mass of cow-dung. SSMAs extracted from cow-dung are negatively charged particles (0.5-7µm) of low specific surfaces that are water repellent and rich in fatty acids. To improve the water resistance of CD-CEBs further, some of the strategies (recommendations) that can be followed are: 1. The use of wet cow-dung is advised over dry cow-dung as it provided over 80 times better water resistance, 2. Adopting a higher compaction water content (by 3%) improved the water resistance by over 40 times, and 3. The water resistance of CD-CEBs can be improved over 30 times by using soil with low-swelling clay minerals such as kaolinite. These recommendations are expected to facilitate architects, practitioners, self-builders and natural-building enthusiasts to build earthen houses that are affordable, durable and desirable.

The observations and conclusions drawn from the field survey and additional interviews reveal that communication through online videos is an effective and impactful medium to disseminate scientific knowledge to practitioners and therefore, increase the impact of this research. Hence, online video was explored as a tool to disseminate the insights developed in this thesis. A total of 124 YouTube videos were assessed on 'viewer engagement', 'quality of content' and 'potential impact'. The insights gained were used to develop relevant (how relatable the message is to contemporary issues and target audience), holistic (touches upon the topic from multiple perspectives) and actionable (motivate the viewer to take action in line with the message of the video) videos on the content of this thesis. One video aims at creating a wider awareness of building with earth as an eco-friendly alternative building material and another video provides insights and recommendations on the effective use of cow-dung in earthen construction.

This thesis contributes toward a better understanding of water ingress and water resistance in unstabilised and biologically stabilised earthen materials, especially cow-dung stabilised earthen materials. Moreover, it addresses the three key aspects identified for rural earthen housing in India; 1. Affordability, by using inexpensive techniques and binder; 2. Durability, by enhancing the water resistance in both unstabilised and cow-dung stabilised earthen material, and 3. Desirability, by producing CEBs of good finish and aesthetic and using a stabiliser that is widely acceptable. The research work is expected not only to provide scientific insights that facilitate understanding and adoption of earthen materials but the knowledge that can be directly applied in the construction of earthen houses.

Samenvatting

De regering van India heeft vastgesteld dat er tegen 2022 behoefte is aan 29,5 miljoen huizen voor plattelandshuishoudens met een laag inkomen. Met 16,6 miljoen naar verluid gebouwd tegen december 2021, is de implementatie verre van het aangekondigde doel. Er is dus een enorme vraag naar goedkope plattelandswoningen die op korte termijn moeten worden gerealiseerd. Hoewel constructie met conventionele materialen zoals beton en baksteen vaak haalbaar is vanwege hun brede beschikbaarheid en standaardisatie in gebruik, zijn deze materialen onbetaalbaar voor huishoudens met een laag inkomen op het platteland. Daarom is er behoefte aan alternatieve bouwmaterialen die goedkoop, gemakkelijk verkrijgbaar en ecologisch zijn. Een van die economische en milieuvriendelijke bouwmaterialen is 'aarde'.

Bouwen met ongebakken aarde is een meer dan 10.000 jaar oude praktijk die opnieuw aan populariteit wint door de toenemende bezorgdheid van de bouwsector over het klimaat. Als constructiemateriaal biedt 'aarde' verschillende voordelen, zoals verbeterd thermisch comfort binnenshuis, verminderd operationeel en fysiek energieverbruik en potentieel voor hergebruik. De grondstof voor de aarden constructie, 'grond', wordt over het algemeen van de bouwplaats afgegraven, maar is niet altijd geschikt voor de bouw. Daarom wordt de grond fysiek (door toevoeging van extra klei of zand), mechanisch (door verdichting) en/of chemisch (door toevoeging van een bindmiddel zoals cement of hydraulische kalk) gestabiliseerd om de sterkte en duurzaamheidseigenschappen te verbeteren. Hoewel de sterkte van aarden materiaal in de eerste plaats voldoende is om laagbouw te realiseren, is de weerstand tegen aantastingsmechanismen relatief laag, met name de gevoeligheid voor binnendringend water. De slechte waterbestendigheid samen met de heersende mythen en vooroordelen rond aarden materialen beperken de wijdverbreide toepassing van aarden constructie wereldwijd.

Hoewel het bouwen van huizen met aarden materialen een praktische keuze is voor huishoudens met een laag inkomen die op het platteland wonen , nemen de aarden huizen in India de afgelopen decennia gestaag af. Het wordt dus noodzakelijk om te evalueren of het bouwmateriaal aarde een waardevolle bijdrage kan leveren aan de hedendaagse woningnood. Daarom werd in India een veldonderzoek uitgevoerd om inzicht te krijgen in factoren die de bouw en het dagelijks gebruik van aarden huizen bevorderen of beperken. Als resultaat van het onderzoek werd het lage imago van de aarde geïdentificeerd als de belangrijkste barrière voor de acceptatie van aarde als bouwmateriaal voor huishoudens met een laag inkomen op het platteland. Het imago is sterk verbonden met armoede en wordt sterk beïnvloed door de slechte prestaties van aarden materialen (in termen van slechte water- en weersbestendigheid en aantasting door termieten), frequent onderhoud en overheidsbeleid dat een negatieve reputatie aan de aarde geeft. Om de bredere acceptatie van landelijke woningen in India te verbeteren, is het daarom noodzakelijk dat aarden gebouwen betaalbaar zijn (voor huishoudens met een laag inkomen), duurzaam (goede waterbestendigheid, beperkt vereist onderhoud) en vooral wenselijk (goede esthetiek

van zowel het materiaal als de structuur, goede technische prestaties). In dit opzicht kunnen moderne aarden constructietechnieken zoals maken van aangestampte (gecomprimeerde) aardblokken (‘compressed earth blocks’ - CEB) levensvatbaar zijn vanwege de goede kwaliteit van het eindproduct en de brede beschikbaarheid van goedkope CEB-persen/machines in India.

Het gebruik van niet-gestabiliseerde (zonder toegevoegd bindmiddel) gecomprimeerde aarden blokken (CEB’s) in de bouw wordt vaak beperkt door hun gebrekkige waterbestendigheid. Daarom kan het verbeteren van de waterbestendigheid de aanvaardbaarheid er van verbeteren. Om die reden is er een experimenteel onderzoek uitgevoerd om inzicht te krijgen in de invloed van bodemsamenstelling, verdichting en watergehalte op de waterbestendigheid en druksterkte van niet-gestabiliseerde CEB’s. Het bleek dat in CEB’s met vergelijkbare droge dichtheid, sterkte en bodemsamenstelling een hoger ‘verdichtingswatergehalte’ (watergehalte in het aarden blok direct na verdichting) resulteert in een betere waterbestendigheid. Een toename van het gehalte aan verdichtingswater met 3% resulteerde in een vermindering van de door water veroorzaakte erosie tot 70%, terwijl een verdubbeling van de verdichtingsdruk de erosie tot 60% verminderde. CEB’s met een hoog initieel watergehalte (watergehalte in het aarden blok net voor de waterbestendigheidstest of tijdens de sterktetest) van 12,6% weerstonden 6 keer meer erosieaantasting dan CEB’s met een laag initieel watergehalte (<6%), wat wijst op de belangrijke rol van mate van waterverzadiging bij het verminderen van de door water veroorzaakte erosie van niet-gestabiliseerde muren. De CEB bereid met bentoniet-rijke grond overleefde 5 dagen water onderdompeling, veel meer dan andere CEB’s die al binnen 30 minuten uiteenvielen, wat wijst op het dominante effect van de klei-mineralogie op het binnendringen van water en de waterbestendigheid . Op basis van dit onderzoek zijn selectie van geschikte grond, voorbereiding van CEB’s met een hoger verdichtingswatergehalte en indien mogelijk een hoge verdichtingskracht essentiële stappen om de waterbestendigheid van niet-gestabiliseerde aarden huizen te verbeteren.

De waterbestendigheid van CEB’s kan verder worden verbeterd door toevoeging van een bindmiddel (ook wel stabilisator genoemd) zoals portlandcement of hydraulische kalk. De hoge kosten van deze bindmiddelen en het bredere debat over de negatieve milieu-impact ervan hebben echter geleid tot een groeiende belangstelling voor biologische stabilisatoren. Hoewel het versterkende mechanisme van biologische stabilisatoren breed wordt behandeld in wetenschappelijke studies, is de informatie over hun waterbestendigheidsprestaties beperkt. Daarom werd een overzichtsstudie van een breed scala aan biologische stabilisatoren (koemest, caseïne, chitosan, zetmeel, guargom, cactusslijm, lignine, tannine, lijnolie, alginaat, agar, carrageen, xanthaangom en gellangom) uitgevoerd om het waterbestendigheidsgedrag van biologisch gestabiliseerde aarden materialen beter te begrijpen. Hieruit bleek dat een biologische stabilisator de poriestructuur van aarde kan wijzigen door porievulling (zoals met name in het geval van cactus en lignine), of door de fysisch-chemische eigenschappen van het bodemoppervlak te veranderen door een ionische binding te vormen met klei (zoals gerapporteerd voor chitosan, caseïne en lignine) of door het verkrijgen van hydrofobiciteit (waargenomen voor chitosan, lijnolie en carrageen). Een biologische stabilisator kan ook worden omgezet in een meer waterstabiele vorm door verhitting (voor caseïne, zetmeel, agargom en gellangom) en/of door toevoeging van een kation (effectief voor caseïne, alginaat en gellangom), waardoor de algehele stabiliteit van aarde verbetert onder natte omstandigheden. Een technische beoordeling aan de hand van waterbestendigheidstests van biologische stabilisatoren laat zien dat ze niet goed presteren in vergelijking met chemische stabilisatoren. Bovendien zijn de kosten van industrieel geproduceerde biologische stabilisatoren beduidend hoger dan die van cement en hydraulische kalk, hoewel er voor stabilisatie wel lagere hoeveelheden nodig zijn. In dit opzicht kunnen traditionele biologische stabilisatoren zoals koemest, cactussap en tannines kosteneffectief zijn als ze lokaal worden ingekocht en verwerkt. Op basis van de beoordeling van biologische stabilisatoren bleek koemest een economische en ecologische stabilisator te zijn die relevant is voor toepassing op het platteland in India vanwege de bekende waterbestendigheidseigenschappen, brede beschikbaarheid en brede acceptatie.

Hoewel bekend is dat koemest de waterbestendigheid van gestabiliseerde aarden materialen verbetert, heeft geen enkel wetenschappelijk onderzoek tot nu toe een sterk inzicht of bewijs van deze eigenschap opgeleverd. Daarom werd het waterbestendigheidsgedrag van met koemest gestabiliseerde gecomprimeerde aarden blokken (CD-CEB's) onderzocht door middel van een uitgebreid experimenteel programma om de invloed van verschillende keuzes bij de productie ervan te evalueren en om de componenten van koemest te identificeren en te karakteriseren ten aanzien van waterbestendigheid. De toevoeging van koemest verbetert de waterbestendigheid van gestabiliseerde aarden blokken tot meer dan 500 keer. Deze verbetering bleek verband te houden met kleine microbiële aggregaten (SSMA's), die ongeveer een derde van de vaste massa van koemest uitmaken. SSMA's gewonnen uit koemest zijn negatief geladen deeltjes (0,5-7 μm) met een laag specifiek oppervlak die waterafstotend en rijk aan vetzuren zijn. Om de waterbestendigheid van CD-CEB's verder te verbeteren, zijn enkele conclusies en aanbevelingen die kunnen worden gevolgd: 1. Het gebruik van natte koemest wordt aanbevolen boven droge koemest, aangezien dit meer dan 80 keer betere waterbestendigheid biedt; 2. Het toepassen van een hoger verdichtingswatergehalte (met 3%) verbetert de waterbestendigheid met meer dan 40 keer; en 3. De waterbestendigheid van CD-CEB's kan meer dan 30 keer worden verbeterd door grond te gebruiken met beperkt-zwellende kleimineralen zoals kaoliniet. Van deze aanbevelingen wordt verwacht dat ze architecten, beoefenaars, zelfbouwers en natuurliefhebbers in staat stellen om aarden huizen te bouwen die betaalbaar, duurzaam en gewenst zijn.

De waarnemingen en conclusies uit het veldonderzoek en aanvullende interviews laten zien dat communicatie via online video's een effectief en impactvol medium kan zijn om wetenschappelijke kennis te verspreiden onder praktijkmensen en zodoende ook de impact van onderzoek kan vergroten. Daarom werd onderzocht of online video als hulpmiddel kan dienen om ook de inzichten die in dit proefschrift zijn ontwikkeld effectief te verspreiden. Hiertoe werden eerst 124 YouTube-video's beoordeeld op 'betrokkenheid van kijkers', 'kwaliteit van inhoud' en 'potentie van impact'. Vervolgens werd het verkregen inzicht gebruikt om twee video's te maken over de inhoud van dit proefschrift met nadruk op relevantie (hoe verhoudt de boodschap zich tot hedendaagse problemen en doelgroep), holistische benadering (benadering van het onderwerp vanuit meerdere perspectieven) en bruikbaarheid (wordt de kijker gemotiveerd om actie te ondernemen naar aanleiding van de boodschap van de video). De eerste video is gericht op het creëren van een breder bewustzijn van bouwen met aarde als een milieuvriendelijk alternatief bouwmateriaal en de tweede video geeft inzichten en aanbevelingen over het effectief gebruik van koemest in aarden constructies.

Dit proefschrift draagt bij aan een beter begrip van de waterbestendigheid van ongestabiliseerde en biologisch gestabiliseerde bouwmateriaal aarde en in het bijzonder van met koemest gestabiliseerde aarde. Bovendien behandelt het drie aspecten die van belang zijn voor rurale aarden woningen in India; 1. Betaalbaarheid, door gebruik te maken van goedkope technieken en bindmiddellen; 2. Duurzaamheid, door het verbeteren van de waterbestendigheid in zowel ongestabiliseerd als met koemest gestabiliseerde aarde; en 3. Wenselijkheid, door het produceren van CEB's met een goede afwerking en esthetiek en het gebruik van een stabilisator die algemeen aanvaardbaar is. Het in het kader van dit proefschrift uitgevoerde onderzoek heeft niet alleen wetenschappelijke inzichten opgeleverd die het begrip en de acceptatie van het bouwmateriaal aarde kunnen verbeteren, maar ook kennis verschaft die effectieve kan worden toegepast in de constructie van aarden huizen.

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1

Introduction

"It is important to draw wisdom from many different places. If we take it from one place, it becomes rigid and stale"

-Iroh, Avatar the Last airbender (S2 E9)

Chapter 1 presents an introduction to housing needs in rural areas of India and how earthen construction can be a solution for it. The scope of the thesis, research approach and research questions are summarised in this chapter.

1.1 Housing needs in rural India and the role of local materials

According to ‘Universal declaration of human rights’ drafted in 1948, access to adequate housing is important for the health and well-being of humans (United Nations, 1948). The World Bank has estimated a need for 300 million new housing units by 2030 to accommodate three billion people (Grandolini & Ijjasz-Vasquez, 2016). There is high pressure on governments to cater for this enormous demand, as housing is known to have a significant impact on economic development (Arku, 2006; Harris & Arku, 2006; Jahan & McCleery, 2005; Malpezzi, 1999). Around 80% of Gross Domestic Product (GDP) depends on the 54% of the world population that live in urban areas (World Bank, 2018). Therefore, urban housing projects, especially slum upgrades, have been given significant attention by international organisations and media, while rural housing projects are comparatively neglected. However, currently 46% of the world population lives in rural areas. This population is significantly higher in developing countries such as India, where about 65.5% of the population lives in rural areas (World Bank, 2020).The rural economy in India constitutes 46% of the national income (Chand et al., 2017), which is significantly higher than in many other countries in the world. The outcome of a survey carried out by the World Bank, it was considered important to provide better opportunities to low-income families in rural areas in order to achieve shared prosperity in India, and it should be prioritised over providing opportunities to low-income families in urban areas (Public Opinion Research Group - The World Bank Group, 2015). The government of India is actively working towards the provision of houses in rural areas under the scheme of ‘Pradhan Mantri Awaas Yojana – Gramin (PMAY-G)’. To achieve PMAY-G’s aims of housing for all by 2022, the government identified (in 2016) a need for 29.5 million houses for low-income rural households by 2022 (Ministry of Rural Development, 2016). With 16.6 million claimed to be built by December 2021 (Ministry of Rural Development, 2021), the implementation is far from the announced goal.

There is a need for an affordable solution to cater for this shortage of housing. The provision of affordable housing is a multi-dimensional problem that can be addressed through governance, housing policy, finance, planning, stakeholder arrangements, building skills and knowledge, affordable housing design, building materials, construction techniques etc. (Bredenoord et al., 2014). While there are different routes to approach affordable housing, construction materials offer interesting opportunities to address affordability as materials constitute a major portion of the total cost of a structure.

Construction with conventional materials such as concrete or fired bricks is often feasible due to their wide availability and standardisation in use. However, the prices of these materials have risen significantly over the years and are higher than the proportional rise in income (Bhide et al., 2009). To meet the demands of low-income households, traditional and indigenous materials could be re-considered for modern housing. Local construction materials and building practices that are tailored to rural lifestyles, topography, climate and resistance to natural calamities have been proposed to offer solutions to the shortage of housing in rural India (IDFC-RDN, 2013). Traditional building materials are inexpensive, readily available and require minimal processing before use. Furthermore, the labour involved in the construction process is also usually sourced locally, often limited to the household, the extended family or members of the local community (Bredenoord, 2017; Schroeder, 2016), which can reduce labour costs and provide needed local employment. The use of local and environmental friendly building materials for affordable housing also addresses sustainable development goals (SDG's) laid out by the United Nations as the 2030 agenda for sustainable development. While the SDG 11 "Make cities and human settlements inclusive, safe, resilient and sustainable", SDG 12 "Ensure sustainable consumption and production patterns" and SDG 13 "Take urgent action to combat climate change and its impacts" are directly impacted, there is indirect impact on other SDG 3 'Good health and well-being' and SDG 8 'decent work and economic growth', as highlighted in Figure 1.1.

Figure 1.1: Use of local and environment friendly building materials can impact SDG 11, SDG 12 and SDG 13 directly, and SDG 3 and SDG 8 indirectly. Original Image credit: (United Nations, 2019)

Earth or mud is one such abundant resource that has been used as a construction material for over 9000 years (Minke, 2006). Earthen houses are considered environmental friendly and affordable as compared to houses built with concrete or fired clay bricks. These houses have several benefits, for example, earthen houses are known to improve the indoor air quality and thermal comfort (Cascione et al., 2019), they consume minimal energy for material production (Houben & Guillaud, 1994) and the transportation costs are reduced due to local resource utilisation (Morel et al., 2001). In recent years, the increasing price of building materials has resulted in a revival of interest in earthen construction globally (Baiche et al., 2017). The benefits of earthen construction together with growing awareness of the environmental impact of the construction sector provide an interesting opportunity to explore earth as a building material for the construction of affordable housing in rural India.

While building with earth can be an affordable solution, it has some limitations that restrict its widespread use. Earthen houses are susceptible to environmental forces such as heavy rain and wind and their failure is often linked to durability issues (Beckett et al., 2020; Morel et al., 2012). Due to low durability performance, earthen houses have a shorter life span and require frequent maintenance (elaborated in chapter 3). Although design measures such as long roof overhang and raised foundation can improve the durability of earthen structures, these measures are often missing in low-quality earthen houses. Earthen houses in India also suffer from low social acceptance (Chaudhury, 2019). Therefore, unless earthen houses are made desirable, they will not be able to fulfil the aspirations of the dwellers. To cater for the rural housing shortage in India, housing projects with earthen materials should be affordable, durable and desirable. These three aspects are the foundation of this thesis and the discussion in most chapters will concentrate on one or more of these aspects.

1.2 Scope of the thesis

This thesis aims to address the broad challenge of housing shortages in rural India by proposing earth as an ecological and economical alternative to conventional building materials. Earthen construction is an interdisciplinary field that combines knowledge from various disciplines such as civil engineering architecture and planning, industrial design, and material science. Within the discipline of civil engineering, earthen construction is closely associated with geotechnical engineering, structural engineering and building engineering. Within all the aforementioned disciplines, there are multiple aspects that could be investigated and have the potential to contribute towards the construction of affordable earthen housing in rural India. These aspects are summarised in Figure 1.2.

While there are multiple aspects to explore, this thesis focuses on aspects that contribute towards affordable, durable and desirable housing in rural India. Accordingly, a few aspects have been selected to explore in this thesis (marked by yellow colour in Figure 1.2). The selection of the broad parameters, ‘affordable’, ‘durable’ and ‘desirable’ is based on the requirement of low-income households , the limitations of earthen materials and the need to improve its acceptance, respectively. To construct affordable earthen housing in rural India, it is first and foremost required to understand the requirement and aspirations of people living in existing earthen houses. Therefore, an ethnographic survey is included as a part of this research. The outcomes of the survey provided a direction to develop earthen materials for rural housing.

Earthen materials are manufactured by compacting soil into desirable shapes. In addition to the detailed investigation of the soil, it is also essential to select a relevant construction technique to shape the material. Compressed earth block (CEB) technique was selected out of many techniques due to the availability of infrastructure for its mass production in rural areas.

The improvement in durability, specifically water resistance of earthen material, is the primary focus of the thesis. Improvement in water resistance of earthen material is also expected to contribute

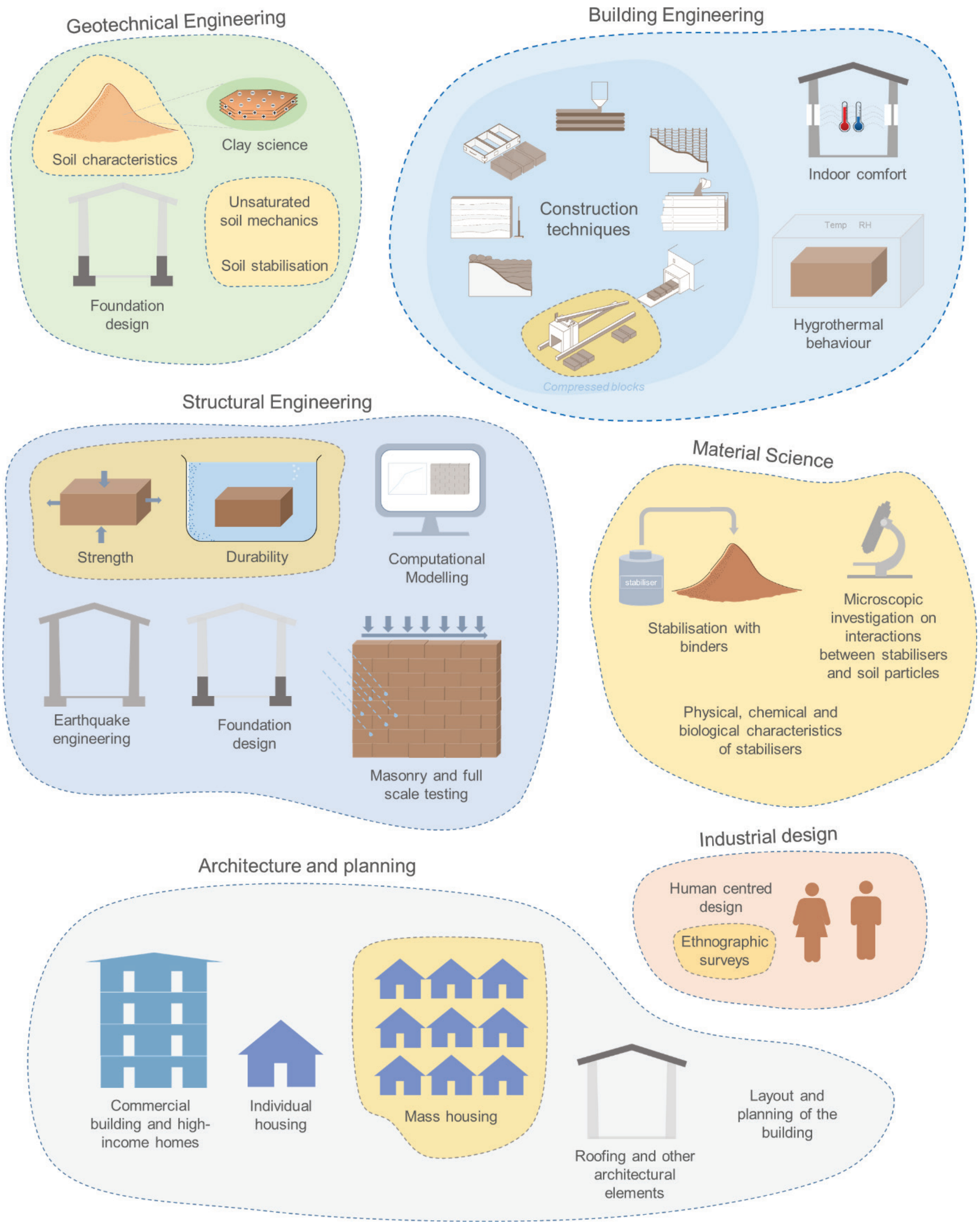

Figure 1.2: Various disciplines of earthen construction that could aid in solving the housing shortage in rural India. The aspects marked with yellow background (including the material science) are investigated in this thesis.

significantly towards the acceptance of earthen houses. The geotechnical aspects on compacted soil are essential to understand the processes that contribute to water resistance and strength characteristics of earthen material. These aspects are investigated to understand the water resistance of unstabilised earthen materials. The improvement in water resistance and strength characteristics of earthen material with the addition of biological stabilisers is investigated by understanding the characteristics of the stabiliser, and their interaction with the soil. The water resistance of earthen houses can be enhanced either by improving the material characteristics or through the inclusion of architectural elements (such as a pitched roof). This thesis takes on the material route to improve the water resistance of earthen houses. One of the most common practices to improve the water resistance of earthen material is to add a 'binder' to the soil. Portland cement and hydraulic lime are such commonly used binders. However, these stabilisers are not affordable for several low-income households. Therefore, this thesis explores the use of low-cost biological binders that can be extracted from locally available resources. These binders are often referred to as stabilisers. Stabilisers are the binders that are often added to earthen materials to improve one or more characteristics (usually strength and durability). In addition to biological stabilisers, the improvement of the water resistance of unstabilised (without any chemical or biological binder) earthen materials is investigated in this thesis.

The dissemination of scientific knowledge is often carried out through journal and conference articles, which are then often used by industry to develop and scale up the technology. In comparison to other disciplines of sciences, earthen construction is still dominated by independent self-learned practitioners which have gained knowledge through hands-on practice. Therefore, to disseminate the outcomes of this thesis and have a substantial impact on the practice, effective communication of developed knowledge is investigated briefly.

1.3 Research approach

1.3.1 Audience of the research

The audience of this research are scholars, architects and practitioners that are active in building earthen houses, especially in India. This thesis is also expected to be useful for self-builders who can utilise the knowledge to improve the durability of earthen houses. This research work could also be valuable for geotechnical engineers looking for ecological and economical methods to stabilise soils. The research work can aid policymakers to make favourable decisions for the widespread adoption of earthen materials. Several policymakers are not yet convinced of earthen materials and looking for scientific evidence on characteristics of earthen materials which were so far anecdotal. This thesis can also provide knowledge to material scientists and bio-designers who are looking to explore natural and bio-based materials for non-construction applications.

1.3.2 Design thinking based research approach

The research approach used in this thesis draws on the 'design thinking approach'. Design thinking is an iterative process that starts with understanding the users to formulate the problem and thereafter, creating ideas and finding solutions before testing it in real life (IDF, 2022). The user of an affordable earthen house is a person living in it. Therefore, a significant amount of time was spent in understanding the factors favouring and limiting their choice of earthen construction. Based on the user survey, the main challenges related to durability and desirability were formulated. Gaps in the knowledge of unstabilised earthen materials were identified and experimental studies were conducted to understand the response of unstabilised earthen material to water ingress. A thorough review of the existing literature was conducted and cow-dung was selected as a potential stabiliser for rural housing in India, which was then investigated thoroughly. The thesis concludes by proposing a communication approach to maximise the impact of this work by disseminating knowledge to the potential users and practitioners. Various elements of the 'design thinking approach' such as researching user need (empathise), defining the user's problem (define), brainstorming to create multiple ideas (ideate), experimental phase to test the ideas and hypothesis (prototype) are an integral part of this thesis. Although testing the developed material with users is a crucial step of 'design thinking approach' to further develop new material, it was challenging due to travel restrictions, and limited time and scope of the thesis.

The research approach of the thesis is also impacted by COVID-19, where testing methods and setups were optimised based on the restrictions. Studies on stabilisers such as waste rice starch were discontinued due closure of restaurant which supplied waste starch in pre-covid times. One of the initial aims of the thesis was to construct a demonstration structure in India, which was also not possible due to imposed restrictions. However, a scaled-up demonstration of wall was still realised in the Netherlands to understand the viability of the proposed solution. Details of this demonstration are not within the scope of this thesis.

Commentary in 'blue boxes'

Traditional scientific research is often confined to formal writing that is based on observation and hypothesis. However, there are interesting aspects of research that are informal (circumstantial or even emotional) and are often excluded from scientific work to avoid any biases. This thesis captures such informal commentary in the blue boxes (such as this) to provide readers with information that may not contribute to scientific understanding but are nevertheless essential to fully understand this research.

1.4 Objective and research questions

The main objective of the thesis is to develop low-cost, water resistant and acceptable earthen materials for rural housing in India without compromising other characteristics of earthen materials such as strength and reusability. In order to build affordable, durable and desirable homes multiple research questions are formulated and clustered in 5 parts:

1. **Can earthen materials be a solution to the contemporary rural housing shortage in India?** What are the factors favouring or limiting the construction and everyday use of earthen houses in rural India? What are the requirement and demands for the re-invention of earthen houses as a necessary step towards its wide-scale adoption?
2. **How can the characteristics of unstabilised compressed earthen blocks be optimised for enhanced water resistance?** What are the factors that influence water resistance and compressive strength of unstabilised earthen blocks? How does the microstructure of earthen block impact water resistance?
3. **Which biological stabilisers are feasible to be used for affordable rural housing in India?** How do various biological stabilisers resist water ingress? How do biological stabilisers compare on technical, environmental and economic performance?
4. **How to enhance the water resistance characteristics of cow-dung stabilised earthen blocks for practical applications?** What makes cow-dung stabilised earthen material water resistant? How do the various components of cow-dung and soil impact the water resistance characteristics of stabilised earthen blocks?
5. **How to maximise the impact of scientific research through alternative science communication approach?** What are the sources of scientific knowledge that enables practitioners to build with earth? What are the characteristics of an effective communication medium to convey the outputs of scientific research to a target audience?

1.5 Thesis outline

The thesis outline is visualised in Figure 1.3. The thesis consists of 8 chapters, out of which chapter 3 to chapter 7 represent the core content of the thesis (marked by yellow colour box). Chapters 3 and 7 are chapters that include interviews and link directly to the users, whereas Chapters 4 and 6 are experimental studies. Chapter 5 is a review chapter (similar to Chapter 2) and contains a thorough discussion on biological stabilisers and their assessment.

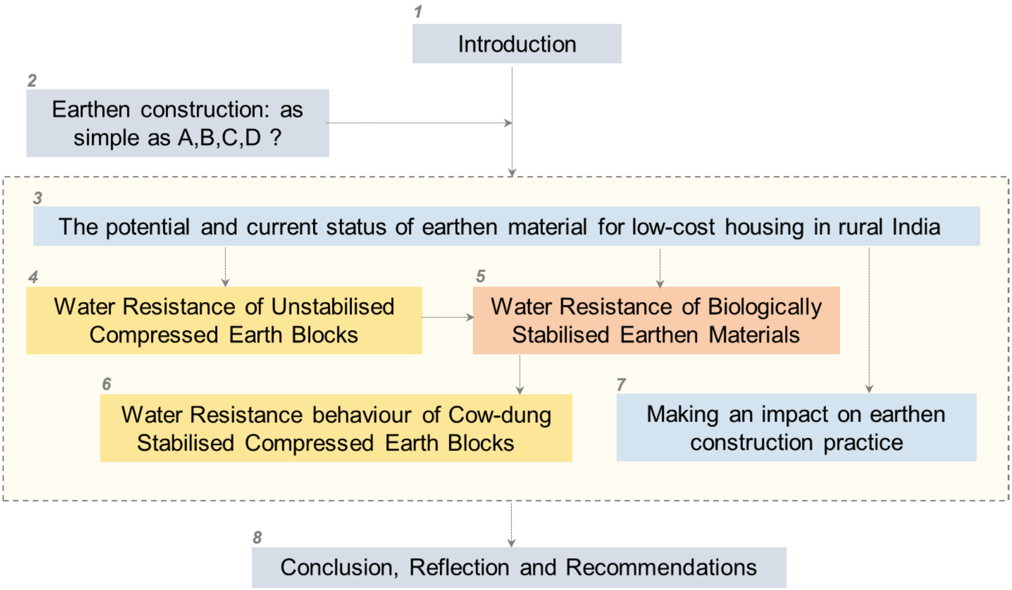

Figure 1.3: Thesis outline. The number next to each text box represents the chapter number. The yellow box represents the chapters that include experiments.

Chapter 2 provides a brief overview of earthen construction and connects the fundamental characteristics of soil and soil behaviour to practical on-site requirements, strength and durability of earthen materials. Several topics such as history, composition and selection of soil, construction techniques, soil stabilisation etc., are introduced. The chapter concludes with uncovering myths and prejudice surrounding earthen material, most of which are barriers to its application in the contemporary construction market.

Chapter 3 investigates the potential of earthen materials as a low-cost alternative for the contemporary housing shortage in rural India. This proposition is evaluated based on a survey that was conducted to understand technical, socio-economical, and other factors influencing construction with earthen materials in India. The dominating factor(s) are identified and discussed to point out the requirements for low-cost earthen housing in India. The research concludes with recommendations that can lead to better acceptance of earthen materials for housing construction.

Chapter 4 provides insight into the water resistance behaviour of earthen material through a mechanistic understanding of their response to water ingress, followed by a series of experiments on unstabilised compressed earth blocks. The influence of compaction water content, compaction pressure, pre-wetting water content, compaction method (technique) and clay mineralogy on the water resistance and strength of compressed block is studied, together with understanding the microstructural fabric and its influence on the water resistance performance. The chapter concludes with a brief discussion on the practical relevance of the results from the investigation.

Chapter 5 is a review of biological stabilisers in earthen construction with a focus on the mechanistic understanding of their ability to alter the water resistance behaviour of earthen materials. The performance of biologically stabilised earthen materials is discussed, together with the interaction mechanism responsible for enhanced water-resistance. Finally, a technical, environmental, and economical assessment is conducted to evaluate the feasibility of biological stabilisers in earthen construction.

Chapter 6 investigates the water-resistance behaviour of cow-dung stabilised compressed earthen blocks (CD-CEBs) through an extensive experimental programme to identify and characterise the components of cow-dung responsible for its water resistance. Various factors related to cow-dung and soil that affect the water resistance performance of CD-CEBs are studied. The insights gained from the experimental investigation are used in answering practical questions required for the valorisation of cow-dung in earthen construction.

Chapter 7 draws on the observation in the field survey (Chapter 2) and extends it to understand the sources and dissemination of scientific knowledge within the earthen construction community of India. Communication through video was recognised as an effective medium for the dissemination of scientific knowledge. A selection of YouTube videos related to earthen construction and building materials were reviewed and used in identifying the characteristics of an impactful video. These insights were then used in developing videos to communicate selected aspects of the thesis to the target audience.

Chapter 8 concludes the thesis with reflection, recommendations, and important outcomes of the thesis.

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Picture Credit: Justyna Botor

2

Earthen construction: as simple as A, B, C, D?[1]

“You call it dirt but, I call it a healthy coating of earth”

– Toph, Avatar the Last Airbender (S2 E15)

Unfamiliar with earthen construction? This chapter introduces earthen construction to non-experts and provides a holistic view on multiple aspects of building with earth, ranging from its history and evolution, composition and selection of soil, construction techniques, technical characteristics, stabilisation etc. to uncovering myths and prejudice against earthen materials which limits its widespread application. While building with earth is not complicated; practical experience and understating of raw materials are important to build high-quality earthen structures. An **A**ffordable, **B**reathable, **C**limate adaptive, **D**urable and **D**esirable earthen structure can contribute to housing shortage and mitigation of climate change.

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[1] The title is inspired from the review article “Starch: as simple as A,B,C?” by Wang et al. (1998)

2.1 Introduction

Building with earth (mud) is gaining popularity as an eco-friendly and economical alternative to conventional building materials such as concrete and fired bricks. The revival of earth as a building material has garnered significant interest within the architecture and research community, which has led to the development of a diverse discipline called 'earthen construction'. The advancement in the field of earthen construction over the past millennia was primarily through anecdotal knowledge that was transferred from one generation of builders to another. However, the progress in scientific understanding of earthen materials and technique is new, and research efforts in the past four decades have extended the capabilities of earthen materials and methods to suit contemporary housing needs and desires.

While it is indisputable that practical field experience is essential to acquire skill and knowledge to build with earth, a theoretical foundation in earthen construction is also as important to understand, develop and extend the potential of earthen materials. This chapter provides a brief overview of earthen construction and attempts to deliver the fundamental characteristics of soil (the raw material that is processed into the building element) and connect them to practical on-site requirements, strength, and durability of earthen materials. Several topics such as history, composition and selection of soil, construction techniques, soil stabilisation etc., are introduced. The chapter concludes with uncovering myths and prejudice surrounding earthen material, most of which are barriers to its application in the contemporary construction market.

2.2 History and evolution of earthen construction

Humans appeared on the planet earth about 7 million years ago. From then until the agricultural revolution about 10 000 years ago, humans procured food through hunting, and lived predominantly in temporary shelters (Weisdorf, 2005). The shift to agriculture for food production in ~8500 BC necessitated the need for permanent shelter to protect humans and their domesticated animals from predators and environmental forces (heavy rain and wind, and extreme temperatures). The switch from the use of readily available organic materials to the development of prefabricated materials (such as sun-dried mud bricks) appeared with the agricultural revolution (Love, 2013).

One of the earliest types of earthen structures were constructed with woven reeds and branches covered with mud (now referred to as wattle and daub technique) in ~8500 BC, but earthen blocks such as adobe (handmade unfired bricks) soon became popular (~8400 BC). The development of earthen construction techniques such as rammed earth (thick monolithic wall constructed with rammed layers of soil) happened in 1320 BC (Schroeder, 2016). Cob construction (a thick monolithic wall raised from the foundation) is known to have existed from 1400 AD (Jaquin, 2012) and compressed earthen blocks were introduced in 1956 (Pacheco-Torgal & Jalali, 2012). The dominance of earthen materials in human history is visualised in Figure 2.1. It is interesting to note that a part of the great wall of china is known to have been built with rammed earth about 2200 years ago (220 BC), remains of which can still be seen (National Geographic, 2021a).

While several existing earthen structures are widely covered in the literature on the history of earthen construction (Houben & Guillaud, 1994; Jaquin, 2012; Schroeder, 2016), the use of earth in large settlements is particularly interesting as it is closely related to the theme of this thesis. Unfired bricks (together with fired bricks) were used in Mohenjo-Daro, a large settlement of about 40000 people built around 2500 BC (Jaquin, 2012). Similarly, unfired bricks were used in construction of Taos Pueblo, one of the earliest settlements in New Mexico which was constructed in ~1000 AD and is still inhabited (Jaquin, 2012). A total of 46 apartment type earthen structures were constructed between the 15th and 20th century in Fujian, China. These buildings of 3-5 storey high, houses up to 800 people in each structure. The thick walls (up to 1.5 m) of the structures were built with rammed earth, which also functioned as fortress walls during wartime (UNESCO World Heritage Centre, 2021). The city of Shibam in Yemen, also known as the Manhattan of the desert, is the oldest example of vertical urban development (urban areas with dense configuration of high-rise buildings) and was built in the 18th century. These adobe buildings have between 5-8 stories and house over 7000 people (National Geographic, 2021b; UNESCO, 2021).

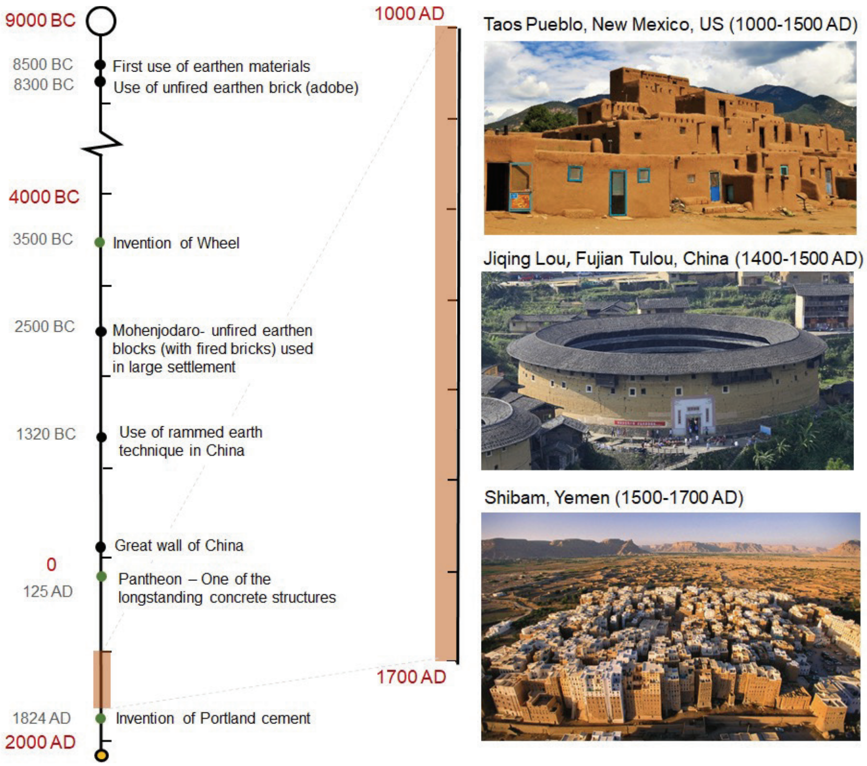


Figure 2.1: A timeline of earthen construction (with a few significant achievements in building materials), and examples of earthen settlements in New Mexico, China and Yemen, all of which are still inhabited. Photo credits: Patricia Henschen (Taos Pueblo, New Mexico), Zhangzhugang- Wikimedia (Jiqing Lou, China) and National geographic (Shibam, Yemen).

The increase in the use of fired brick after the industrial revolution in the 19th century and the subsequent rise in the popularity of concrete in the 1980s (Bories et al., 2014) has led to a sharp decline in construction and use of earthen structures. The improved production process and the performance of industrial building materials have significantly contributed to this decline (Jaquin, 2012). While estimates from the 1980s suggested that a third of the world population lived in earthen houses (Rael, 2000), according to the most recent study, it is estimated that 8-10% of the global population lives in earthen houses, with the percentage increasing to 20-25% in developing countries (Marsh & Kulshreshtha, 2021). While the proportion of earthen dwellings in developing countries is in consistent decline, growing concerns over the environment and health, coupled with cultural motivation to use local and indigenous material in developed countries, has renewed interest in earthen materials (Hall et al., 2012). This renewed interest has also motivated scientific research in the discipline. A scientific understand of building with earth starts by learning about its raw material - 'soil'.

2.3 Composition of soil and its impact on earthen materials

Soil (also referred to as mud, loam, raw earth, or leem (in dutch)) is a widely available resource that differs significantly from one location to another. It is composed of 3 phases, as illustrated in Figure 2.2; a solid phase consisting of different minerals and organic materials, a liquid phase consisting of water (often with partially dissolved salt and mineral compounds) and a gas phase consisting of air (Houben & Guillaud, 1994).

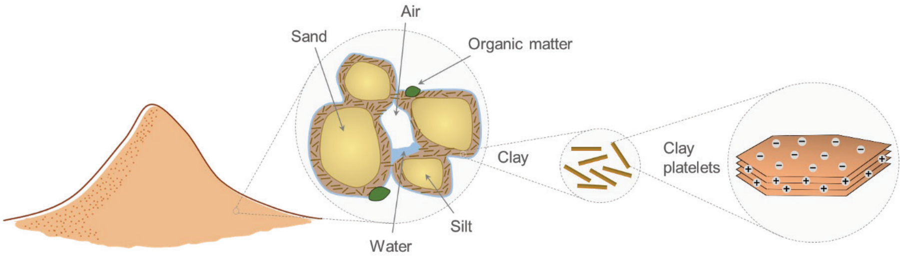


Figure 2.2: Phases and components of soil

The solid phase is rich in minerals and consists of aggregates or grains. Soil aggregates such as clay, silt and sand represent the sizes of minerals present in the soil. These aggregates are classified based on the size range recommended in national and international standards. The size ranges of aggregates indicated in some national/regional standards are inconsistent with others. Therefore, the classification of soil into clay, silt, sand, or any other coarser aggregate depends on the referred standard. For example, soil with aggregates 2-4.5 mm will be classified as sand in Europe, whereas gravel in India (Figure 2.3). Irrespective of variation in the values, these standards provide consistent values for two classes of aggregates in soil: cohesive aggregates of clays (that has binding properties) and non-cohesive silt, sand, and other coarser aggregates. Clay represents all the particles or aggregates less than 2μm or 0.002mm.

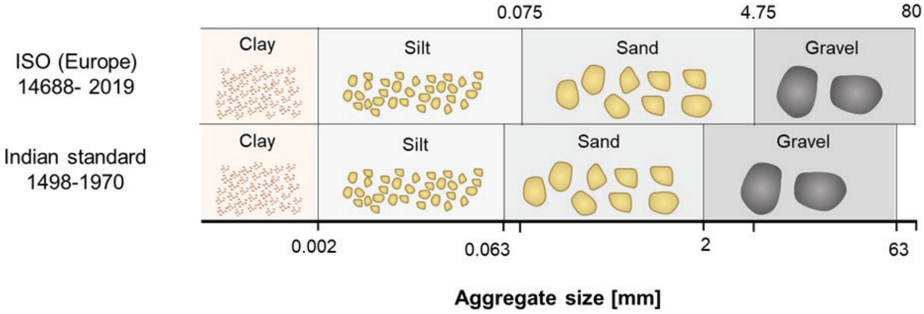


Figure 2.3: Classification of soil aggregates based on ISO and Indian standards.

Sand aggregates found in nature are often composed of silica or calcium. Silt, sand, and other coarser particles are generally inert, and force transfer between aggregates occurs due to high internal friction. Although sand and silt are inert, they can form solid structures of low strength and low durability by adding sufficient quantity of water. A classic application of this characteristic is the building of sandcastles. The water between the sand grains provides capillary suction that pulls the sand grains together and keeps the structure stable. In addition, slight compaction of sand contributes to stability by increasing inter-aggregate locking. When the water in between aggregates evaporates completely, the suction reduces to zero, making the sand grains fall apart. Conversely, too much water can also reduce suction, making the sandcastle unstable.

The addition of clay particles in sand can improve the strength and durability properties significantly, especially in low confining stress conditions. The smallest aggregates can often determine some aspects of soil behaviour, and therefore, the quantity and properties of clay can determine the overall behaviour of soil (Terzaghi et al., 1996). Clays are the result of the chemical weathering of rocks and are composed of hydrated aluminosilicates. Clay has a layered structure with a sheet-like arrangement that can be compared to pages of a book (Figure 2.2). The layered structure provides them with a large surface area to interact with clay and other aggregates in soil. Clays are negatively charged particles that interact through electrostatic forces and act as a binding agent in the soil. While the surface of clay is negatively charged, its edges can be positively or negatively charged depending on the surrounding environment (pH).

Clay minerals have a major influence on the strength and durability properties of earthen materials. The large surface makes them quite reactive but also increases their susceptibility of structural failure upon water ingress. The large surface area corresponds to a larger water holding capacity. Therefore, clay minerals can swell and shrink with the movement of water, potentially causing durability issues of earthen materials. There are different types of clay minerals varying in sheet arrangement and surface area. Some of the most common clay minerals found in nature are kaolinite, illite and montmorillonite. Montmorillonite has an extremely large specific surface area

(800-1000m^2/g) when compared to illite (80-100m^2/g) and kaolinite (5-15m^2/g) (Budhu, 2010; Terzaghi et al., 1996). In comparison, surface area of sand is extremely low (<0.5m^2/g) (Pennell, 2016). Soils found in nature often consist of a mixture of different minerals at various proportions. Therefore, identification of these minerals is of paramount importance in any earthen construction research project.

The solid phase also consists of organic material. Organic materials are often found in the top layer of soil (5-35cm), often referred to as humus, and is formed by the decomposition of leaves and other plant material by micro-organisms. Organic material can also be found in layers buried by geological processes, for example in peat deposits (usually dark brown and rich in plant matter). The organic material tends to swell and shrink by absorbing or releasing water. Therefore, they have a negative influence on the strength and durability performance of earthen material. Organic materials can also cause a nuisance of smell, making the earthen material undesirable. A soil rich in organics is unsuitable for earthen construction and should be avoided (Houben & Guillaud, 1994).

The liquid or water in soil also has a strong influence on its strength and durability properties. The water content in soil for earthen construction is often adjusted depending on the soil and the desired construction technique. A low quantity of water in soil results in a brittle material that is challenging to mould, and an extremely high-water content usually results in formation of a slurry. While the use of soil or mud slurry is impractical for most techniques, it can still be useful for earthen techniques that require high amount of water, e.g., plastering. The quantity of water in the soil while building earthen structures strongly influences the overall strength and water resistance of the structure. This will be explored briefly in this chapter, and in detail in Chapter 4.

The air phase is often a neglected phase of soil that can have a significant effect on the characteristics of earthen materials. Entrapped air is often reduced to provide required strength (Schroeder, 2016). Conversely, more air improves the insulation properties of earthen materials. The air phase also allows water vapour transfer (Houben & Guillaud, 1994), which affects the thermal characteristics of earthen structures. Therefore, the amount of air (or voids) in the earthen materials should be optimised based on the functional requirements of an earthen structure.

Soils are natural materials and therefore they often have different compositions, which can affect their behaviour. Additionally, they also vary in composition from place to place. The complex nature and variability of soil often create challenges when selecting an appropriate soil for earthen construction.

‘Earth’, ‘Mud’, ‘Loam’, ‘Dirt’, ‘Clay’: what do they all mean?

There are various terms that all refer to building structures and elements from (minimally) processed soil. ‘Earth’, ‘Mud’, ‘Loam’ and ‘Clay’ are used in scientific literature, whereas ‘dirt’ is occasionally used in non-scientific communication. While these terms are often used interchangeably, the definition of all the terms are unclear and can sometimes result in heated arguments. The use of ‘Earth’ or ‘raw earth’ is most common in scientific publications and in fact, the discipline dealing with construction from soil is commonly referred as ‘earthen construction’. According to Schroeder (2012), “Earth is a soil suitable for building purposes, which contains an appropriate mixture of silty, sandy and/or gravelly particles, together with clay minerals as a natural binder and water”. ‘Earth’ is a word that can be easily confused with the name of our planet and therefore, some people prefer use of ‘Mud’ over ‘Earth’, especially when speaking to a non-scientific audience. According to Houben & Guillaud (1994), “Mud is soil saturated with water that forms a viscous, liquid mass”. ‘Mud’ is also often used to describe fine grained soils, i.e. silt and clays. ‘Loam’ is also often used in textbooks, but not as common as ‘Earth’ and ‘Mud’. According to Budhu (2010) and Venkataramaiah (2006) “Loam is a mixture of sand, silt and clay size particles that may contain organic materials”. ‘Dirt’ is a term that has a negative connotation of being a waste or something worthless. According to Marriam-Webster dictionary, “Dirt is a filthy or soiling substance”, but also “Dirt is loose or packed soil or sand.” Building with ‘clay’ is also sometimes used but technically, it only represents soil particles that are less than 2μm in size.

2.4 Soil selection for earthen construction

A variety of soils are available on our planet, but not all soil is suitable for earthen construction. The selection of soil for an earthen construction depends on the chosen construction technique. The most commonly adopted selection criteria of soil is based on its texture (proportions of varying aggregates in the soil). The recommended range of values for different soil aggregates is shown in Figure 2.4. The proportion of different aggregates can be determined through field and lab tests, described in various earthen construction and soil mechanics textbooks, such as Houben & Guillaud (1994); Terzaghi, Peck & Mesri (1996); Venkataramaiah (2006); Budhu (2010). As mentioned earlier, the properties of soil can be strongly influenced by the amount of clay particles, and therefore, the quantity of clay should be controlled to suit the construction requirements. A low quantity of clay may not be enough to bind all the other non-cohesive aggregates, and therefore, the earthen material may have insufficient strength. Whereas a higher amount of clay can result in increased shrinkage (Hamard, 2017; Liu & Tong, 2017; Xu, 2018), therefore, jeopardising the strength and durability characteristics.

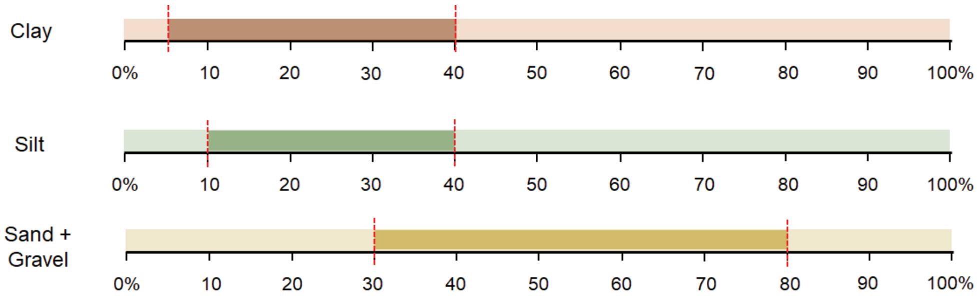


Figure 2.4: Recommended proportions of soil aggregates (lower and upper bond) based on the compilation of various normative, standards, and technical documents by Jiménez Delgado & Guerrero (2007) and Schroeder (2012). The range of values presented here are recommended for adobe, compressed earthen blocks, and rammed earth construction techniques.

While the recommended proportions of aggregates are convenient to select a suitable soil for construction, it does not take into account the variability of clay minerals. Therefore, the soil selection for earthen construction is often based on the plastic properties of soil (property that determines their mouldability). The plasticity properties of soil are linked to the quantity of water in it. The following terminologies are essential to understand the role of water in processing aspects of earthen materials:

The natural water content is the water content (defined as the mass of water [m_W] divided by the mass of solid [m_S] in the soil) in the natural state of soil i.e., when it was excavated.

The optimum water content (W_O) is the water content in the soil corresponding to the maximum dry density with a specified compaction effort of the soil. This density can be obtained through a 'Proctor compaction apparatus', a standard geotechnical test (comprehensive information on Proctor test can be found in standards such as BS/NEN-EN 13826-2:2010). An earthen block compacted at optimum water content can achieve a high density and a high strength. The plastic limit (W_P) is the water content at which soil transits from a semi-solid to a plastic state. Soil with a water content over its plastic limit can be deformed without the appearance of cracks (Budhu, 2010).

The liquid limit (W_L) is defined as a water content at which soil changes from a plastic state to a liquid state. Soil above this water content behaves like a liquid and can flow (but is non-mouldable).

The plasticity index is defined as the liquid limit minus the plastic limit, W_L-W_P, representing the range of water content where the soil is plastic and mouldable.

The impact of water content on the plasticity or consistency of soil is represented in Figure 2.5. It should be noted that while plastic soil is easily mouldable, it is unsuitable for techniques such as compressed earthen block (CEB) and rammed earth (RE) where lower water content than the plastic limit is used. A lower water content can aid high energy compaction usually applied in CEB and RE techniques. The water content should be selected based on the construction techniques, which is further discussed in Section 2.6. Irrespective of the amount of water needed to be added for construction, the determination of these limits can facilitate soil selection based on the recommended values, as shown in Figure 2.5. The plastic and liquid limits can be easily determined by simple laboratory and field tests. Information about these tests could be found in Houben & Guillaud (1994); Terzaghi et al. (1996); Venkataramaiah (2006); Budhu (2010).

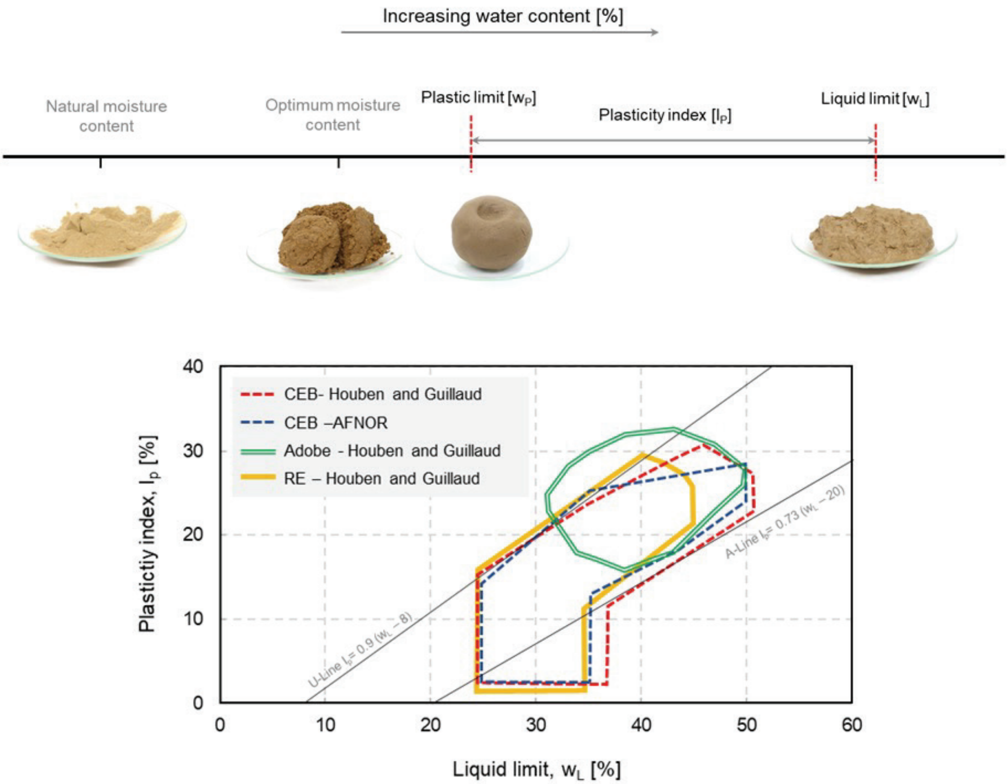


Figure 2.5: Representation of plastic and liquid limit and the soil suitability based on the relation of plasticity index and liquid limit. The upper image is based on Dutch soil that will be discussed in detail in Chapter 4. The image is taken for samples that were moulded into a ball (at least attempted for all water contents); the base plate with the sample was lightly tamped on hand, and a finger was pushed on to the top of the sample to demonstrate plasticity, where possible. Plasticity index and liquid limit chart after Jiménez Delgado & Guerrero, (2007) and Muguda et al. (2020). Information CEB and RE: Houben & Guillaud (1994), Adobe: Houben & Guillaud (1994), CEB: AFNOR French standard, AFNOR. XP P13-901 (2001).

In addition to aforementioned recommendations for soil selection, other suggestions are often applied. Soil organic materials should be avoided, where possible (Houben & Guillaud, 1994). The amount of salt in soil should be restricted to a maximum of 2% (Jiménez Delgado & Guerrero, 2007). The maximum size of aggregates should be limited (a maximum of 5mm – 40mm based on technique and respective norms). The rammed earth technique primarily employs a larger aggregate size; otherwise, for most techniques, an upper limit of 5mm is appropriate (Jiménez Delgado & Guerrero, 2007).

Although a soil can meet all the criteria for selection, it may not necessarily satisfy the desired characteristics for construction purposes. If that is the case, the soil needs additional treatment, known as stabilisation.

2.5 Soil stabilisation

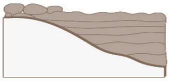
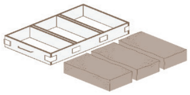
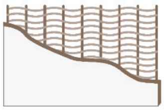
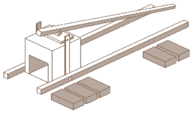
The technical limitations of earthen material are often solved by 'stabilisation'. Soil stabilisation can be achieved through: 1. Physically modifying the texture and plasticity of soil by adding sand, clay, aggregates and fibres; 2. Mechanically compacting the soil to modify the density, porosity and inter-particle friction; and/or 3. Adding binders to improve the mechanical behaviour (such as compressive, tensile, flexural strength) and durability (such as water-resistance, termite resistance) of earthen materials (Hall et al., 2012; Houben & Guillaud, 1994). Physical and mechanical stabilisation is an inherent part of earthen construction techniques. For example, rammed earth and compressed earth blocks both employ compaction to improve performance. Whereas, in techniques such as adobe or cob, which use higher water contents, fibres are added to reduce the shrinkage cracks, provide tensile strength and accelerated drying due to improved drainage of moisture through the fibres (Houben & Guillaud, 1994).

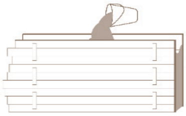
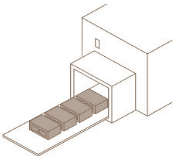
A soil stabilised by physical or mechanical modification is still often considered in literature as 'unstabilised'. Earthen materials stabilised with a mineral binder are those often referred to as a stabilised earthen material. The most common 'binders' or 'stabilisers' used in contemporary earthen construction are Portland cement and hydraulic lime (often referred to as 'chemical stabilisers'). The choice of a stabiliser is based on the texture of the soil. In general, soil with a higher clay content is stabilised with lime, whereas Portland cement is recommended for sandy soils (Hall et al., 2012; Houben & Guillaud, 1994). Stabilisation of soil with mineral binders has received criticism due to its negative environmental impact (Van Damme & Houben, 2017). Therefore, research on biological or organic stabilisers is on the rise. Biological stabilisation of earthen materials is thoroughly discussed in Chapter 5.

2.6 Earthen construction techniques

Various methods and processes are available to transform soil (stabilised or unstabilised) into a building material. Table 2.1 gives a brief overview of selected traditional and modern earthen construction techniques. The information in this section is primarily drawn from Houben & Guillaud (1994); Schroeder (2012); Van Damme & Houben (2017); Beckett et al. (2020).

Table 2.1: A summary of traditional and modern earthen construction techniques. Traditional techniques: Cob, adobe, wattle and daub and rammed earth. Modern techniques: Compressed earthen blocks, poured earth, extruded earthen blocks and 3D printing. Icon Illustration credit: Krithika Samavedula

Technique	Description	Illustration
Cob	Clods or big lumps of moist or wet soil (often mixed with straw or other fibres) are stacked on top of each other and hand packed (lightly tamped) layer by layer to form freestanding monolithic walls.	
Adobe	Moist or wet soil (often mixed with straw or other fibres) filled in a wooden mould to form brick-shaped units. The mould is removed once it is full, and the blocks are air or sun-dried. Adobe is one of the most used traditional methods of earthen construction.	
Wattle and daub	Wet soil, often mixed with straw or fibres, is pressed or daubed against a woven lattice of wooden strips (or bamboo, split willow branch) on vertical wooden struts (or bamboo) (assemble referred to as wattle). In this technique, the wattle acts as a load-bearing element. Due to its light weight, this technique is often used in earthquake zones.	
Rammed earth (RE)	Slightly moist soil is filled into a formwork in layers and each later is compacted to raise a monolithic wall. The formwork can be removed before complete drying and support the layers above. The soil can be compacted with manual or pneumatic rammers. The soil used in this technique is much coarser than that used in other techniques. Rammed earth walls are often stabilised.	
Compressed earth block (CEB)	CEB is the most widespread modern earthen technique in which soil is compacted with a manual or a hydraulic press. Due to moderate to heavy compaction, these blocks are denser, stronger, and dimensionally more uniform than adobe. These blocks are often stabilised and referred to as compressed stabilised earthen block (CSEB).	

Technique	Description	Illustration
Poured earth	Slurry of soil is poured into formwork to cast a monolithic wall, similar to the construction of an in situ poured concrete wall. The soil consolidates under self-weight. This technique can use available equipment used for concrete construction. Stabilisers are usually added to improve workability and flowability.	
Extruded earthen blocks	Clayey soil is compacted and vented in a vacuum chamber before it is pushed through an extrusion nozzle to form blocks (often hollow) that can be cut to the desired dimensions. This process is used in making fired bricks, but instead of firing, unfired bricks are air-dried. These blocks are often stabilised.	
3D printing	In this additive manufacturing technique, layers of wet flowable soil are deposited on top of each other using a movable and programmed nozzle to form monolithic elements. This technique has recently been used in research (Perrot et al., 2018). Additives are used to prepare a flowable mix.	

Earthen construction techniques such as cob, adobe are low resource-intensive and, therefore, still commonly found in several rural areas of developing countries. CSEB technique is increasing in popularity due to the availability of inexpensive manual block making machines. With the advancement of the techniques, the required equipment generally increases, which on the one hand negatively impacts the carbon footprint of a structure, but on the other hand, improves the production rate and reduces labour requirements.

The amount of water to be added differs significantly for each construction technique, as shown in Figure 2.6. While the water content at optimum (corresponding to maximum density) could result in higher strength, a higher water content facilitates mouldability and provides versatility in shaping the soil. It is also worth pointing out that with an increase in water content, the need for adding fibres or additives increases. Earthen material prepared with high water content shrinks, and therefore, reinforcements such as fibres or binders are used to control the shrinkage and flowability.

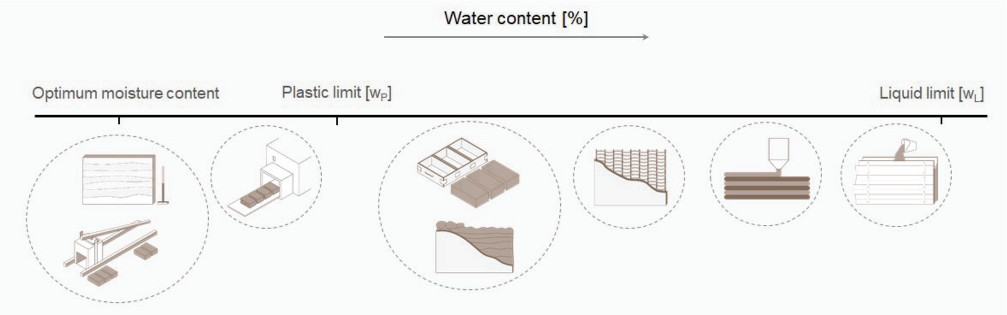


Figure 2.6: Earthen construction techniques arranged based on the water content adopted during its manufacture. This sequence is based on the information aggregated from Kouakou and Morel (2009); Maskell et al. (2013); Hamard et al. (2016); Beckett et al. (2020)

Once the soil is shaped into the desired form and structure using water, it is dried in the air to gain strength and other characteristics required for a functional earthen structure.

2.7 Strength, durability and moisture buffering capacity of earthen materials

The strength of unstabilised earthen material (such as rammed earth) is demonstrated to be dependent on the capillary suction between soil aggregates and is related to the dry density and the moisture content (relative humidity) in the sample after drying (Bui et al., 2014; Chauhan et al., 2019; Gerard et al., 2015; Jaquin et al., 2009). The capillary suction and strength increase with increasing dry density and decreasing moisture content (up to a limit). The increase in dry density can be facilitated through compaction, which is often incorporated in several construction techniques. The moisture content in earthen material while in use depends on the surrounding environment. Unlike concrete and fired brick, the strength of earthen materials therefore fluctuates with fluctuating temperature and relative humidity. In dry and hot conditions, the strength of earthen material would be higher than the average, whereas, in humid, rainy and cold conditions, the strength would be lower. This characteristic of earthen materials often affects the lab-based research, and therefore defining the testing or curing condition is essential to make sense of the strength data. The strength is also known to be influenced by soil texture, especially clay mineralogy (Fabbri & Morel, 2016).

It is generally accepted that the unconfined compressive strength of over 2 MPa is sufficient to construct with earth (Burroughs, 2001). However, the strength requirement of earthen material depends on the overall design and load distributions in the dwelling. In most countries, earthen materials have to pass the minimum strength criteria recommended by the national or regional guidelines. Figure 2.7 presents the minimum compressive strength requirement based on national guidelines and other normative documents in various countries. Of course, a higher strength gives more flexibility in construction and use.

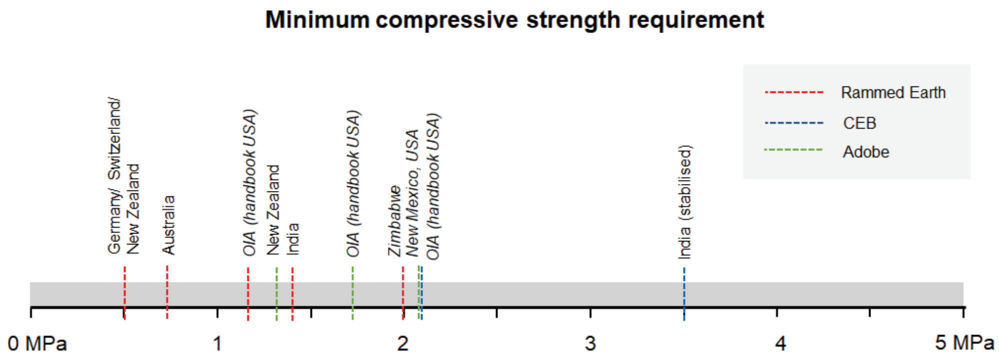


Figure 2.7: Unconfined compressive strength requirements of earthen materials based on national standards and normative documents. Information based on Jiménez Delgado & Guerrero (2007) and Schroeder (2012)

The tensile and flexural strength of earthen material is low, but the flexural properties can be improved with the addition of fibres (Laborel-Préneron et al., 2016). The compressive and tensile strength can be improved with the use of stabilisers or binders. Earth is considered a non-tensile material, and therefore, reinforcements are required to provide sufficient strength in earthquake zones (Fabbri et al., 2018).

While the strength of earthen material is sufficient for the construction of low-rise structures, its failure is often a result of low durability (Beckett et al., 2020; Morel et al., 2012). The durability of earthen structures is affected by environmental actions such as water ingress, erosion due to the wind, fire, solar radiation, growth of micro-organism and burrowing from animals (Fabbri et al., 2018; Laborel-Préneron et al., 2016). Amongst these actions, erosion due to water ingress has the highest impact on the performance of structure during its service life (Fabbri et al., 2018). It is agreed that a good hat and strong boots, meaning a good roof and strong foundation, are critical for durable earthen structures. Therefore, the design of earthen structure has a crucial role to play in its durability.

The disintegration of earthen material, such as earthen blocks, upon water ingress, can be attributed to a reduction in capillary suction that holds the aggregates together (Tadepalli & Fredlund, 1991). The loss of bonding reduces cohesive strength and makes material susceptible to damage. Unlike compressive strength parameters of earthen materials, the water-resistance mechanisms of earthen materials are poorly understood. In this thesis, Chapter 4 is dedicated to understanding the water-resistance of unstabilised earthen material.

The durability of earthen materials and structures can be accurately estimated through long term field tests, but these tests are rarely feasible due to high cost and long duration (Fabbri et al., 2018). Laboratory tests have been developed to quickly predict the water-resistance and other durability parameters of earthen material. Erosion test (water sprayed or dripping on the material at low or high pressure) and immersion tests (partial or complete) are commonly used to test the water-resistance behaviour of earthen materials. However, these tests often simulate extreme conditions and give an indication of stabilisers efficacy (Beckett et al., 2020). Unlike the compression tests that are commonly found in most labs, durability tests are often custom made due to a lack of accessible standardised testing equipment.

An important characteristic of earthen material, which also provides a significant advantage over the conventional building material, is its excellent moisture buffering capacity. This characteristic along with other hygrothermal (coupling of mass transfer of water and heat transfer (Fabbri et al., 2018) properties of earthen material are responsible for providing good indoor thermal comfort and for reducing energy required for heating and cooling a building (Cascione et al., 2019; Giada et al., 2019; McGregor et al., 2016). The moisture buffering capacity of earthen materials is also commonly referred to as 'breathability', due to its ability to adsorb and release moisture, similar to human skin. Clay content and clay mineralogy are known to impact the moisture buffering of earthen materials (McGregor et al., 2014). The clay surface can adsorb moisture in a high relative humidity environment and release it when the relative humidity in the surrounding environment is low. This characteristic of earthen wall allows smoothening of peak (upper and lower) relative humidity values, often leading to a narrower range of values within 40-60%, which is known to be good for human health and well-being (Cascione et al., 2019; McGregor et al., 2016). The adsorption and release of moisture also impacts the thermal properties of the wall. Adsorption of moisture lead to latent heat generation, that can increase indoor temperature. Whereas release of moisture from earthen walls leads to evaporative cooling, therefore, lowering the indoor temperature (Cascione et al., 2019; McGregor et al., 2016). Similar to relative humidity values, indoor temperature is maintained in a narrower range as compared to outside temperature. Therefore, earthen materials provide comfortable indoor temperature in all seasons, and are known to reduce the energy required to heat or cool a building. The moisture buffering value of building materials can be found using laboratory tests, such as recommended by the Nordtest project. In this test, a material is exposed to varying humidity steps of 33% (for 16h) and 75% (for 8 hours) at a constant temperature and the change in its mass is recorded (Rode et al., 2005). The maximum amount of water adsorbed by the material indicates the moisture buffering value of the material. For an in-depth understanding of moisture buffering capacity and overall hygrothermal behaviour of earthen material, readers are referred to McGregor et al. (2016); Fabbri et al. (2018); Cascione et al. (2019); Giada et al. (2019).

While the strength, durability and moisture buffering characteristics of earthen materials are encouraging to construct structures, the myths and prejudice surrounding earthen construction is a barrier to its widespread application.

2.8 Myths related to earthen construction

This section introduces the myths associated with earthen construction that are a barrier to its contemporary application. These myths are uncovered while discussing and revealing various characteristics of earthen materials that are interesting for scientific and practitioner communities.

2.8.1 Unstabilised earthen houses are not durable!

A poorly designed unstabilised earthen dwelling is not durable (elaborated in in Chapter 3), but a well-designed earthen structure could survive for centuries. Although durability is a concern for earthen materials, there are earthen structures, such as those discussed in Section 2.1 that have survived for over 300 years. One of the most common approaches used in improving the durability of earthen structures is through architectural design. Building elements such as high-pitched roofs and roof overhangs could prevent water ingress routes and thus, improve the lifespan of a structure (Medvey & Dobszay, 2020; Norton, 1997).

The issue of durability of earthen construction partially arises from the poor performance of unstabilised earthen material in laboratory experiments. However, laboratory experiment results do not agree with actual practice (Houben & Guillaud, 1994), where unstabilised earthen materials do not pass the laboratory tests designed for stabilised materials (Beckett et al., 2020). For example, an unstabilised earthen block disintegrates within a few minutes during both immersion and accelerated erosion test, while stabilised samples never disintegrate. However, long term durability studies on earthen materials clearly indicate the gap between actual and lab performance of unstabilised materials. In a study by Bui et al. (2009), the erosion recorded in an unstabilised rammed earth wall exposed to 20 years of natural weathering (in France) was 6.4mm (wall thickness 400mm), compared to stabilised wall which had an erosion of 2mm. In another study on unstabilised rammed earth wall exposed to 9 years of natural weathering (in US), the average erosion was measured to be 10-14mm for a 305mm thick wall (Dahmen, 2015). In the prior study, the walls were partially protected, whereas in the latter case, no protection was used. With adequate protection (through a well-designed roof), erosion or weathering could be reduced significantly. Unstabilised earthen structures can be durable, provided due consideration is given to architectural design and material manufacturing processes.

2.8.2 Earthen materials are not strong!

While it is undeniable that earthen materials are not as strong as concrete, they can have sufficient strength to build at least 1-2 storey dwellings. In fact, as mentioned in Section 2.1, buildings in Shibam (Yemen) are up to 8 storeys high. The low strength of earthen material for high rise structures is compensated by higher wall thickness. The structures in Shibam are known to be thick at the bottom, and gradually the wall thickness reduces to the top (UNESCO, 2021). The strength of earthen materials can be improved through the stabilisation process, such as modifying the texture, high compaction, and addition of mineral binders. The use of mineral binders and compaction processes has the potential to increase the strength significantly to meet the performance criteria developed for conventional building material. This is particularly relevant in countries where earthen construction standards are missing, or the market demands are governed by the strength characteristics of building material. Strength of more than 10 MPa can be achieved through stabilisation with a high amount of cement (Danso et al., 2015). Compressive strength up to 8-10 MPa was also achieved through hyper-compaction (compaction with a pressure of 50-100 MPa) (Bruno, 2016).

2.8.3 Building with earth is ancient and is not relevant now!

Earthen construction is a technique that has been practised for over 10000 years, which makes it an ancient practice. With growing concerns over the environment and with the rise in prices of conventional building materials, building with earth is particularly relevant now. Buildings and the construction sector together account for 36% of global energy use and 39% of energy and process-related carbon dioxide emissions (UN Environment and International Energy Agency, 2018). The high impact of a building is partly due to its operational need (example space cooling and heating) and partly due to the production of building materials. The high emissions during the production of Portland cement coupled with a scarcity of sand (Ioannidou et al., 2017) and high-water use (Miller et al., 2018) has led to growing interest in building with earth.

As a construction material, 'earth' offers several advantages such as improvement of the indoor air quality and thermal comfort (Cascione et al., 2019), reduced operational and embodied energy[2] use (Gallipoli et al., 2017; Morel et al., 2001) and potential to be reused (Fabbri & Morel, 2016; Minke, 2006). These characteristics have contributed significantly to the revival of earthen building materials and technology. Moreover, print and digital media is also contributing towards the awareness of earthen materials (Down to Earth, 2020; Jayaraj, 2020; VICE, 2020; Volpe, 2018; Wustemann, 2020). The local availability of raw materials is useful for low-cost housing in developing countries (discussed further in Chapter 3), whereas the increasing awareness toward environment and indigenous material is attracting people towards earthen materials, especially in developed countries.

The question on use of earth in contemporary construction often arises due to its association with poverty (discussed in Chapter 3). This association is based on poorly designed earthen houses that are widespread. Poorly designed structures are often built by low-income households, with no access to experts and tools. However, a well-designed structure is often designed and constructed by architects and contractors experienced in earthen construction. Some examples of contemporary or modern earthen construction are shown in Figure 2.8. These structures are not only good in performance, but have also been praised for their aesthetic qualities.. Earthen construction is increasingly included in national building codes and standards (refer to Appendix 2A for a list of such standards), which promotes its application. In addition, professionals and companies with expertise related to earthen construction are growing. For example, over 300 companies are active in Germany (Dachverband Lehm, 2021), whereas France has over 650 professionals active in the field of earthen construction (Leylavergne, 2012).

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[2] energy consumed in all process used in making the building or any material

Figure 2.8. Example of some Modern earthen structures. Top left: Ricola Kräuterzentrum, Laufen, Switzerland (Image credit: TERRA awards); Top right: School, Rudrapur, Bangladesh (Image credit: The Architectural Review); Middle left: Tucson mountain house, Arizona, US (Image credit: Bill Timmerman / Studio Rick Joy);Middle right: Children's Nursery, Oranienburg-Eden, Germany (Image credit: Natural building blog); Bottom left: Ann and Rebecca house, Bangalore, India (Image credit: Vivek Muthuramalingam/ Biome environmental solutions); Bottom right: The great wall of WA, Pilbara, Western Australia (Image credit: TERRA awards)

2.9 Prejudices related to earthen construction

There are strong prejudices (preconceived opinions that are not based on reason) for and against earthen materials. While myths against earthen constructions are widely held, prejudice, in the context of this thesis, is a term used for the opinions and biases that are highly contextual and create groups of individuals holding contrasting sentiments. These conflicting sentiments often limit the cooperation that is required for the advancement of the field of earthen construction. In this section, a balanced argument for and against selected prejudice is discussed. Some of these common prejudices are:

2.9.1 Earth or mud is a poor people's material

The majority of existing earthen structures are in developing countries and are part of housing stock that is marked by poor quality construction (Marsh & Kulshreshtha, 2021). The inferior quality is often due to a lack of financial resources in low-income households. Quality of housing, together with household income, are indicators of quality of life. Therefore, it fuels the prevailing attitude that earthen materials are poor people's material. Multiple studies have found this link between earthen structures and low-societal image in developing countries (Adegun & Adedeji, 2017; Hadjri et al., 2007; Sameh, 2014; Zurakowska et al., 2009).

While low-quality housing forms a major part of housing stock, there is a rise in high-quality earthen structures in developing countries. Earthen structures constructed in recent times are often commissioned or self-built by middle or upper upper-income households conscious about the environment and do not want to build with energy-intensive building materials. These new developments can be extremely expensive, especially when the project is executed by a luxury housing developer and well-known contractors and architects. Some of the examples of such high-end development are Goodearth[3] in India and Tierratec[4] in Colombia. Therefore, while earthen materials are often linked to poverty and poor-quality housing, modern earthen structures challenge the prevailing attitude and are expected to improve the perception of earthen materials.

In contrast to the number of earthen structures in developing countries, developed countries have a smaller number of existing earthen structures. In these countries, building with earthen materials is a niche market which is more expensive than conventional housing due to a higher labour cost (Williams et al., 2010). These structures are high quality and therefore have a positive social image and have no correlation to poverty. However, it should not be ignored that people unaware of earthen construction in developed countries may still have a negative association with earthen materials due to the prevailing attitude in developing countries which are often communicated globally by the mainstream media.

2.9.2 Earthen houses are sustainable as compared to concrete and fired brick houses!

Advocates of building with earth claim that earthen structures are more sustainable than concrete and fired brick houses. 'Sustainability' is a misused term that is often generalised for carbon emissions, while it encompasses a larger framework that includes, amongst others, social and economic factors. A life cycle analysis (LCA) can be performed to evaluate the environmental impact

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[3] https://goodearth.org.in/bengaluru/

[4] http://www.tierratec.com/

of building materials. This analysis could be used to compare materials with similar functional performance and service life. However, the contrasting characteristics of earthen materials compared to conventional materials (such as concrete and fired brick) make it challenging to conduct a fair comparative analysis.

Multiple researchers have conducted life cycle analysis and embodied energy calculations and have concluded that earthen materials are more ecological than conventional building materials (Arrigoni, Beckett, et al., 2017; Chel & Tiwari, 2009; Christoforou et al., 2016; Dahmen et al., 2018; Fernandes et al., 2019; Melià et al., 2014; Shukla et al., 2009; Treloar et al., 2001; Venkatarama Reddy & Prasanna Kumar, 2010). The majority of studies revealed that the transportation distance of raw materials (e.g. soil) and the use of stabilisers are responsible for the environmental impact of earthen building materials. In the study by Fernandes et al. (2019), lime stabilisation (3-3.5%) of earthen material was responsible for over 60% of the impacts in the Portuguese context. The environmental footprint of rammed earth and compressed blocks was calculated to be around half to that of fired bricks and concrete blocks (comparison based on similar thermal transmittance values). Reddy and Kumar (2010) calculated embodied energy of cement stabilised rammed earth (8%) in the Indian context and found the values to be 15-25% of fired bricks. In a study by (Dahmen et al., 2018), stabilised hollow blocks (4% cement) had about half the embodied carbon when compared to hollow concrete blocks (of 11% cement).

While the results of these analyses support earthen construction, they cannot be fully generalised due to variability in the building design, context, and processing of earthen materials. In a study on the environmental and economic impact of stabilisation, Ouedraogo et al. (2020) recommended not to use over 4% mineral binder. This recommendation was supported by the fact that 4% Portland cement can be used to make hollow concrete blocks of superior water- resistance and compressive strength (up to 8 MPa). Using the same quantity of cement to produce stabilised earthen blocks often results in a building material of comparatively inferior performance. It is known that earthen structures are often stabilised with a higher content of Portland cement (5-12%). Rauch (2020) argues that it is perhaps better to use the high amount of cement content with sand and gravel to form a high-performing concrete of strength and water resistance multiple times better than stabilised earthen materials. Moreover, an earthen structure is usually thicker than concrete construction (due to low compressive strength); therefore, the amount of cement used in the structure could be comparable to concrete construction (Rauch, 2020).

In a scenario where the environmental footprint in the construction phase of earthen structures is similar to concrete and fired brick structures (especially due to longer transportation distance), earthen structures can still benefit the building use phase. The moisture buffering capacity of earthen material is known to provide good thermal comfort and reduces the energy required for heating and cooling (Cascione et al., 2019; Giada et al., 2019; McGregor et al., 2016). Therefore, less energy is consumed during the service life of the structure. Additionally, unstabilised earthen structures can be demolished and completely re-used.

Pioneers and experts in the field of earthen construction emphasise that construction with unstabilised earth should be complemented with good design to protect potentially vulnerable elements (Rauch, 2020; Van Damme & Houben, 2017). This could guarantee the ecological benefit of earthen structures. They also strongly advise against the use of mineral stabilisers to preserve the ecological characteristics of earthen structures.

2.9.3 'One should never stabilise earthen materials'

The most common 'binders' or 'stabilisers' used in contemporary earthen construction are Portland cement and hydraulic lime (often referred to as 'mineral or chemical stabilisers'). The use of chemical stabiliser is a subject of widespread debate due to a multitude of reasons. Stabilisers increase the embodied energy of structure (Dahmen, 2015; Treloar et al., 2001; Venkatarama Reddy & Prasanna Kumar, 2010) and result in the reduction of moisture buffering capacity of earthen construction (Arrigoni, Grillet, et al., 2017). They increase the cost (Gallipoli et al., 2017; Hall, Najim, et al., 2012) and impacts the reusability of earthen structures (Gallipoli et al., 2017; Morel et al., 2013; Schroeder, 2016). The negative impact of stabilisation has led some researchers to strongly advise against the use of mineral binders, especially Portland cement in contemporary earthen construction (Rauch, 2020; Van Damme & Houben, 2017). These researchers argue that instead of using a high Portland cement content in earthen construction, it is reasonable to use the similar amount of cement to build higher performing concrete structures.

Although stabilisation has disadvantages, the use of stabilisers such as Portland cement can increase the strength and water resistance properties significantly. Contrary to the opinion against stabilisation, other researchers maintain that the use of Portland cement depends on the context and is not necessarily detrimental in all scenarios. Marsh et al. (2020) argues that the use of a mineral binder to stabilise earthen material using local soil could be preferred over concrete construction as the latter results in the depletion of sand, leading to its scarcity, and often involves long-distance transportation of raw materials. Furthermore, stabilisation can also result in a wider acceptance of earthen materials, especially in developing countries. Stabilisation of earthen material can help build trust in the material and can also facilitate passing material standards and requirements essential to begin construction.

The use of stabilisers is debatable but context-driven and may be appropriate in some scenarios. Although a good architectural design (strong foundation and good roof) is sufficient to minimise the effect of environmental forces, stabilisation is required where a good design cannot be guaranteed. For instance, It is challenging for a low-income family with limited financial means and lack of assistance to construct an earthen structure with attention to architectural detail. Similarly, the need to stabilise is also advantageous in mass housing projects where multiple houses have to build in a short period of time and standardisation of building material is essential.

2.9.4 'Earthen buildings are not scalable'

Building with earth is often not considered scalable, which means that while it is appropriate for building independent housing units, it is not feasible for mass housing projects that have potential to cater to the global housing shortage. In mass housing projects, several houses are arranged in spatially repeatable units. Although the architectural design of housing plays a crucial role in the feasibility of a housing project, building materials, especially locally available building material, has a paramount importance in housing for low-income families (Bredenoord, 2017). Earthen houses are often built with consideration to the local knowledge, culture, traditions, and personal aspirations thereby, giving a unique identity to individual houses. In contrast, a mass housing project benefits from prefabrication and the standardisation of building material and design.

Even though earth is not a standard material, the earliest examples of housing with earthen materials are over 300 years old and still used (Figure 2.1). More recent mass housing project such as in New Gourna village in Egypt were built with adobe in 1945 for 9000 inhabitants (World Monuments Fund (WMF), 2011) have not been entirely successful and have met with criticism. While stabilisations and large prefabrication facilities were not adopted in earlier construction projects, they are more common in the mass housing projects due to the urgency of providing housing for the growing population. An example of such housing was constructed in Odisa, India, using interlocking stabilised blocks to construct 1450 housing units in 2002 (Chaudhury, 2019). In fact, the use of stabilised earthen blocks is recommended over fired brick and concrete due to ecological and economic benefits in bridging the housing gap in the Indian context (Mastrucci & Rao, 2019). Although stabilisation leads to standardisation of earthen material, it does not guarantee good performance as experienced in unsuccessful housing projects of Yelahanka, Bangalore (Jagadish, 2009).

Earthen materials are not the conventional choice for mass housing projects in developing countries due to its social image, lack of experienced contractors, maintenance requirements and costs involved in stabilisation. However, there is a potential for using earthen materials for low-cost mass housing projects, which is thoroughly discussed in Chapter 3. While there is a lack of successful mass housing projects with earthen materials, modern earthen technologies and advances in material understanding could open up several pathways to explore their potential and scale it to build resilient structures.

2.10 As simple as A, B,C,D?

Earthen structures are often constructed by self-builders with the help of volunteers and local masons. In recent decades, the role of contractors, engineers and architects in earthen construction is becoming critical. As building with earth does not require complicated processing, anyone with some experience can take a building project and construct. Does that mean that building with earth is simple?

There is no straightforward answer to this question, but an analogy with baking bread can facilitate understanding. While the recipe of baking bread is easily accessible online, it does not guarantee that the bread made using the recipe would be as tasty. Adjustments to the recipe would be required based on the quality of ingredients available and variability in the heating process. It will take many iterations before a bread of high standards can be baked. To further raise the quality of bread, in-depth knowledge of the physical and chemical characteristics of ingredients and heating process is required. One who thoroughly understands the science of bread making can even tune the process to make desirable bread of specific taste and texture. Similarly, experience and understanding of raw earthen material and processes are required to make good quality earthen structures. Earthen construction has evolved as a trial-and-error method of construction where the focus mainly was the end product. However, in recent decades, scientific aspects of earthen material have received significant attention. This has led to advancement in building techniques and material properties, to suit contemporary construction requirements.

Moreover, soil is a diverse material that is complex to understand. One factor that makes building with earth challenging, is that unlike concrete chemical bonds are not generally responsible for strength and durability. The interaction between different aggregates are pre-dominantly physical in nature (e.g. due to friction, compression, capillary suction and electrostatic forces). Therefore, these forces are sensitive to the production process. While stabiliser can change the governing forces into chemical and permanent bonds, it could still not always provide the required quality. In fact, several concrete structures are of poor quality and are not durable. Therefore, unless design of the structure complements the material characteristics, building a durable earthen structure is challenging. In order to promote earthen construction and include it in action to fight climate change, it is recommended to ensure that it should have the following characteristics:

Affordable: High-quality earthen structures need to be affordable to low and middle-income groups; otherwise, it will remain a niche material. Reducing material costs or labour costs could lead to a reduction in costs. However, the suitability of the approach will depend on the local context.

Breathable: Moisture buffering capacity, often referred to as breathability, is an essential characteristic of earthen material that regulates indoor climate and saves energy and cost during the service life of structure. While stabilisation and other external treatment of structures can improve strength and durability, it can significantly impact the breathability of structures. Complementing a good quality material with a good architectural design is required to tackle durability issues without compromising the breathability of the structure.

Climate adaptive: Earthen structures should be adaptive to a changing climate. Earthen materials can regulate variation in temperature and humidity. Therefore, earthen structures are inherently climate adaptive, especially considering the shorter time frame of daily and monthly variations. However, consideration of rising sea levels and increasing disaster risks need to be considered while designing the structure. A structure should be resilient to tackle disaster scenarios. Otherwise, the susceptibility of earthen structure to water-ingress could turn out to be its most significant disadvantage. Providing a strong and durable foundation plays an essential role in making earthen structures resilient.

Desirable: Often neglected in technical literature, desirability is an essential characteristic that governs the application and demand of the material. The low social image of earth has a strong influence on its desirability and therefore unless earthen structures are desirable, they will not be able to cater for the global housing shortage.

Durable: Durability, the most essential characteristic of earthen structures, is a facilitator to all the characteristics mentioned above. Although earthen structures are considered not so durable as compared to conventional materials, there are several ways to make them better. It is essential to guarantee sufficient durability to a structure by improving material properties and employing intelligent design solutions.

2.11 Summary

Building with earth (mud) is an over 10000 years old practice, but its use over past decades has declined due to the increase in popularity of industrial building materials such as concrete and fired bricks. However, concerns over climate change have led to re-gain its popularity as an ecological and economical alternative. This chapter provides an overview of various aspects of earthen construction in an attempt to introduce this field to non-experts.

Soil, the raw material in any earthen construction project, comprises of different aggregates of varying sizes (classified as clay, silt, sand, gravel etc). Clay aggregate acts as a binder in the silt, sand and gravel matrix and plays a key role in strength and durability characteristics of earthen materials. The selection of soil for construction is often made by following the guidelines prescribed by national standards and normative documents. A suitable soil can be selected either based on the proportion and quantity of various aggregates or through the consistency behaviour of overall soil, i.e., how plastic it is. Soil found on or near building sites is often stabilised physically, mechanically, or chemically (or with a combination) to improve its strength and durability characteristics. The soil is then shaped into different forms and elements using a chosen earthen construction technique. Different physical and mechanical stabilisation process can be used in combination with additives (mineral binders or stabilisers) such as Portland cement and hydraulic lime. These techniques range from traditional techniques such as cob and adobe to modern techniques such as CSEB and extruded earth.

The freshly built elements are dried resulting in an increase of strength due to increased capillary suction between the soil aggregates. Compressive strength of over 2MPa is considered sufficient for most low-rise construction. While the strength of earthen material is primarily adequate, its failure is often due to low durability, especially its sensitivity to water ingress. The water-resistance of an earthen structure is often improved through good architectural design (strong foundation and good roof), but in several scenarios also by using a mineral binder such as Portland cement and hydraulic lime. Earthen buildings have several characteristics, including their moisture buffering capacity, which enables them to regulate indoor climate and reduce energy need for heating and cooling space.

Widespread application of earthen construction is limited by several factors, including myths and prejudice surrounding earthen materials and construction. Some of these myths have been disproved to demonstrate that earthen structures can be durable, strong, and highly relevant. The prejudice for and against earthen construction are also discussed to give a broader and balanced picture on the preconceived notion of earth.

While building with earth is not complicated; practical experience and understating of raw materials are important to build high-quality earthen structures. To make a dual contribution to climate change and housing shortage, earthen construction should be affordable, breathable, climate adaptive, desirable, and most importantly, durable.

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3

The Potential and Current Status of Earthen Material for Low-Cost Housing in Rural India

"Sharing a tea with a fascinating stranger is one of life's true delights"

– Iroh, Avatar the last air bender (S2 E8)

Building with earth is proposed as an economical and environmental friendly alternative due to rising price of conventional building materials. However, earthen houses have significantly declined in India and thus, it becomes necessary to evaluate if earth can make a valuable contribution to contemporary housing shortage. Therefore, a survey was conducted in India to understand technical, socio-economical, and other factors favouring or liming construction and daily use of earthen houses. As an outcome of survey, 'Image' is recognized as the key barrier towards acceptance of earthen houses. The 'Image' and other related factor(s) are discussed to point out the requirements for low-cost earthen housing in India. Research into inexpensive stabilisers and design, initiative by government and middle-high income households, education and demonstration of earthen projects are expected to improve the acceptance of earthen materials for housing construction.

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3.1 Introduction

The local availability, ease in processing and economy of earthen materials have made it one of the potential solution to contemporary housing shortage in India. The potential of earthen material for low-cost housing in India was already recognised in 1980s (Agarwal, 1981) and restated by multiple scholars and organisations in 1990s (DownToEarth, 1992). Although the role of earthen materials for housing is recognised for several decades now, the desire and access to modern building materials have resulted in a decline in interest towards earthen construction in India. The changing trend of housing based on predominant materials of wall in rural and urban India is shown in Figure 3.1. A significant decline in earthen houses in favour of burnt brick houses can be observed in past 40 years in rural India.

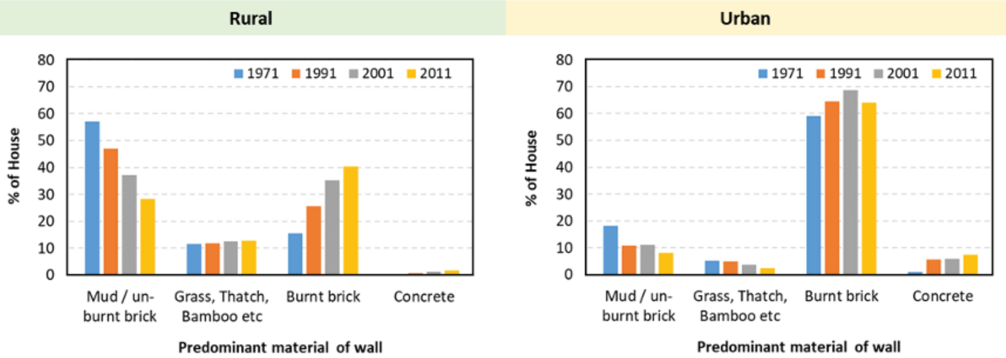


Figure 3.1: The trend of housing based on predominant material of wall in rural and urban India. The data have been acquired from Census of India (COI) 1971 (Chandra Sekhar, 1972), COI 2001 (Bhathia, 2001) and COI 2011 (Chandramouli, 2011). Data for the year 1991 is obtained from the research of Ramancharla & Murty (2014). The data for year 1981 was not available.

Until 1971, earth was the most widely used building material in rural India. However, the number of earthen houses in rural areas declined from 57% in 1971 to 28% in 2011. Mud or unburnt brick was the predominant material of wall construction in rural areas until 2001 when it was replaced by fired/burnt brick. In urban India, burnt brick is currently the most commonly used walling material whereas concrete is gaining popularity due to increase in construction of high-rise buildings.

Contrary to the popular perception that claims that the use of Portland cement is rising in India, the census data does not directly reflect this trend (at least not as a predominant material for walling). The survey, however, does not show the data for secondary materials. For example, in brick construction, cement is the most used secondary material as a binder between bricks and as a material for plastering. Therefore, the popularity and availability of cement is one of the main causes for decline in earthen houses in India.

A decline in earthen houses indicates that the local and traditional materials and techniques have been unable to compete with industrial materials. In spite of low interest in earth as a building material, the potential of using earthen materials to build contemporary housing has been recognised by several studies and scholars. Mastrucci & Rao (2019) proposed earthen materials as a low-cost and ecological alternative to conventional building materials for bridging the housing gap in India. Organisations, such as Infrastructure Development Finance Company (IDFC) have recommended the government of India to promote earth construction (IDFC-RDN, 2013). Some authors argue that earthen houses are expected to make a comeback (Menon, 2016; The times of India, 2018; Varghese, 2012; Vijayan, 2017). Moreover, the consumer price of cement is likely to increase due to the rise in price of petrol and therefore transport costs (The Economic Times, 2018). This can lead to financial difficulties in using cement for housing projects, especially in rural areas. Whereas, earthen houses are claimed to be up to 35% cheaper than concrete construction (The times of India, 2018; Varghese, 2012).

The disparity between the long-standing acknowledged potential of earthen houses and their declining proportion raises a critical question. Is building with earthen material a solution to contemporary housing shortage in rural India? To answer this question, it is important to understand the experience of current users and other stakeholders responsible for construction and promotion of earthen houses.

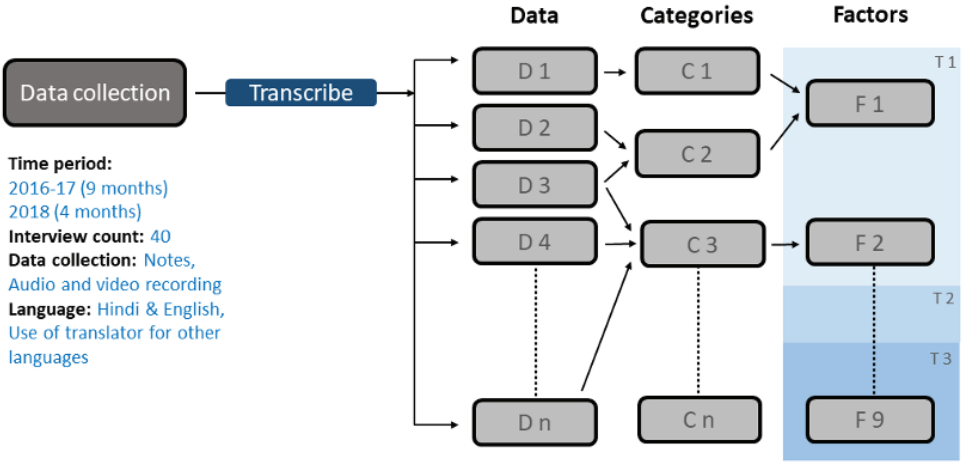
3.2 Survey: methodology and scope

A survey was carried out in five different bioclimatic regions of India in order to understand factors favouring or limiting the construction and everyday use of earth houses. Forty informal and semi-structured interviews (Bernard, 2006) were conducted in different locations of India as shown in Figure 3.2, with further information presented in Appendix 3A. The scope of information provided by the interviewee was kept as broad as possible in an attempt to understand the emotions of each interviewee connected with the everyday use of an earth house. The adopted explorative research approach is close to the method suggested by O'Reilly (2004) and in particular, similar to research work of Singh et al. (2017) which was conducted in an rural Indian context.

Informal talks and conversation can facilitate insight into sensitive topics (Narayanasamy, 2009) and are important to gain insight into people's needs and beliefs (Mink, 2016). According to Narayanasamy (2009) the informal talks should be complemented with observations. Visual remarks on state of housing and neighbourhood together with talks unrelated to housing were included in the discussion as tools for observation. Together with traditional earthen houses, earthen houses constructed in recent times were also considered in this research. The interviewee group consisted of people involved directly in earth construction. This included earth house dwellers with different socio-economic background, earth construction experts, architects, engineers, masons, contractors, consultants, educators and volunteers. More information on the survey group can be found in Appendix 3B.

The field survey was complemented by data analysis of notes, audio and video records. The data were compiled to form factors as shown in Figure 3.3. These factors include motivation to construct an earthen house, performance of already existing structures, maintenance requirements, economy, image, influence of government and policies, and education and training.

Figure 3.2: Map of India marked with interview locations. Information on bioclimatic, geographical and meteorological classification of the interview location can be found in Appendix 3A.



Time period: 2016-17 (9 months)
2018 (4 months)
Interview count: 40
Data collection: Notes, Audio and video recording
Language: Hindi & English, Use of translator for other languages

Figure 3.3. Flowchart of data analysis of the survey. The data were transcribed and complied into categories that were combined to form factors. These factors were clustered together in specific themes.

3.3 Results: Factors affecting choice for and against construction and everyday use of earthen houses

An overview of major techniques and type of earthen construction in India is important for understanding the factors affecting choice. Earthen construction in India has a strong link to the climate, available local resources, soil type, traditions and heritage of a location. A short review of earthen construction techniques (with example of typical house construction) is presented in Table 3.1. Some earthen houses visited during the survey are shown in Figure 3.4. The detailed information regarding earthen construction in India can be found in Kulshreshtha et al. (2019).

Table 3.1: Information on few aspects of construction of a typical house visited during survey

Construction technique	Bioclimatic region	Locations	Preparation of earth	Typical earthen house construction and materials	Note
Adobe (Rectangular blocks of mud/ earth are cast in moulds and joined together with mud mortar)	Cold and Cloudy	Bir and Dharmshala, Himachal Pradesh	Pine needles and rice husk was added to soil and mixed. Soil was kept undisturbed up to 3 days. Block cast in mould and dried in sun for 2+ days.	Foundation: Often with stones packed with mud mortar and first 75-90cm raised (Figure 3.4.a) Wall: Adobe blocks with mud mortar. Roof: Stone tile roof/ metal sheets supported by wooden beams / truss.	Special provision: Reinforcement rods used on the edges of wall for the protection against wind and earthquakes (new constructions). Use of fired bricks in toilet and bathroom (areas with use of water)
	Hot and Dry	Gandi na gam in Khavda, Gujarat and Kriparampur in Jaipur, Rajasthan	Soil was mixed with rice husk and cow dung. Blocks formed in a mould or were handmade.	Foundation: Often missing Wall: Adobe blocks with mud mortar (often mixed with cow-dung). Roof: Thatch, asbestos sheet, metal sheet roof supported by bamboo truss.	Stone bricks placed over metal roof to protect from wind. (Figure 3.4.c)

Construction technique	Bioclimatic region	Locations	Preparation of earth	Typical earthen house construction and materials	Note
Cob (a thick monolithic wall raised from foundation)	Composite/ Warm and Humid	Khunti, Jharkhand and Sundargarh, Odisha	Soil was mixed with water and left undisturbed overnight. Mixing of soil by stamping to form a uniform slurry. Soil moulded into balls that are easy to carry and pass.	Foundation: stones packed with mud mortar Wall: raised layer by layer as a monolithic structure. Roof: ‘Khapra’ Curved country fired tiles, asbestos sheet or thatch roof supported on bamboo, wood or metal tube.	Fired bricks placed over the asbestos sheet to protect the roof from wind. (Figure 3.4.d) The walls are extended to make sitting platforms which serves as community spaces for cooking and get-together. (Figure 3.4.e)
	Warm and humid	Tiruvannamalai and Sittlingi, Tamil Nadu			
Wattle and daub / ‘Ikara’ (timber or bamboo frames with split bamboo weaves act as the structural wall members that are daubed with mud)	Cold and Cloudy	Namchi, Sikkim	Soil was mixed with water and a slurry is formed. The slurry was left undisturbed for some time and later daubed on the bamboo or timber frame.	Foundation: Stone packed with mud/ cement mortar and raised. Sometimes, concrete foundation is used in newly constructed traditional houses. Wall: Bamboo/ wooden frames with split bamboo weaves and daubed with mud (Figure 3.4.f, 4.g) Roof: Metal or Bamboo roof usually supported by metal tubes/bamboo.	The living unit and bathrooms have a plinth and floors made of concrete. Kitchen and bathroom separate from living area.
	Composite	Delhi			The foundation was missing in the houses in Delhi and roof were covered with plastic to protect against rain.
CSEB – Compressed stabilised earth block (blocks made by compressing the earth in a manual or hydraulic press)	Cold and Cloudy	Namchi, Sikkim	Soil mixed with 8-10% cement or hydraulic lime and compacted in a manual press to make CSEB.	Foundation: RCC foundation, stone packed with cement mortar Wall: CSEB bind together with cement mortar. Roof: CSEB or RCC roof, Metal roof supported on Wooden truss.	In some cases, columns and beams were made with Reinforced Cement Concrete RCC. (Figure 3.4.i)
	Warm and humid	Auroville, Tiruvannamalai, and Sittlingi, Tamil Nadu			

Figure 3.4: (a) Adobe structure in Bir built with attention to design and engineering [owned by an organisation], (b) Traditional earthen house 'Bhunga' in Khavda, (c) Adobe house with metal roof in Kriparampura, (d) Cob house with asbestos roof in Serjitkhel, Khunti, (e) Cob house with country fired curved tile in Tangerpalli, Sundargarh, (f) 'Ikara' house with metal roof in Namchi, (g) Under construction house in Delhi [split bamboo and grass visible on walls], (h) Earth bag house with thatch roof in Tiruvannamalai, (i) CSEB house in Namchi, (j) CSEB arch structure near Pondicherry [9.5 m span and 42m length is 10cm thick] , (k) Poured earth houses near Pondicherry and (l) rammed earth wall with country fired brick tiles and thatch roof in Tiruvannamalai.

Two types of earthen houses were identified in the survey: 'traditional earthen houses' and 'modern earthen houses'. Traditional earthen houses are commonly found in most rural areas and adopted based on local conditions and cultural motives. These houses are often constructed with use of raw earth, with or without addition of natural fibre. Cob, adobe and wattle and daub are examples of traditional earthen construction techniques (Figure 3.4). A modern earthen house uses contemporary construction techniques in combination with earth as a building material. CSEB (compressed stabilised earthen blocks), rammed earth construction' (soil is filled in formwork in layers and each layer is compacted with mechanical force to construct a monolithic structure) and poured earth (cement is mixed with soil and sufficient water or plasticiser so that earth is fluid enough to be poured into the formwork) are some examples of modern earthen techniques (Figure 3.4). Modern earthen construction is usually labour intensive and use of inorganic binder such as Portland cement and hydraulic lime is common. A comparison between these constructions is shown in Table 3.2. Several of the comparisons are qualitative due to the nature of the research methods and are further explained in the sections below.

Table 3.2: Comparison between Traditional and Modern earthen construction. The distinction is made based on the information collected in the survey.

Characteristics of earthen construction	Traditional earthen construction	Modern earthen construction
Life span	5-30 years (reported)	50+ years (estimated)
Construction	Non-engineered, foundation sometimes missing	Engineered, attention to details
Common construction technique	Cob, wattle & daub, adobe	CSEB, rammed earth, poured earth
Construction cost	Low	Medium to expensive
Type of labour	Self-help construction	Expensive and trained labour
Stabilisation	Some degree of physical stabilisation, biological stabilisation	Physical, mechanical and chemical/inorganic (cement and lime)
Weather resistance	Poor	Good
Termite resistance	Poor	Good
Compressive strength	Low (<3.5 MPa)	Medium (>3.5 MPa)
Maintenance requirement	Frequent	None to occasionally
'Re-use of soil' potential	High	Medium- low
Standardization	No	Some degree of standardisation

The factors identified from the survey have been merged in the following 3 themes namely: Technical (based on facts related to earthen construction), Socio-economical (based on emotions that relates to economic status) and, Political and educational (based on policies and initiatives that are independent of households).

3.3.1 Technical

The technical aspects related to the performance of earthen construction such as environmental friendliness, better indoor climate and positive effects to health were widely acknowledged. However, the limitations such as poor resistance to external environmental forces (that result in frequent maintenance) and insect infestation were motivating factors behind the choice of conventional (industrialised) building materials.

3.3.1.1 Environmental and health benefits

Earthen houses were widely considered environmentally friendly due to local availability, minimum processing of raw material and recycling and reuse. Limited transportation and simple processing techniques also make earth an economical and user-friendly material. Earthen houses, especially those which are unstabilised, disintegrate in nature and can be re-used numerous times. Examples of traditional earthen houses built with materials of ancestral house were found in Bir and Khunti.

Earthen houses were reported to be good for health. The reason behind the positive effect on health were unclear but most dwellers attributed it to comfortable indoor climate and ability of soil to absorb pollutants. Conversely, issues such as cleanliness and problems with rodents were also acknowledged. For example, an interviewee mentioned that the mud flooring results in unhygienic conditions during the rainy season, i.e., when a person enters the house with wet feet, the whole house gets dirty, and the floor becomes an active site for parasites which can be harmful for inhabitants.

3.3.1.2 Thermal performance

Earthen houses are known to regulate indoor temperature and humidity, thus providing comfortable indoor climate in all seasons. This was considered by far the most beneficial aspect of earthen houses. Although, widely acknowledged to be cool in summers, some earthen houses were reported to be colder in winters. A farmer in Khunti mentioned that the family prefers to stay in rooms constructed with earth during summer and in concrete rooms during winter. Although, the precise reason was not given, even after further questioning. In many cases, traditional earth houses were modified over time without full consideration, and they lost the essential characteristics such as thermal behaviour and aesthetics of an earthen construction. Building elements such as roof was often replaced with modern materials such as metal or asbestos sheets. These materials have a high thermal conductivity and low thermal inertia resulting into excessive heat in summers and cold in winters.

3.3.1.3 Durability

The durability of traditional earthen houses was a major concern of all the interviewees. Most of the traditional earthen houses faced significant deterioration due to rain in past and required frequent re-plastering. Sometimes, construction without a foundation and inadequate protection against rainfall resulted in structural weakening of the earthen walls leading to their collapse (Figure 3.5.a). Several houses that were deteriorated by rainfall and flooding were abandoned (Figure 3.5.b.). The performance of traditional earthen houses in case of flooding was considered poor. However, in some instances such as in Namchi (thin and light weight walls) and Bhuj (cylindrical wall geometry), the houses were found to be earthquake resistant.

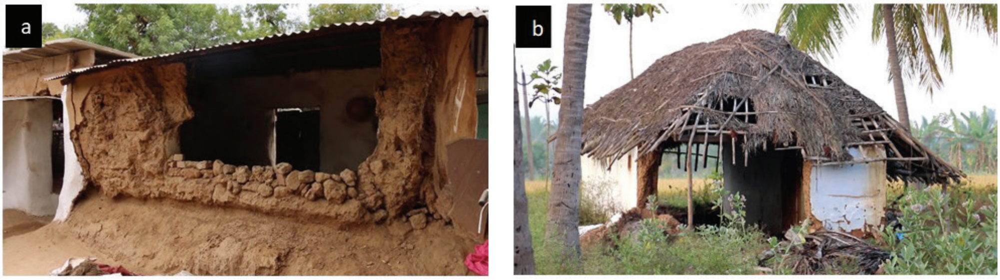


Figure 3.5: Failure of structure due to the action of rain. (a) A collapsed adobe wall in Kriparampura, Jaipur that failed due to rainfall irrespective of being located in hot and dry climate and (b) An abandoned cob house in Sittlingi, Tamil Nadu.

One of the most commonly identified limitations of traditional earth houses was termite infestation. This problem was more prevalent in the houses which were not continuously functional for many years. This was attributed to change in method of cooking over the years, i.e., the traditional method of cooking in 'Chulas' (wood/coal fired stoves) resulted in smoke that worked as termite repellent whereas the modern gas or electric cooking does not emit smoke. The building and material techniques have not been upgraded to accommodate changes in lifestyle.

In modern earthen structures, good design, addition of inorganic stabiliser and adequate engineering measures results in a durable structure. These structures do not require frequent maintenance (re-plastering). However, the problem of weathering of CSEB (due to lack of proper curing and poor understanding of soil stabilisation), flaking on the wall (due to rise in water from foundation in absence of impervious lining) and cracking on the exterior surface in cold climate (due to improper curing of CSEB) were also acknowledged.

3.3.1.4 Maintenance requirement

Traditional earthen house requires frequent re-plastering whereas modern earthen houses were reported to be low maintenance. Weekly plastering of floor and biannual plastering of walls in a traditional earthen house was a common practice which was reported to have declined possibly due to the influence of modern materials that do not require frequent plastering. A dweller in Khavda reported to use plastic sheets during rain to prevent re-plastering of walls. The roofs of traditional houses need to be replaced in 5-15 years, depending on the material used for roofing. Although the maintenance (repair and plastering) of traditional earthen houses is simple and economic, several dwellers reported the need for frequent maintenance took a significant amount of time which made earth construction undesirable.

3.3.1.5 Construction cost

The cost of construction of a typical earthen house depends on the price of stabilisers, transportation requirements, labour availability (if required) and involvement of engineers and designers. Traditional earthen houses are often self-help structures (structures built by the dweller with the assistance of neighbours and family members), using local soil and stabilisers, thereby reducing the cost of construction. In some households, such as in Khunti, the dwellers re-used the wooden frames and roof of an abandoned earthen house, resulting in no monetary investment in the house construction. A cob house construction in their neighbourhood in 2016 was built with an investment of ₹630 /m^2 (~ €8/m^2). The wattle and daub houses in Delhi were reported to be built for ₹1000-2000 /m^2 (~ €12.5-€25/m^2) with major expenditure being the cost of timber and labour for timber construction. The quality of construction of these inexpensive houses was observed to be poor with an estimated lifespan of 10-20 years. The low-cost of traditional earthen houses is a determining factor for many dwellers for choosing earth as a building material. However, they are in general perceived to be inferior in quality as compared to conventional or 'Pucca' houses.

Contrary to the traditional houses, modern earthen houses were reported to be expensive and comparable to the cost of concrete and fired brick houses. The cost of a modern earthen construction such as CSEB (the most prevalent modern construction technique in India) depends on the cost of earthen blocks, which are affected by the labour costs, quantity and price of stabiliser used. In most places, the difference in cost of fired brick and CSEB is marginal whereas the volume(size) of CSEB is up to 2.5 times (of fired brick). In addition, there is no need to plaster well finished CSEB walls which results in 10-15% cost saving in comparison with conventional construction (which typically use lower quality burnt bricks which must be plastered). It was mentioned by an architect that the running (life cycle) cost of an earthen house is lower than concrete and fired brick houses (over the lifespan) due to decrease in energy required for cooling/heating the building. In some instances, it was observed that the sale price of modern earthen houses was significantly higher due to high commission charged by engineers and architects involved in its (bespoke) construction, use of lavish finishing and interest from high-income communities.

Some architects and dwellers reported carrying out a cost analysis before deciding on material for construction. A lime stabilised earthen house was constructed with the investment of ₹9000 /m^2 (~ €112/m^2) which was calculated to be cheaper than construction with concrete and fired brick. Conversely, the cost of a rammed earth house in Sikkim was calculated to be twice that of a reinforced cement concrete (RCC) house and therefore, the owner decided to build with RCC.

The cost of earthen construction varies significantly based on location, availability of material and labour, and a proper investigation is required to decide if earthen construction is an economical option. The cost information reported by the dwellers, especially the ones living in traditional earthen houses, is anecdotal and in most cases, a crude estimation that the dweller could recall during the interview. Thus, there are concerns over the reliability of these figures. Collection of reliable cost information is a practical challenge and should always be considered while evaluating the impact of construction cost on decline of earthen houses. In the houses built in recent times (modern earthen houses) which are often built with the involvement of architects and engineers, the cost figures are much more reliable.

3.3.2 Socio-economic

The socio-economic factors such as motivation for building and image of an earthen house play an important role towards acceptability and use of earthen construction. Socio-economic factors are considered as the guiding factors that affects the potential of earthen construction in future.

3.3.2.1 Motivation for building earthen houses

The motivation to build earth structures has been observed to correlate with the economic situation of households. A low-income household may choose to build an earthen house due to economic reasons, whereas middle and high-income households may prefer to build earthen house due to their consciousness towards the environment.

A significant number of low-income interviewees responded that they are forced by their economic situation to live in earthen houses. A family dwelling in a poorly built earthen house mentioned that the need for frequent maintenance and termite issues were demotivating factor in their interest in earthen houses. Contrary to the common viewpoint against building with earth, a few low-income households reported to prefer earthen houses due to the indoor comfort and belief in its medicinal properties. A mason from Bir mentioned that earthen construction was preferred in the mountainous area due to higher costs of cement and fired brick. Fired bricks and Portland cement can cost up to 5 and 2 times (than in plain areas), respectively, because of higher transportation costs.

Contrary to low-income families, people with good income, good education and high societal status who were aware of the benefits of earthen construction were interested in earthen houses due to its low ecological footprint and good aesthetics. The availability of skilled labour, professionals and infrastructure for earthen block production were recognised as important parameters for choosing modern earthen construction over conventional fired brick construction. In fact, in Bangalore, the availability of infrastructure for earthen construction has resulted in construction of over 20,000 CSEB houses in past 3 decades. Although desirable, the economic aspects may also sometimes restrict people (that are aware of earthen construction) from constructing modern earthen houses.

Irrespective of economic and social status of households, several people reported that their decision to build with earth was influenced by successful examples of earthen houses in their neighbourhood. A rural family in Khunti mentioned that they noticed a similar roof construction in a nearby house and thus opted to replicate it in their new cob house. Whereas a modern CSEB house dweller in Namchi was influenced by a CSEB house built by their relatives in the same region.

3.3.2.2 Image

Earthen construction in India and perhaps, in most of the developing countries suffers from a low societal image. A Pondicherry based architect elucidated the issue, *"Village people don't want a house which looks like a village house. They want something which urban people aspire for. It may be eco-friendly, or good for the climate or may be good for your health, but status and associations that people have with a concrete house is something which you can't change easily"* (transcribed from video recording). An architect from Gangtok mentioned that the powerful families which migrated to Sikkim started building their houses with RCC (reinforced cement concrete) which was perceived maintenance free and much more durable. RCC gave an opportunity to build taller in cities which was a definitive choice due to increase in land prices. Over time, *"RCC became a status symbol in Sikkim and people aspire for it"*. The architect added that the banks don't consider a 'Katcha' or temporary house such as earthen house as collateral or asset and hence one may face significant issues in getting a loan based on it.

People from the tribal community of Sundargarh shared their views: *"Nowadays it has become all about the money in the world. Today we are in an independent India. The mud house days are gone. Before we used to use lungi (traditional pants) and now we use jeans pants. Likewise, slowly people are learning and getting educated and therefore they decided to move to a brick house. When we started earning some more money, we wanted to go for a proper concrete roof. Whoever has a bicycle, they think that their life will be better with a motorbike. We see changing from a mud house to concrete building as a positive change. We do it mostly to show to others that we are also modernising. We do not want to be left behind. When people see this place changing then they will get a good impression of the people who live here. The mud houses stay strong for 30 years, but the brick houses will stay strong for more than 90 years. Hence, we have accepted change and have moved on to brick and concrete houses"* (translated from Oriya and transcribed from recording). A low-income family living in traditional earthen house in Bir mentioned, *"When we see our neighbours, we see houses with bricks, and it makes us feel that our house should also be made with bricks. Our kids also say that we want these houses, one with lintels and beams"* (translated from Hindi and transcribed from recording).

Considering the observations gathered during the survey, image is the most important factor that influences the choice of building materials. However, as the statements reproduced above confirm, for low-income households in the rural area the image of earth construction is low and associated with something that is outdated. They aspire for a house similar to the one they imagine urban people have. Although, the traditional building materials and techniques are cheap, people prefer conventional building materials despite the higher cost. This results into improper and unfinished construction that leads to disinvestment. The majority of people living in urban areas also have a low image of traditional earthen construction. However, modern earthen construction is desirable and accepted by people with a self-conscious interest in living a sustainable lifestyle. The number of such people is still limited but expected to rise. These people tend to have an educational background above the average and consider cement and other industrialised material as a major cause of pollution and find it highly undesirable. For this particular social group, the contribution of earthen construction in local economy and its natural aesthetics were the key reasons for the acceptability of earthen construction. An educated and environmentally conscious owner of stabilised cob house located near Tiruvannamalai shared the viewpoint, *"People are really searching for a different way of life and they are looking for a different style of architecture. People have been very stifled with the consumeristic and materialistic society and the concrete boxes in which they are living. Cement is not locally sourced and coming through big MNC's (Multi-national companies). It is a material that is really not as durable as people imagine. All the cement construction happening now are also going to fall down someday as they are constructed in an improper way. The idea that an earth construction is not durable need not be true. It depends on how scientifically you are constructing it. The mud houses are living spaces, they breathe. Air can pass through it and the feel of living in these spaces is good and natural"*. (Transcribed from recording).

In summary, the 'image' or 'acceptability' of traditional earthen construction is predominantly low in India. This is recognised as the main barrier towards the rise in earthen construction and its application as a low-cost housing technique.

3.3.3 Political and educational

The political and educational factors depend on the agenda of the government and independent initiatives (sometimes in collaboration with government) that can promote or decline the use of earthen materials.

3.3.3.1 Influence of government and lack of code

The government has a direct and indirect influence on the image and acceptability of earthen construction. The Census of India (COI) classifies building material as temporary or 'Katcha', semi-permanent or 'Semi-pucca' and permanent or 'Pucca' (Bhathia, 2001). A permanent or 'Pucca' structure has walls and roof made up with materials such as cement, concrete, fired bricks, stone, iron, metal sheets, timber etc. Whereas a temporary or 'Katcha' structure has walls and roof made up of mud (earth), unburnt bricks, bamboo, grass, leaves, reeds, thatch etc. Classifying earth and other traditional materials (that are locally sourced and produced) as 'Katcha' or temporary results in a bias against these materials. Government policies aim to convert all the temporary and semi-permanent houses to permanent or 'Pucca' (Ministry of Rural Development, 2016), making materials such as concrete and fired bricks attractive, while 'Katcha' remains an undesirable material that is associated with poverty.

India's Ministry of Rural Development (MoRD) and the United Nations Development Programme (UNDP) have proposed over 130 affordable housing prototypes/designs based on the climatic conditions, disaster risk factors, locally available materials and traditional skills of different regions of India (UNDP, 2016). A majority of the proposed houses are built with local materials such as earth and bamboo. This proposal is, in fact, contradicting to the ambition of converting all the houses to 'Pucca' or permanent. Therefore, instead of choosing the proposed low-cost designs incorporating local material, people often prefer conventional materials that might be more expensive. This leads to an inferior quality of construction or incomplete construction.

The negative perception of government officers and their lack of trust in earthen materials results in lower approval rates of earthen construction projects. The transfer (relocation) of concerned government officers was reported to result in discontinuation or revision of earthen projects by multiple architects. However, in areas with successful examples of modern earthen construction, the acceptance and approval by government was higher.

The lack of official guidelines was also recognised as a barrier to construction with earth. Although, a building code on earthen construction, IS 1725, exists in India, not all architects and builders were aware of it. The building code is limited to CSEB construction with cement and lime stabilisation and does not cover other earthen construction techniques. On a contradicting note, lack of code was also reported to provide flexibility to innovate with earthen materials.

3.3.3.2 Education and training

The education and awareness of earthen construction is rising in India. Several institutes, organisations, and NGOs are advocating ecological construction with earth. Organisations such as Thannal (in Tiruvannamalai), Auroville Earth Institute (Auroville), Hunnershala (Bhuj), Dharmalaya (Bir) and Mrinmayee (Bangalore) were visited during the survey.

The common objective of all these organisations is to promote construction using local materials and provide consultancy and knowledge for safe construction with earth. These organisations provide training courses on earthen construction for people who are seeking knowledge to construct their earthen houses. Mrinmayee and Auroville Earth institute are also involved in production of equipment (such as block making press) for construction of earthen houses.

Academic institutes such as the Indian institute of Science (IISc) in Bangalore have been active in research and development of earthen construction (since 1975 in the case of IISc) and have produced several scientific outputs related to it. The engineers trained in the Application of Science and Technology for Rural Areas centre (ASTRA) at IISc have contributed significantly to the dissemination of the CSEB technique. An independent educator from Jharkhand reported on their effort to teach the benefits of earthen construction to school children which resulted in shift towards positive perception of earthen buildings in the region. The educator emphasised that the importance of building with local materials should be inculcated at a smaller age.

3.4 Discussion

This survey into factors affecting construction and daily use of earthen houses demonstrates that the 'image' of an earthen house is a key factor that needs to be addressed in order to consider earth as a practical solution to the contemporary housing shortage. The following section addresses this factor and discusses necessary requirements for mass housing with earth in India. Firstly, the qualitative data collected from the survey is linked to the quantitative data in order to validate the findings. Thereafter, strategies for mass housing with earth in rural India is discussed after drawing on the experiences in low-cost housing from Africa and other countries. Finally, steps towards the acceptability of earthen construction is proposed.

3.4.1 Linking image to economic development

Earthen materials are associated with poverty and widely considered as a material for the poor. Poverty is often linked to housing condition and therefore, housing materials may have direct or indirect impact on factors used for determining the poverty line. The poverty line in India is selected by individual states using the data of 'Socio Economic and Caste Census' survey which is conducted by the government of India. The data collected are then used to rank/score the households based on various deprivation indicators. The households with high deprivation score have a high probability to be included in the households below poverty line (Department of Rural Development, 2011). The indicator of deprivation related to housing type/condition is "Households with one or less rooms, Katcha walls and Katcha roof". Therefore, the houses made of 'Katcha' or temporary materials are an indicator of poverty. Earth/mud is one of the most widely used 'Katcha' material in India and thus, can be an indirect measure of poverty.

The correlation between the number of earthen households in surveyed states (based on 'Socio Economic and Caste Census' 2011 (Department of Rural Development, 2011)) and the respective population below poverty line is presented in Figure 3.6. The data of population below poverty line were collected from the Reserve Bank of India (Department of Statistics and Information Management (RBI), 2018) for the year 2011-2012. The graph presented in Figure 3.6 shows that a higher number of earthen houses correlates to a higher population below poverty line.

Figure 3.6 seemingly confirms the traditional assumption that earthen houses are symbol of poverty. This assumption is not just a perception or anecdote but has statistical and quantitative root. Interestingly, rural people interviewed in Himalayan states (Himachal Pradesh and Sikkim) had an overall perception of earthen construction more positive than people interviewed in Odisha and Jharkand, the states with higher percentage of people living below poverty line.

3.4.2 Lessons from earthen construction in Africa and other countries

The use of earth as a building material is widespread, especially in developing countries. Surveys and case study analyses, similar to the one reported in this article, have been carried out in Zambia (Hadjri et al., 2007), Ghana (Danso, 2013), Algeria (Baiche et al., 2017), Uganda (Nambatya, 2015) and other countries. All these studies have concluded that the traditional earthen construction lacks several aspects that hinder its promotion in contemporary construction practice.

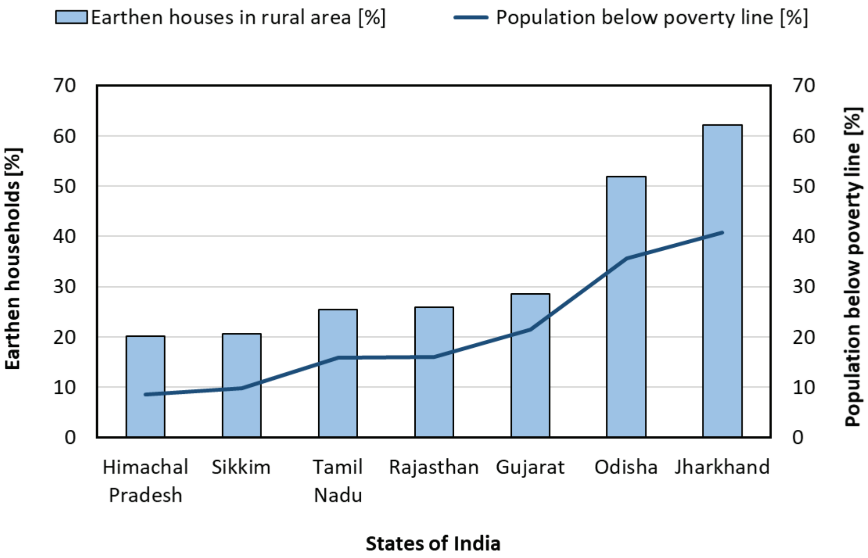


Figure 3.6: Correlation between earthen households (based on predominant materials for wall) and population below poverty line for the surveyed states of India. The information related to surveyed locations and corresponding states can be found in Table 3.1.

Issues related to low social image of earth and link to poverty have been reported by several authors (Adegun & Adedeji, 2017; Chaudhury, 2019; Hadjri et al., 2007; Sameh, 2014; Zurakowska et al., 2009). Issues such as erosion due to rain and other environmental forces (Baiche et al., 2017; Danso, 2013; Hadjri et al., 2007; Hammond, 1973; Ngowi, 1997; Sameh, 2014), susceptibility to termite attack (Sameh, 2014), low structural strength (Baiche et al., 2017; Danso, 2013; Hadjri et al., 2007; Ngowi, 1997), short life span (Hadjri et al., 2007), frequent maintenance (Danso, 2013; Hammond, 1973), and lack of standardization (Sameh, 2014), have been reported to limit the construction of earthen houses. The experience of earthen construction elsewhere in the world resonates with the Indian scenario. Therefore, it can provide learning lessons that can be implemented locally in the Indian context. Moreover, the successful examples of low-cost earthen construction elsewhere can suggest the necessary strategies for construction of low-cost houses with earth in India.

Improvement in the material properties and access to infrastructure and knowledge is important for the promotion of earthen construction. In their study on structural aspects of earthen houses in Algeria, Baiche et al. (2017) pointed out that the selection of appropriate soil and construction techniques, provision of training and implementation of suitable structural design and construction can lead to building safe and resilient earthen houses. Hashemi et al. (2015) also recommended improving the quality and structural stability of earthen material in order to reduce the extent and frequency of maintenance required in houses proposed for low-income tropical housing in Uganda. Adegun and Adedeji (2017) recommended the need of standardisation, availability of building codes, need for skill-training and opportunities to setup small-scale industries as the necessary steps towards acceptance of earthen construction. Additionally, Sameh (2014) recommended educating and increasing awareness in youth, investment by government on earthen structures, incentives (such as tax reduction) for earthen construction and including earthen construction in curriculum of technical institutes. Zami (2011) investigated the drivers that help adopting contemporary earthen construction and observed that the exposure of earthen construction through public media is important for wider acceptance of earth in low-cost urban housing.

While the technical recommendations for enhanced performance are important, the impact of government, entrepreneurs and education can be significantly higher. Although the government in some countries have shown interest in earthen construction (particularly in re-building after disaster), the initiatives by non-governmental organisations have played a key role in promoting earthen construction globally. For example, a social entrepreneur, named Hav Kongngy, in Cambodia has developed the 'My dream home' concept designed to provide quality housing with interlocking CSEB to those who cannot afford to buy conventional houses. These blocks are claimed to be up to 40% cheaper than conventional fired brick in this location (My Dream Home, 2019) (note that due to transportation costs of conventional materials, this comparison is location dependent). In Nepal, the organization 'Build up Nepal' also uses interlocking CSEB for the construction of low-cost houses and schools that are able to withstand earthquakes. Their approach of community and entrepreneurship driven re-construction has promoted use of earth as a building material in Nepal (Build up Nepal, 2019). In El Salvador, the NGO Fundasal has been working in the re-development of adobe blocks, improvement of its performance for application in contemporary construction and training building teams for construction of low-cost housing. In a social housing project in Bamako, Mali, LEVS architect (with partners) have constructed 280 homes from hydraulically compressed earth blocks (HCEB) that were manufactured with a mobile press and team of local workers (LEVS Architecten, 2019). A carefully prepared development plan, high level material performance and high quality of construction resulted in comfortable, attractive and desirable earthen houses. In Thailand, the use of interlocking CSEB or Interlocking Stabilized Soil Block (ISSB) was extensively promoted by Thailand Institute of Scientific and Technological Research (TISTR) for the past 35 years. Their efforts resulted in 665 ISSB manufacturing factories run by entrepreneurs spread across the country. These blocks were also offered online in 2017 with free delivery services and a house construction package, increasing the accessibility.

The construction of New Gourna village in Egypt is a classic example of rural mass housing with earth. Hassan Fathy, a renowned Egyptian architect, was commissioned in 1945 to construct housing for 7000 people who would relocate immediately from old Gourna and planned to be later expanded to 20 000 inhabitants. After the first three years, the project was stopped due to financial and political reasons, and people's resistance to be re-located, leaving the project only one third complete (World Monuments Fund (WMF), 2011). The design of the village was made incorporating ecological aspects, passive cooling techniques and community participation. A survey by World Monuments Fund (World Monuments Fund (WMF), 2011) in 2010 found that the houses were incompatible with the current needs of the residents. In addition, they suffered from significant structural deterioration due to unpredicted rise in underground water flow which deteriorated the foundations and affected the structural integrity of the buildings. People mentioned that repairing earthen buildings is expensive and ineffective, therefore they have shifted to concrete buildings. Moreover, the housing project was designed for smaller families and the growth of families was not anticipated during the planning phase of the project.

The experience of New Gourna and other projects puts forward planning as an important aspect to consider while designing mass housing in rural areas. The change in ground water flow and modification of physical infrastructure can be harmful for earthen material thus, a proper foundation design with protective layers should always be incorporated. People should be included in the planning process and the structure should be designed considering the future growth of the family. Moreover, a community driven approach that involves local community and entrepreneurs is essential for the promotion of earthen construction. Understanding the socio-economical aspects, culture, values and aspiration of owners is necessary before introducing a new material in to a community (Marsh et al., 2016).

3.4.3 Low-cost mass housing with earth in rural India

The shortage of rural housing in India in 2011 was estimated to be in order of 40 million houses (Ministry of Rural Development, 2011). With about 17.8 million houses claimed to have been built until 2018 (Ministry of Rural Development, 2018), the need for housing remains a major concern in India. The housing shortage and the ambition of government prioritises the requirement of building millions of houses in a significantly short time span. Affordable or low-cost mass housing projects are one of the options that has the potential to overcome the housing shortage. Affordable mass housing focuses on construction of multiple units in a planned manner. While mass housing projects are common to cities where there is a constant inflow of migratory population, rural mass housing projects have been adopted only in special circumstances such as post-disaster housing (example multi-hazard resistant houses in Odisha and Bengal (Chaudhury, 2019)), housing developments near overcrowded urban areas (Belapur housing in New Mumbai (Correa, 2000)) or forced relocation (example of New Gourna in Egypt). In order to develop a mass housing project, areas with inadequate housing need to be identified and a redevelopment plan of the entire village has to be made including re-designing, repair and retrofitting of existing infrastructure. The re-development should not only empower and generate income for locals through construction but also post construction. While construction of individual houses is possible in the selected area, low-rise medium to high density mass housing can significantly reduce the total expense and reduce haphazard growth of a single or multiple villages located at a practical distance to each other.

As people have the tendency to modify their houses through time, many scholars suggest incremental housing strategies should be adopted by policymakers, planners and designers (Mundus Urbano International cooperation and Urban Development- TU Darmstadt & SIGUS group-MIT, 2012). This provides residents an opportunity to extend their house based on their personal needs and growth. The availability of space in rural areas is an advantage for incremental housing. A sufficient distance is provided between the houses during the planning phase. Incremental housing was adopted in the Artists' Village, a mass housing project designed by one of India's most famous architects, Charles Correa and built in 1986. The Artists' Village was built in Belapur (New Mumbai) and includes 550 houses of different sizes (catering for different income groups) constructed in an area of 5.4 hectares (54000 m^2), and collective amenities such as recreational areas and educational facilities (Correa, 2000). While the original houses were only one or two floors high, today many plots are occupied with houses with three floors, maximizing the potential of the plot to match the growth through time of the household, as well as the family's improved economic situation. In some cases, this transformation results from the expansion of the original houses (incremental growth), while in other cases is a completely new construction (redevelopment). To avoid the production of construction waste and reduce the embedded energy in the production of affordable housing, the design solutions and the construction materials and techniques should favour incremental growth rather than redevelopment.

The scalability of the adopted material and construction techniques is yet another key requirement of mass housing. Although, (traditional) earthen construction is often considered as non-standard, modern techniques such as CSEB is gaining popularity as a standard building material. The availability of CSEB making press at reduced rates and its increase usage in contemporary construction has made it cost-effective and desirable. In fact, it was reported that more than 600,000 blocks have been produced (with a hydraulic press) and sold in just 2 years by an entrepreneur in Tirthahally village, Karnataka. To ensure standard quality of blocks, a centralised production plant/unit for excavation and production of bricks is desirable. In the mass housing project of constructing 'Multi-hazard resistant houses' in Odisha (1450 housing units built in 2002) and West Bengal (200 housing units built in 2006) a central production unit was established in between two villages and pre-casting was adopted (Chaudhury, 2019). Prefabrication, as a tool for standardization, can be an important aspect of mass housing. The prefabricated elements should be light as to facilitate transportation from the production site to housing plot.

The construction of houses can be executed by house owners or artisans that are trained on site with the assistance of local building centres or local entrepreneurs. An assisted self-help can lead to better quality of construction (Bredenoord & van Lindert, 2010). Building centres can therefore play an important role in assisting the construction of houses by imparting knowledge and training to people. Nirmithi Kendra (Building Centre) in the state of Kerala, with over 15 centres spread across the state, has been successful in training artisans in low-cost construction techniques, producing and selling low-cost building materials, employment generation, housing guidance and counselling (Goel, 2002). Inspired by their success, the Housing and Urban Development Corporation of India (HUDCO) reported the establishment of more than 500 building centres in the country and claimed to impart training to over 300,000 artisans on cost effective, environmental and energy efficient building techniques (HUDCO, 2019).

The finance required for the execution of rural mass housing project can be arranged through residents own funds or funds from government or external organisation. The government, under the scheme of Pradhan Mantri Awaas Yojana-Gramin (PMAY-G), gives a financial assistance for low-income households of ₹120,000 (~ €1500) in plain areas and ₹130,000 (~ €1625) in hill states to each eligible rural household for construction of a housing unit (Ministry of Rural Development, 2016). Additional funds and loans can be availed through complementary schemes leading to a total housing finance of up to ₹200,000 (~€2500) for construction of houses with a minimum required floor area of 25m². It was reported that the people eligible under the scheme receive a total amount far less than promised due to corruption and malpractices. This amount was considered insufficient for construction of the desired housing unit by most interviewees. On a positive note, the manufacturing of CSEB bricks has been included by the national rural employment guarantee act (scheme), thus it can also provide employment opportunities for rural people (Ministry of Rural Development, 2014).

The low-cost design for housing can be selected from over 130 affordable incremental housing prototypes/designs proposed by UNDP and Ministry of Rural development that are suggested can be built within an investment of ₹200,000 (₹2500-4000 /m²) (UNDP, 2016). Most of the proposed houses use locally available un-stabilised and stabilised earth for the construction of walls. Use of modern earthen technique such as poured earth foundations and CSEB for walls can raise the cost. However, careful spatial planning of housing units and sharing facilities can lower the overall expenditure. Any mass housing project constructed with earth without full consideration to material properties, design, aesthetics and requirement of dwellers, will face rejection by the dwellers. In order to provide mass housing with earth, community participation, professionally trained labour and a superior quality of supervision is required. In addition, the material used in construction should match or exceed all the desirable requirements satisfied by conventional building materials otherwise the project won't be able to contribute towards acceptance of earth.

3.5 Recommendations: 'Catalysts of change'

In order to promote earthen construction especially for mass housing projects, these suggestions can play an important role in changing the image of earthen houses by acting as catalysts of change.

3.5.1 Improvement of material functional properties

The poor performance of earth during rainfall, weathering and erosion along with termite infestation are some of the material characteristics that need to be improved in order to increase its acceptability. Research is required into the understanding the durability performance of earthen materials, especially its water resistance. A thorough study on water resistance performance of earthen materials could assist in building earthen structures without the use of a stabiliser. Research is also required into inexpensive stabilisers, perhaps stabilisers that can be sourced locally. Stabilisers derived from local biomass can provide exciting opportunities. In locations where cement and hydraulic lime is inexpensive, they shall be used in earthen construction or otherwise locally available, possibly bio-based, alternatives should be used based on properties of locally available soil. Biological stabilisers such as cactus extract (Heredia Zavoni et al., 1988) and cow-dung (Millogo et al., 2016) have been proven to improve water-resistance properties of earth and such stabilisers could be further explored.

Although the CSEB technique has a great potential to be applied for housing projects, scalability and adaptability of (more affordable) new construction techniques such as stabilised adobe (stabilised soil manually compacted in improved moulds) or poured earth for self-help construction could provide sound alternatives for CSEB. Research into design and architectural aspects on the different types of earthen houses can lead to bio-climatic designs that are affordable, optimal for specific locations and climate conditions and easy to build within the framework of assisted self-help construction.

3.5.2 Improvement of desirability

The presence of large number of earthen houses of good performance in multiple locations and contexts can lead to wider acceptance of earth. Two architects interviewed in the survey shared their viewpoints on the future of earthen construction. They believe its future is built upon the use of earthen materials by middle- and upper-income households. The desirability of concrete and brick is largely due to its widespread use by middle- and high-income classes. If middle- and upper-income families initiate building with earth, this can upgrade the perception of earthen construction from 'Katcha' to 'Pucca', contributing to make earthen construction an aspirational reference for low-income families.

Also, the government can also play a pivotal role to turn the image of earthen construction. The classification of traditional material as 'Katcha' gives them a negative connotation. Revising the nomenclature can be the first step towards improving the image. A detailed code and guidelines for construction with stabilised and unstabilised earth that caters to local needs of different bio-climatic regions would enable requirements of local populations to be met. Moreover, if such a guide would include instruction for assisted self-help construction, costs would be substantially reduced, and trust would increase. Furthermore, entrepreneurs and researchers must also play a pivotal role. Researchers can provide insight into how earthen construction can be designed and optimized to local conditions such that the dwellers requirements are met equally to that using conventional construction (at lower costs without compromising the aesthetic value that modern earthen houses such as shown in Figure 3.4 (i,j and k) can offer). Entrepreneurs must set up the commercial infrastructure required and promote earthen construction throughout the country. If the government can support these initiatives, it can lead to wider dissemination of modern earthen construction techniques. Only by doing all of these steps, 'building with mud' revolution be implemented.

3.5.3 Education and need for demonstration

Educating the people on earthen construction technology is a vital step for its acceptance. In an investigation carried out in Uganda on the barriers to widespread adoption of ISSB technology for low-cost urban housing, the author found that the earthen building, even though stabilised with cement, is perceived inferior, expensive and inappropriate use of cement (Nambatya, 2015). The study suggested that educating the potential users on ISSB technology as sustainable and cost-effective technology could improve its perception. Educating young architects and engineers about earthen construction by including it in the curriculum can also promote the dissemination of earthen construction. Inculcating the importance (and limitations to overcome) of traditional construction to children can change the perception from a young age. Education on earthen construction should be transparent and non-biased.An effective and comprehensive education can lead to successful demonstrations.

Demonstration of successful earthen house projects has the upmost impact on the perception of people and government. Rabie (2008) demonstrated a wall of curved compressed stabilised earthen bricks to a group of rural families who had a negative perception of earth construction. This wall was readily accepted by them due to its aesthetic appeal and a demonstrated proof of its water resistance. On contrary, a failed demonstration in Bangalore lead to loss of trust and set back the growth of earthen construction in the region by several years (Jagadish, 2009). The negative demonstration should be taken as an opportunity to identify the limiting aspects of earthen construction in order to re-invent earthen construction to suit contemporary requirements. Successful implementation of earthen techniques in large scale projects such as schools, museums and shopping centres can alter the image of earth as a building material and boost the confidence of people to use it in house construction. Design education is thus instrumental to empower a new generation of architects and planners and give them sound support to develop innovative design solutions for earthen construction.

Demonstration for the sake of demonstration!

Demonstration of new building materials and techniques is an important step to evaluate the feasibility and real scale performance. While a demonstration often creates positive awareness, lack of liability and lack of comprehensive planning (taking into account the full lifespan of structure) can have contrary results. Several abandoned and unfinished earthen buildings were observed during the survey. While most belonged to dwellers who shifted to new houses, some of these were demonstration structures built as a part of student projects.

Student projects are carried out with utmost enthusiasm and creativity, and these projects are extremely valuable learning experiences. However, it may lack necessary quality especially when students are un-trained, and the project is predominantly carried out by volunteers. An international university student who participated in an unsuccessful earthen construction project in India mentioned that the demonstration was built exclusively by students with no prior knowledge of working with the earth. Therefore, they faced multiple challenges and forced the completion within the restricted duration of the project. The project could not finish at the anticipated quality level and the house was deemed unsafe for living. A similar experience was shared by a mason who assisted a group of students but could not finish the construction in time. With the completion of their coursework, students moved on to other courses and the project was never finished. Compared to a regular construction project, a student project is strictly time-bound, and students and their university are often not liable for the maintenance and demolition of the structure. This is disadvantageous for the local community and other stakeholders who do not get financial assistance to maintain the building. Therefore, universities should only invest in the demonstration project when they have finance and personnel to support the project throughout its lifespan. Involving the local community actively (and if possible, financially) in a demonstration project is important to keep their interest and enthusiasm in the project. Moreover, while most demonstration projects are carried out by volunteers (as a way to reduce labour cost), proper training before the beginning of construction is absolutely necessary. Experts and masons should be hired to maintain the quality of the construction. Demonstration for the sake of demonstration has and will impact the image and acceptance of earthen construction negatively.

3.6 Conclusions

Building with earth is widely considered ecological and economical. However, the low image of earth, in particular traditional earthen construction, is recognised as the key barrier towards its acceptance as a building material for low-income households. The image is strongly linked to poverty, and it is significantly influenced by poor performance of traditional earth houses (in terms of poor water and weather resistance and termite infestation), frequent maintenance, governmental policies and nomenclature that gives a negative reputation to earth.

The performance of modern earthen materials such as CSEB is comparable to conventional building materials, while its production is economical and eco-friendly. The CSEB technique is gaining popularity in India due to good quality of the finished product (which has an appearance similar to fired brick) and availability of low-cost CSEB making presses/machines. While modern earthen construction techniques are attracting environmentally conscious middle- and high-income families, earth is still a material that is less preferred than concrete and fired brick for the construction of houses. Earth as a building material triggers the image of a poor performing traditional house in people's mind which results in a resistance to the rise of modern earth construction in India. Earthen construction might be a practical choice for many rural areas that are disconnected from building material supply-chain network. However, unless it meets the desired specifications met by conventional materials in terms of durability, aesthetics, and economy, it will not be adopted as a standard construction material.

While lifespan, resistance to external environmental forces, durability, and structural related properties, of modern earthen construction are desirable, the economic, self-help construction potential and recyclability aspects of traditional earthen construction are valuable. A combination of the two construction types can result in structures that are economically, socially, and ecologically sustainable. The high cost of modern (stabilised) earthen material can be reduced by minimising the use of cement and hydraulic lime in favour of bio-based alternatives. Assisted self-help construction can also reduce the cost of a building project significantly.

Modern earthen construction practices have a great potential to be used in low-cost housing in India. The availability of low-cost design options and access to building centres can provide necessary infrastructure for successful realisation of mass housing. However, earth may not be immediately applied to contemporary construction of mass housing due to lack of successful demonstration and trust of government and people. Demonstrations in diverse location and contexts can lead to wider dissemination of modern earthen techniques. The way forward is to build small-scale high-quality structures where a significant attention to detail is given and the project should be implemented considering all the technical requirements and desires of the dweller. The PMAY-G programme offers a good opportunity to explore new applications for earthen construction.

The future of earthen construction rests on entrepreneurs, designers and researchers who can provide materials which have appropriate material properties, designs with minimal costs, the supply chain and manufacturing infrastructure, and training to result in a superior quality of construction. The research work on earthen construction in the context of India should be based on the pillars of affordability, durability and most importantly, the desirability for a wider acceptance.

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4

Water Resistance of Unstabilised Compressed Earth Blocks: An Experimental Investigation

"Mud, water, fire, air (blast).. it is just plain mud"

– Priest & Aang, Avatar the Last Airbender (S2 E1)

The strength of earthen materials is usually sufficient to build low-rise structures. However, its deterioration is often a result of poor water resistance. This chapter investigates the water resistance of unstabilised Compressed Earth Blocks (CEBs) through a series of experiments and provides recommendations for enhancing the water resistance of CEBs. The influence of material composition, water content and compaction on water resistance and strength of CEBs is evaluated, together with an understanding of the microstructural fabric and its influence on water ingress. This study reveals that increasing the water content and compaction pressure improves water resistance of CEBs due to decrease in the volume of macro-pores which drive the flow of water into the material. An increase in compaction water content beyond optimum moisture content resulted in up to 70% reduction in water-driven erosion, while doubling the compaction pressure decreased the erosion by up to 60%. CEBs with higher pre-wetting water content (12.6%) resisted 6 times more erosion than CEBs with low pre-wetting water content (<6%) due to the reduced rate of water ingress in them. The CEB prepared with bentonite rich clay survived 5 days in immersion, more than other CEBs (that typically disintegrate within 30 min), indicating the dominant effect of clay mineralogy on water ingress. The chapter concludes with a discussion on the practical relevance of the results and the need for future developments that could aid the commercial production of unstabilised CEBs with enhanced water resistance.

Data accompanying Chapter 4 is available in Kulshreshtha (2022).

4.1 Introduction

Building with unstabilised or 'raw' earth (without chemical or biological binder) is a traditional practice that has existed for over 10 000 years. Unstabilised earth is still a dominant material used in several regions of the world, especially in rural areas of low-income countries. Several examples of long-standing and inhabited unstabilised earthen construction exist throughout the world (as shown in Chapter 2), exhibiting its potential as a durable building material in the contemporary housing market. An unstabilised earthen dwelling designed with appropriate architectural details, such as a long overhang and pitched roof, could limit water ingress routes and provide durability (Medvey & Dobszay, 2020; Norton, 1997). However, modern architectural aspirations (with exposed walls) and a lack of confidence in unstabilised earthen materials have led practitioners prefer the use of stabilised earthen material. However, the growing debate around the economic and environmental impact of stabilisers is leading a way towards the renaissance of unstabilised earthen material, especially in Europe. Climate change and its consequences have also made people aware of ecological and indigenous practices and, thus, the use of unstabilised earthen material is expected to increase in the near future.

While the strength of earthen material is sufficient for the construction of low-rise structures, its deterioration is often a result of low durability (Beckett et al., 2020; Morel et al., 2012). The durability of earthen structures is affected by environmental actions such as water ingress, erosion due to the wind, fire, solar radiation, growth of micro-organisms and burrowing from animals (Fabbri et al., 2018; Laborel-Préneron et al., 2016). Amongst these actions, exposure to water (or moisture) and subsequent erosion due to water ingress is known to have the highest impact on the performance of structure during its service life (Fabbri et al., 2018). Water ingress in earthen materials can occur due to wind-driven rainfall, condensation, infiltration, absorption from the surrounding ground, etc. (Beckett et al., 2020). In extreme cases, flooding can also lead to the failure of earthen structures (often experienced in delta regions and river basins of developing countries). Water ingress routes in a typical earthen dwelling are shown in Figure 4.1.

Water ingress and its subsequent impact on mechanical stability dictate the water resistance of earthen material. In the context of this thesis, water resistance is referred to as resistance of earthen materials against water-driven erosion and water ingress, action that results in de-bonding of soil aggregates (sand, silt, clay etc.) leading to reduced strength and partial to complete structural failure of earthen material. Although understanding the water resistance of unstabilised earthen materials is important, it remains an understudied research topic. While multiple studies have been conducted on the understanding of strength development, fundamental studies on the response of earthen material to water ingress are missing. Therefore, a theoretical and experimental study looking into water resistance (possibly at different scales) is required for multitude of reasons such as, 1. Insight into the water resistance can be used in enhancing the durability of unstabilised earthen structures, 2. Limited water resistance is a barrier to the widespread application of unstabilised earthen material and thus, a scientific understanding of this characteristic can provide the necessary trust in unstabilised earthen materials, 3. Unstabilised earthen materials are an economic and ecological alternative for low-cost housing. An understanding of water resistance could guide the necessary requirements for building low-cost houses, where stabilisation is not economically feasible. 4. The knowledge would be also useful in understanding the effect of stabilisers, particularly biological stabilisers, on water resistance characteristics of earthen materials, and 5. The water resistance of unstabilised earthen material is known to be dependent on the scale (or size). While small-sized unstabilised earthen materials often do not pass most water resistance tests performed in research lab (and fail in a few minutes), in reality, walls from the same earthen material have been seen to survive harsh outdoor environments for decades. There is a lack of scientific explanation behind this anomaly and a thorough investigation could provide an answer to this missing gap.

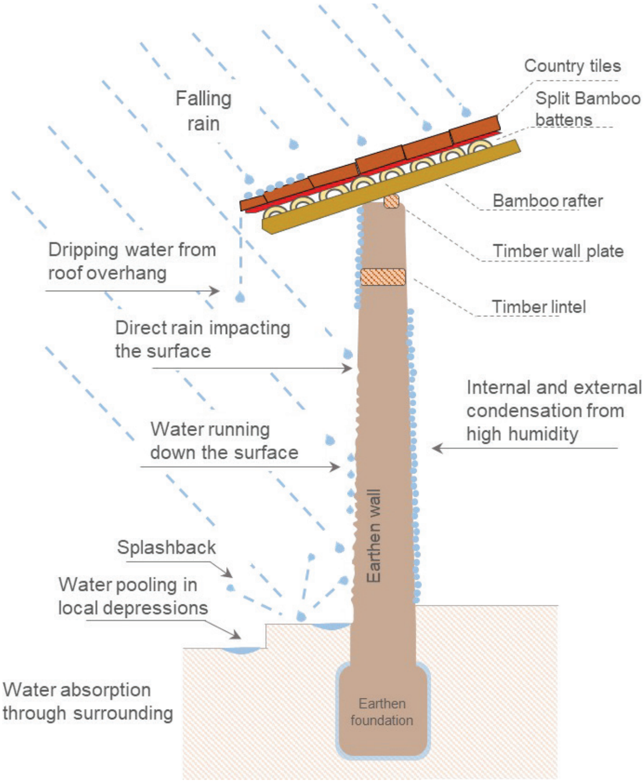

Figure 4.1: Water ingress or moisture exposure route in an earthen dwelling (after Beckett et al. (2020)). The cross section of earthen dwelling is based on an unstabilised earthen dwelling located in Chhattisgarh (eastern India).

The aforementioned arguments provide motivation for an empirical investigation of the water resistance of unstabilised earthen material. Therefore, the factors influencing the water resistance (and strength) of unstabilised earth blocks are investigated to determine how they can be optimised for enhanced water resistance. Understanding the role of microstructure of earth blocks on water resistance is also included within the scope of this study. Although, earthen materials with fibres and occasionally with fibre rich biological stabilisers (such as cow-dung) are often classified as unstabilised, for the purpose of this thesis, unstabilised earthen materials are classified as earthen material with no added fibres or biological stabilisers to enhance their performance. This distinction is made for a variety of reasons; 1. The addition of fibre introduces an extra variable in the understanding of earthen material which is challenging to investigate in the limited time frame of this thesis, 2. The role of fibre in improving water resistance is unclear (Laborel-Préneron et al., 2016), 3. Studies on water resistance of unstabilised earthen material without added fibre are missing and therefore should be prioritised, and 4. Modern earthen techniques such as rammed earth and compressed earth blocks are often produced with no added fibres.

In the subsequent sections, the existing literature is compiled to develop theoretical insight into the water resistance characteristics of unstabilised earthen materials (at multiple scales). Factors affecting the water resistance of unstabilised earthen materials are identified for a thorough experimental investigation. The materials and method utilised for testing are explained, followed by a presentation of results and in-depth discussion of the test results and their practical relevance.

4.2 Theoretical insight into water resistance of unstabilised earthen materials

The behaviour of earthen materials and the interaction with forcing conditions changes with scale. The following sub-section discusses the water ingress, and subsequent water resistance of earthen material in multiple size scales (levels), as shown in Figure 4.2.

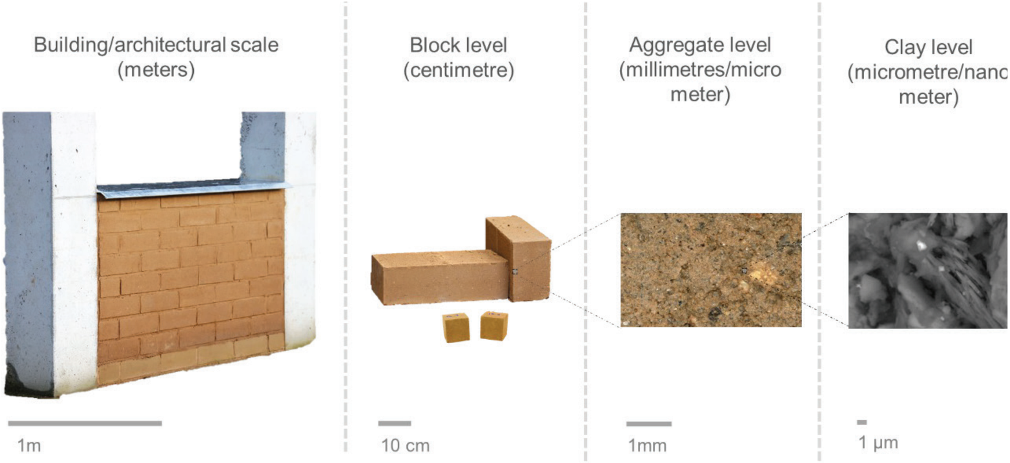

Figure 4.2: Earthen materials at different scales / levels. Left to right: An earthen wall (made from compressed earth blocks); compressed earth blocks; a microscopic image showing various aggregates and clay matrix; and a microscopic image of clay particles. Scale bars below the images provide size reference.

4.2.1 Architectural scale

The water resistance of unstabilised earthen materials can be accurately estimated through long term field tests. However, these tests are rarely performed due to high cost and long duration (Fabbri et al., 2018). A few researchers carried out long term studies on earthen walls and provide evidence on good water resistance characteristics of these walls at architectural scale. In a study by Bui et al. (2009), the erosion recorded in an unstabilised rammed earth wall exposed to 20 years of natural weathering (in France) was 6.4mm (of a wall with thickness of 400mm). In comparison, a cement stabilised wall had an erosion of 2mm. In another study on unstabilised rammed earth wall exposed to 9 years of natural weathering (in US), the average erosion was measured to be 10-14mm for a 305mm thick wall (Dahmen, 2015). In the first study, the walls were partially protected by a roof (short overhang), whereas in the latter case, no protection was used. The adequate protection of earthen structures (through a well-designed roof) is therefore seen to be important to reduce erosion due to water ingress. Erosion (in limited) quantity is not considered a major threat to the functional performance of an earthen structure.

Morel et al. (2012) have discussed the factors responsible for the erosion of an earthen wall. They concluded that erosion in earthen walls is mainly due to rainfall and rain splash at the foot of the wall. This erosion was seen to be dependent on the water content in the wall and the kinetic energy of rainfall. A higher water content in the wall was observed to correspond to a lower cohesion, and consequently low structural strength. In the event of heavy rainfall, the wall could be saturated quickly with water, making it susceptible to erosion. The kinetic energy of rainfall depends on the intensity of rainfall and its angle (which is determined by wind). Rainfall with higher intensity and angle close to horizontal is expected to cause more erosion.

The water falling on the wall of an earthen wall needs a route to travel in order to saturate the wall. The pores between the soil aggregates can act as a route for moisture transport. A force is also required to facilitate the movement of water. This force can be capillary suction, wind pressure (rain drops acquiring kinetic energy) or differential vapour pressure (Morel et al., 2012).

In a case study of a rammed earth wall, Rauch (2020) observed that after rainfall exposure, the finer particles eroded from the outer surface, exposing larger-sized gravels. It was hypothesised that these gravels acts as a barrier to further erosion due to the interlock between particles. Rauch (2020) also proposed that clay particles in the wall can swell due to interaction with water and can prevent the flow of water to the interior part of the wall, therefore limiting the saturation with water to the outer layer of the wall.

Multiple factors such as water content in the earthen wall, material composition of the wall and amount and kinetic energy of rainfall are proposed to affect the erosion of earthen wall. This means that the characteristics of earthen material, climatic conditions (rain duration and intensity, humidity, temperature) and architectural design (presence of roof overhang, raised foundation etc) determine the extent of water driven erosion in earthen structures. However, experimental investigation at architectural scale is limited.

4.2.2 Block and aggregate level

Laboratory tests have been developed to quickly predict the water-resistance and other durability parameters of earthen materials at block level. Erosion tests (water dripping or sprayed on the material at low or high pressure) and immersion tests (partial or complete) are commonly used to test the water-resistance behaviour of earthen materials (Beckett et al., 2020). Although researchers often use these experiments to evaluate the performance of earthen materials, there is lack of fundamental studies that explores the factors affecting the water resistance performance of unstabilised earthen materials. Therefore, information is drawn from the field of geotechnical engineering and unsaturated soil mechanics, in particular, studies on wetting induced deformation relevant for landfill and embankment design. These are compiled to propose factors that influence water resistance of unstabilised earthen materials at block/aggregate level.

Unlike concrete and fired brick, water-resistance of unstabilised earthen materials is expected to be linked with water ingress. In concrete and fired bricks, water-resistant ionic-covalent bonds hold aggregates together (Pellenq & Van Damme, 2004; Watson, 1998). Even though water can flow through these porous materials, water ingress does not result in structural weakening. These water resistant ionic-covalent bonds are usually absent in earthen materials. It is the combination of aggregate interlock, cohesion and capillary suction that hold the aggregates together and provide strength to compacted soils or earthen materials (Fredlund & Rahardjo, 1993). As the water resistance of earthen materials is linked to reduction in strength upon water ingress, the parameters responsible for strength could provide insights into parameters responsible for water resistance performance.

The combination of the classical Mohr-Coulomb failure theory with Bishop's effective stress theory (Bishop, 1959) (both soil mechanics theories) suggest that the strength of compacted soil or earthen materials is dependent on three parameters: (i) cohesion (binding due to clays), (ii) aggregate interlocking (frictional resistance offered by silt and sand), and (iii) capillary suction (Fredlund & Rahardjo, 1993). The interconnection between these parameters, variables influencing them and their link to strength and water resistance is shown in Figure 4.3 and discussed briefly in the subsequent paragraphs.

Aggregate interlock is the interlocking of various aggregates of soil (typically silt and sand) in relation to their geometry. Aggregate interlock is influenced by the composition of soil (material composition) and degree of compaction (density). Aggregate interlock can be improved by increasing the density and grading of the soil, both actions leading to an increase in strength. In geotechnical engineering, aggregate interlock is characterised by the 'friction angle', which relates the confining stress (force experienced due to surrounding and overlying mass of soil) to the strength. At high densities, soils needs to dilate (increase in volume) in order to fail, which results in higher block strength due to dilation and boundary constraints, and the generation of suctions temporarily (refer to 'critical state soil mechanics theory' by Wood (1991) and 'wetting collapse' by Alonso et al. (1990) for detail). Aggregate interlock is not expected to have a significant influence on the water resistance, however, remains an important aspect for strength and so cannot be eliminated.

The cohesion in earthen material depends primarily on material composition and is influenced by water content and compaction (Figure 4.3). The cohesion is linked to the quantity and type of clays which act as a binder between (non-cohesive) soil aggregates. In absence of clay, soil (in this case a mix of sand, silt and other non-cohesive aggregates) exhibit strength due to aggregate interlock (and partially due to capillary suction if water is present). With addition of clay, cohesion becomes a prominent parameter that affects strength. The increase in clay content and increase in density are expected to increase cohesion. However, the addition of clay increases the strength of earthen material to a certain extent, after which further addition of clay is expected to result in reduced strength. Cohesive force in clays and their physico-chemical characteristics are sensitive to water and are influenced by water ingress. Water ingress often results in a decrease in cohesion, therefore loss of strength of earthen materials. The influence of clays on water resistance is discussed further in section 4.2.3.

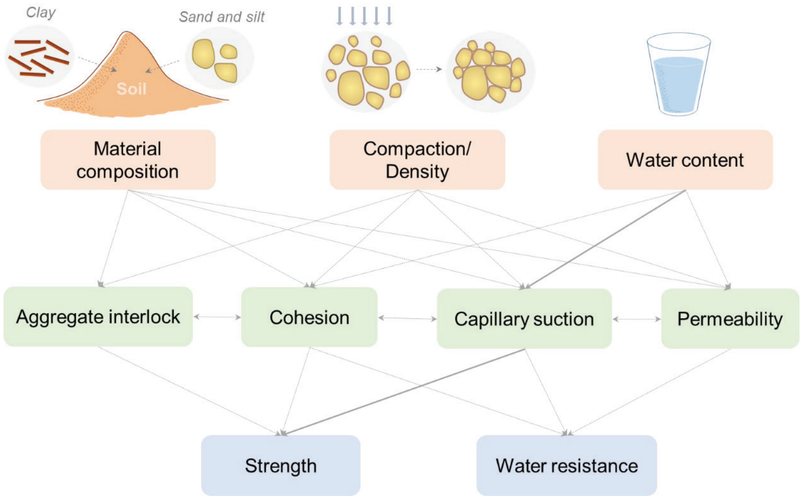

Figure 4.3: Various interdependent parameters that could affect strength and water resistance characteristics of earthen material. The bolder lines represent the link between parameters that are discussed and investigated in the existing literature on earthen construction. Other parameters are drawn from the field of geotechnical engineering and soil mechanics.

The capillary suction increases the strength of soil by increasing the confining stress (Bishop, 1959), which can be quantified as an effective cohesion (Fredlund & Rahardjo, 1993) . Capillary suction is a force arising due to surface tension between water and soil aggregates. Capillary suction of soil is expected to increase with clay content due to its affinity with water. Increases in density are also expected to increase capillary suction (as aggregates come closer to each other and pore sizes decrease). One of the dominant factors influencing capillary suction is the water content in the soil. A higher water content (or higher water saturation) corresponds to lower capillary suction, thus lower strength. Whereas a lower water content (until a limit) corresponds to higher capillary suction and higher strength. In a completely dry earthen material, the capillary suction is expected to reach zero and hence not contribute to the strength. Although zero capillary suction in materials containing clays is not expected due to the hydrophilic nature of clays which absorb water from the surrounding environment and requires extremely high suctions to remove.

The relationship between strength and capillary suction has been explored in the literature on earthen construction. The strength of unstabilised earthen material (such as rammed earth) is demonstrated to be dependent on the capillary suction between soil aggregates which in turn is known to be dependent on the water content (or relative humidity) of the sample (Bui et al., 2014; Chauhan et al., 2019; Gerard et al., 2015; Jaquin et al., 2009). The capillary suction is a function of the water content of the sample, which can change significantly due to water ingress and dehydration. Water ingress reduces capillary suction resulting in loss of cohesion between the aggregates leading to disintegration of earthen material (Tadepalli & Fredlund, 1991). As water ingress occurs during finite length precipitation events, the rate of reduction in capillary suction is an important factor that determines the stability of earthen material upon water ingress. This rate of reduction in capillary suction is related to the rate of water flowing through the earthen material, i.e., the flow rate. The flow rate is known to depend on the water permeability (or hydraulic conductivity) of the soil and the hydraulic gradient (Fredlund et al., 2012).

The liquid water permeability (ease of flow of water) through earthen material is affected by the material composition, water content and compaction (Figure 4.3). Water permeability is linked to microstructural fabric (arrangement of particles, packing density and resulting pore size distribution and connectivity) and is influenced by the material's largest pores and degree of saturation (or water content) in earthen material (Fredlund et al., 2012; Leroueil & Hight, 2013). Compacted earthen materials display two types of pore spaces: inter-aggregate pores between solid aggregates and intra-aggregate pores between the individual particles within the aggregates (Romero, 2013). The inter-aggregate pores, which are significantly larger in size than intra-aggregate pores, are known to be mainly responsible for water permeability (Romero, 2013). Therefore, a reduction in inter-aggregate pores size can reduce the susceptibility of earthen material to water ingress. The process of compaction can reduce inter-aggregate pores size (especially when water content is low), thus, the compaction force has a significant effect on the microstructural fabric (Lawton et al., 1992; Rao, 2011). With an increase in compaction effort, the inter-aggregate pore size is expected to decrease. A higher level of compaction, and therefore a higher dry density, reduces the susceptibility to water ingress (Lawton et al., 1989; Lim & Miller, 2004; Yesiller & Shackelford, 2011).

The compaction water content (amount of water in the soil during compaction) also impacts the microstructural fabric significantly. With an increase in compaction water content, especially beyond optimum moisture content (OMC) (water content corresponding to highest dry density as measured through proctor compaction test), compacted soil exhibits a lower water permeability than the same soil compacted at a water content lower than OMC (Lim & Miller, 2004; Romero, 2013; Watabe et al., 2000). At lower water content, compacted earthen material exhibit an inter-aggregate pore dominant fabric (also referred to as aggregate dominated matrix in soil mechanics), where pores are connected and dry (continuous air-phase). Whereas, at higher water content, inter-aggregate pore are smaller and disconnected (air is occluded), leading to an intra-aggregate pore dominant microstructural fabric (also referred to as clay dominated matrix) (Delage et al., 1996; Leroueil & Hight, 2013), as shown in Figure 4.4.

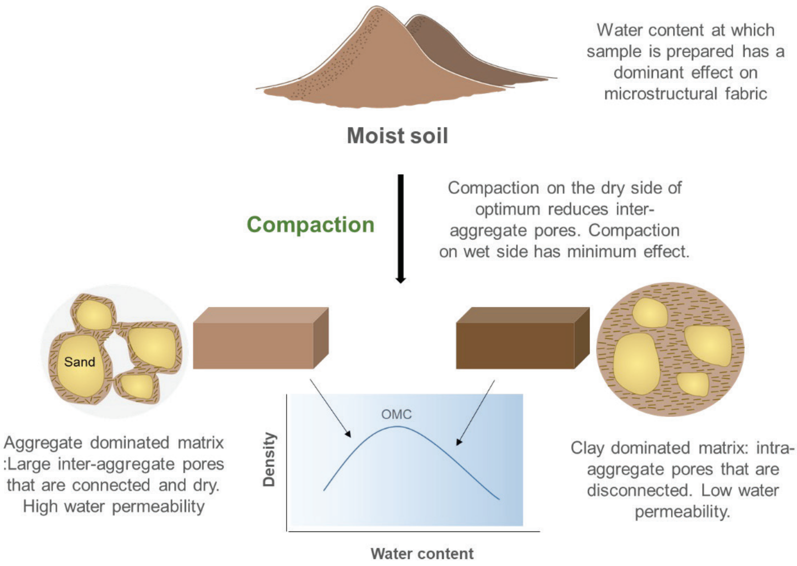

Figure 4.4: Influence of compaction water content on the microstructural fabric of earthen material.

The degree of saturation (water content) is yet an important factor that affects the water permeability and hence, the water resistance. Earthen materials have pores that contain water and air. When exposed to water (through immersion or rain), the water flows through the pores due to significant pressure differences between external water and earthen material (hydraulic gradient). In the earthen material with a low water content (in most situation), the water is expected to flow through pores causing a decrease in capillary suction and resulting in disintegration due to a reduction of strength and possible volumetric expansion of soil. Whereas a nearly saturated earthen material (with high water content) has all pores filled with water. Even though nearly saturated earthen materials have a high permeability, they have a low hydraulic gradient and therefore, no driving force for the water to flow.

In summary, the study on block and aggregate level reveals that the water ingress in earthen material (and thereby, water resistance) is expected to be dependent on inter-dependent factors such as material composition: clay content and grading of soil aggregates; compaction or density: degree of compaction (compaction energy) and dry density; and water content: water content during compaction (compaction water content) and degree of saturation or water content during exposure to the water. The water resistance is also dependent on the strength which in turn is affected by the same factors.

4.2.3 Clay level

Clay can act as a binder in soil or earthen materials holding aggregates such as silt, sand and gravel together and can fill pores due to the small particle size. In general, it increases cohesion (strength) and decreases permeability. In parallel to the physical characteristics of the microstructural fabric, the resistance to water ingress also depends on the soil's (or soil aggregate's) vulnerability to the physico-chemical interaction between water molecules and soil surface (Yesiller & Shackelford, 2011). The physico-chemical process includes the forces and energy responsible for adsorption and desorption of water molecules, thereby affecting the moisture retention and moisture transport in the earthen material. The extent of physico-chemical interaction with water depends on the activity of soil aggregates which is related to its surface area (Lu & Likos, 2004) (refer to Chapter 2, Section 2.3 for information on the surface area of soil aggregates). The specific surface area of silt, sand and larger aggregates is significantly smaller (<0.5m^2/g) than compared to clays (5-1000 m^2/g). Therefore, the amount and activity of the clay minerals in the soil are expected to have a dominant influence on the water-resistance.

Most clays are hydrophilic. They therefore absorb water readily and swell. The large surface area and the negative charge makes them reactive but also increases their susceptibility to structural failure upon water ingress. The large surface area (and mineralogy) corresponds to a larger water holding capacity. Therefore, clay minerals can swell and shrink depending on water content. Studies on compacted soil reveal that clay content in soil has a significant influence on water ingress. The susceptibility of compacted soil to erosion therefore, can increase with increasing clay content (Lawton et al., 1989; Lim & Miller, 2004). Moreover, the type of clay mineral and type of exchangeable cation present within the clay is also known to impact the hydraulic conductivity (Yesiller & Shackelford, 2011).

Clay minerals can be classified into various categories based on their microstructure, e.g. the sheet arrangement and surface area. Detailed Information on clay minerals can be found in the study of Theng (2012) and Aboudi Mana et al. (2017). Some of the most common clay minerals found in nature are kaolinite, illite and montmorillonite (also known as bentonite). Montmorillonite has an extremely large specific surface area (800-1000m^2/g) when compared to illite (80-100m^2/g) and kaolinite (5-15m^2/g) (Budhu, 2010; Terzaghi et al., 1996). Studies on the hydraulic conductivity or liquid water permeability of clays reveal that highly swelling clays (such as montmorillonite) have a significantly lower hydraulic conductivity than non-swelling clays (such as kaolinite) (Yesiller & Shackelford, 2011). Therefore, montmorillonite clays are expected to both decrease permeability, yet increase swelling and shrinking, which will make them less susceptible to water ingress, yet more susceptible to disintegration should water ingress occur. It should be noted that these observations are for clays that are inundated with water once. However, an earthen structure experiences cyclic drying and wetting and therefore, swelling and shrinking of clays could also lead to cracks which can act as a route for flowing water.

To summarise, existing studies on clays indicate that clay type (mineralogy, specific surface area, activity, exchangeable ions present in them) and clay content is expected to have a significant impact on water ingress and swelling/shrinkage behaviour and thereby, water resistance of earthen materials.

4.3 Experimental plan

The theoretical insight on the water ingress in compacted soil provides useful information on various factors that could influence the water ingress, and thereby water resistance of unstabilised earthen materials. However, the difference between compacted soil and earthen materials should not be discounted. The compacted soil is often moist and the tests carried out are usually confined (like most soil mechanics research). Whereas, earthen materials are relatively dry and tests are unconfined (like building material research). Hence, the factors influencing water ingress in compacted moist soil may not necessarily affect the water resistance of unstabilised earthen material, but they may act as a benchmark for an experimental investigation on earthen material, especially in the absence of studies exploring their water resistance behaviour.

Based on the discussion in Section 4.2, the factors that could affect the water resistance of earthen material were selected as variables for experimental investigation. Due to a large number of variables, it was decided to use a single soil type for the whole investigation and hence, reduce the variables related to the material composition. Therefore, variables such as clay content, grading of soil aggregates, and the presence of exchangeable ions were excluded from the investigation. However, 'clay mineralogy' was included due to their known and significant influence on water ingress. The complete list of variables, including their brief definition is presented in Table 4.1.

Table 4.1: Variables selected for experimental investigation

Category	Variable	Definition
Material composition	Clay mineralogy	Dominant mineral(s) of the clay aggregates
Compaction	Compaction pressure	Amount of pressure applied during compaction of soil into an earthen block
	Compaction technique	The type or method of compaction (static or dynamic)
	Dry density	Density of soil or earthen material in a dry state

Water content	Compaction water content	Water content in the earthen block immediately after compaction. Note: Water content is defined as mass of water relative to mass of dried earthen material or soil.
	Pre-wetting or residual water content	Water content in earthen block (after drying for a specific duration) just prior to the water resistance test (pre-wetting water content) or during strength test (residual water content).

While there are several earthen construction techniques (refer to Chapter 2) that can be used in the production of earthen materials, the compressed earth block (CEB) technique was selected for the production of earthen blocks for the experiments. CEB was selected due to multiple reasons: 1. Widespread use and availability of CEB presses, especially in India (the context of this thesis), 2. Higher acceptability than other earthen construction techniques (discussed in Chapter 3), 3. Machine compaction yields more consistent mass and density values than techniques using hand-held compaction (adobe, rammed earth etc.), 4. Faster production speed than most other techniques and 5. Reduced human error in casting blocks.

To investigate the performance of CEBs, water resistance and compressive strength tests were conducted. An unconfined (without external confining pressure) compressive strength test was carried out to test compressive strength. Amongst the several tests described in Beckett et al. (2020) to evaluate the susceptibility of earthen material to water ingress, the immersion and drip tests were chosen due to the simplicity of conducting these tests in a low-resource setting and also because it is suggested to be reliable for accessing stabilisers efficacy (Beckett et al., 2020). Moreover, these tests are frequently reported in the scientific literature on earthen construction.

Understanding the microstructural fabric of earthen materials is important to understand its macroscopic physical behaviour. Similar to studies on compacted soil, a microstructural investigation of CEBs can provide information on their liquid water permeability. Therefore, it helps in understanding the water ingress and subsequent disintegration of CEBs. Mercury Intrusion Porosimetry (MIP) was selected to understand the microstructural fabric of CEBs.

4.4 Material and method

4.4.1 Soil selection and classification

The soil used in the experiments was supplied by Oskam V/F (Netherlands). The soil was excavated from a tunnelling site located in the Drenthe region of the Netherlands and was selected for this study because it is used in commercial production of compressed stabilised earth blocks (CSEB) in the Netherlands. The soil was collected by the supplier and air-dried at room temperature before supplying it in pulverised form.

A thorough characterisation of the soil was carried out prior to the experimental work of this study and the results of this preceding study are summarised in Table 4.2. The quantitative bulk mineral analysis, clay mineral analysis and cation exchange capacity test were conducted by Qminerals (Belgium) and their brief report can be found in the Dataset 4X (Kulshreshtha, 2022).

Based on the characteristics of the soil used in this research, it is classified as clayey sand. The bulk soil (including all aggregates) has a low cation exchange capacity, indicating a low reactivity of the overall soil, but the clay aggregates are reactive with a high cation exchange value of 78.7 milliequivalent/100g. The detailed quantitative clay mineral analysis revealed that the clay aggregates are composed of a mix of smectite (37.2%), illite/smectite mineral composed of layers of illite and smectite (35.1%), illite (14.8%), kaolinite/smectite (9.7%) and kaolinite (3.2%). Further classification into the type of smectite (such as montmorillonite or saponite) was not performed due to uncertainties and the high cost of investigation. The sand and silt particles were found to be rich in silicates with traces of carbonates, oxides, and phosphate (details in Dataset 4X).

Table 4.2: Summary of properties of the soil used in this study

Properties	Value	Method	Standard / Reference
Grain size distribution			
Clay (<0.002 mm) [wt.%]	14.8	Hydrometer	ISO 17892-4 (2016)
Silt (0.002-0.074 mm) [wt.%]	16.5	Wet sieving	
Sand (0.075-4.74 mm) [wt.%]	68.5	Wet sieving	
Fine gravel (4.75-6.74 mm) [wt.%]	0.2	Wet sieving	
Unified soil classification system	SC (Clayey sand)		
Predominant clay mineral [wt%]	Smectite (37.2)	XRD (<0.002mm)	In-house protocol, Qmineral
Atterberg limits			
Liquid Limit [%]	28.8	Falling cone	ISO 17892-6 (2017)
Plastic Limit [%]	15.2	Thread	ISO 17892-12 (2018)
Plasticity Index [LL-PL]	13.6		
Natural water content [%]	3.5	Oven drying at 105°C	ISO 17892-1 (2014)
Compaction characteristics		Standard proctor	BS EN 13286-2 (2010)
Maximum dry density [kg/m^3]	1980		
Optimum Moisture content [%]	11.1		
Specific Gravity	2.6887	Ultrapycnometer	ISO 17892-3 (2016)
pH	7.36 (21 °C)	pH meter	

Cation exchange capacity (meq/100 g)		Co (III)-hexamine	Bardon et al. (1983)
Bulk	9.6		
Clay (<0.002 mm)	78.7		
Loss on ignition [%]	1.15	Heating at 550°C	BS EN 15935 (2012)

4.4.2 Production of unstabilised Compressed Earth Blocks (CEBs)

The production of compressed earth blocks was carried out following these steps:

4.4.2.1 Preparation of soil

The soil at its natural water content was mixed with calculated amount of water to reach water content of 9%,11%,13%,15% and 17%. The water content is defined as the mass of water relative to the mass of dry soil. The natural water content of each new batch of soil (each batch of soil represent a bag of 25kg) was measured before the production of samples. The water was added to the soil gradually and mixed manually for a total duration of 5-10 minutes depending on the quantity of water in the mixture. The mixture was then kept in a sealed plastic bag for a minimum of 24 hours for homogenisation. The water content of the homogenised soil was also measured right before the production of samples. In addition to natural Dutch soil, soils were also prepared for studying the influence of clay minerals on performance of CEBs. Commercial kaolinite and bentonite clays were mixed with the sand of size 0.25-0.50mm to create artificial soils. The proportion of both the clays was adjusted to 15% in line with the clay content obtained in the natural soil used in this research. The mixing of water and subsequent procedures were similar to the ones used for natural soil.

4.4.2.2 Compaction method and pressure

A variety of commercially available machines for making CEBs are available in the market and they vary significantly in their design and compaction pressure. Most commercially available CEB presses in India provide a compaction pressure in the range of 2-3 MPa (refer Dataset 4Y1 (Kulshreshtha, 2022)). Based on the compaction pressure range defined by Danso (2016), this would correspond to a low level of compaction (2-4MPa). For this investigation, it was decided to produce unstabilised compressed earth blocks with a compaction pressure of 2.5 MPa. CEBs with very low compaction pressure of 1.25 MPa and a higher compaction pressure of 5 MPa were also produced to study the influence of compaction force or pressure on the water resistance of CEBs.

4.4.2.3 Casting of CEBs

The production of CEBs using a commercial compaction press is challenging in the laboratory due to its large volume, high material requirement and the need for multiple people to operate and produce blocks. The size of 40 × 40 × 40 mm was therefore chosen in this study for CEBs (as compared to 305 × 143 × 100 mm used in commercial CEB production) due to the lower material and labour requirements, and compatibility with available testing facilities.

Due to the unavailability of readily available equipment for compacting soil into small cubes, a mould was designed capable of casting 9 blocks simultaneously. Figure 4.5 provides a visual illustration of the mould and the overall assembly. The mould assembly includes aluminium mould plates (that are assembled to make 9 identical mould spaces) which are tightly fastened and mounted on a heavy metal base plate. The chosen base plate was capable of resisting high compaction pressures.

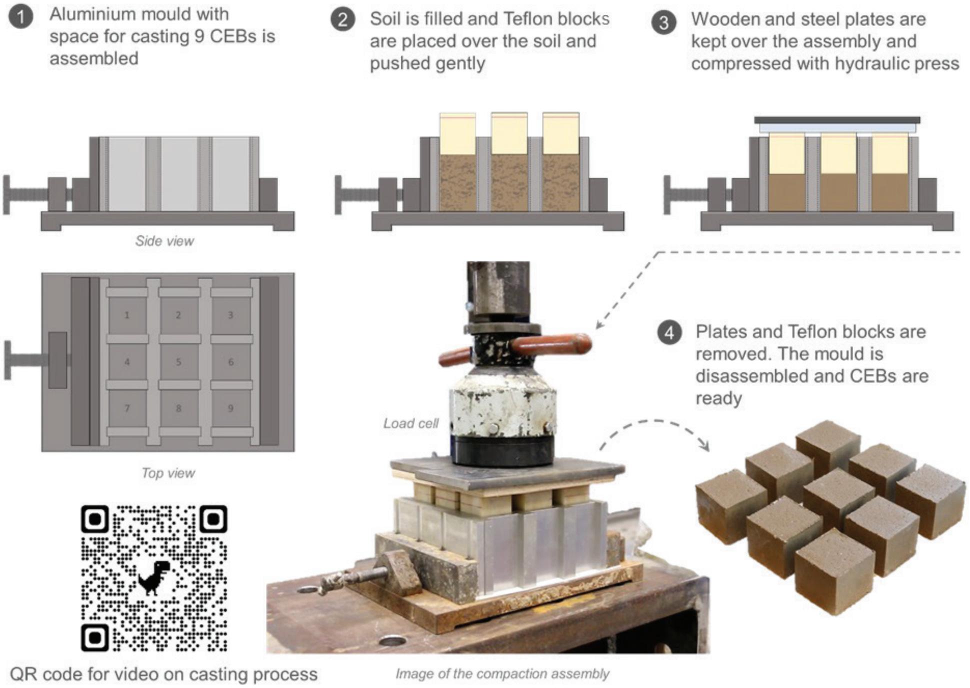

Figure 4.5: The assembly and process of casting 40 × 40 × 40 (±1) mm compressed earth blocks.

A pre-determined amount of soil was filled in individual spaces of the mould (Figure 4.5 (part 1)). The amount of soil filled in the mould was calculated based on the proctor compaction curve (shown in Dataset 4Y2) for the desired outcome of 40 × 40 × 40 mm block size. Based on some preliminary trials, the amount of material used for wet soil (> 13% water content) was higher (by 4%) relative to values obtained from the proctor compaction curve. The column 'Sample preparation parameter' in Dataset 4Y3 provides more clarity on these calculations. No releasing agent (e.g., oil) was used in the mould as it could influence the results of the water resistance test.

After the soil was filled into the mould, hard Teflon blocks were placed and pressed gently over the soil such that at least 10mm of the block is inside the mould (Figure 4.5 (part 2)). A spirit level was used to ensure that the top of all blocks (especially those on the corner) are aligned. This assembly was then placed under a load cell which is connected to a manually controlled hydraulic actuator with a capacity of 200 kN. In order to distribute the force from the load cell evenly on all 9 samples, a wooden and a metal plate was placed over the Teflon blocks (Figure 4.5 (part 3)). The combined mass of these plates was around 3kg. The load cell is lowered to the top of the assembly and the load was gradually increased to a pre-defined compression pressure (18/36/72 kN corresponding to 1.25/2.5/5 MPa per block). This process takes 2-4 minutes based on the water content of the soil and the maximum force. Due to a slower loading, this setup is capable of compressing wet soil, thereby releasing water out of the mould in the compaction process. Lines were also marked on the Teflon blocks to act as a visual guide in the alignment of all blocks, ensuring that all soil samples are compressed with equal force. The data from the load cell and LVDTs were recorded live on a computer. Once the desired compaction pressure was reached, the load cell was released, and the assembly was removed for demoulding. The mould is designed in such a way that CEBs can be immediately removed after the compaction without any damage (Figure 4.5 (part 4)). A video on the process of casting of CEBs can be viewed through this link: https://youtu.be/yc37SiTtrFM or by scanning the QR code in Figure 4.5.

The CEBs were carefully handled, and the mass of each block was noted (precision 0.01g). Three CEBs were selected, and their dimensions were measured accurately using a digital Vernier calliper scale. Only 3 samples were selected for measurement to minimise any damage during the complicated handling of blocks. The dimension and mass measurements were used to determine the bulk density of the fresh CEBs.

In order to get a rough estimation of the comparative 'green' (non-cured) strength (strength of freshly casted CEB) of different blocks, the Equotip hardness test was also conducted on the 3 selected blocks. Equotip is a hand-held equipment that is often used to measure the non-destructive hardness of metallic material but has been used in estimating the strength of construction materials (Kulshreshtha, 2015). The Equotip hardness test was found to be useful in comparing and sorting CEBs on their green strength, without disturbing or destroying the samples. This test provides information on whether a CEB (or set of CEBs) can be easily moved and transported immediately after casting.

In order to understand the effect of type of compaction (or earthen construction technique) on water-resistance of earthen materials, blocks were also prepared by ramming soil in 3 layers. Each layer was compacted with 15 blows from a hand-held metal rammer (base area 2 x 2 mm).

4.4.2.4 Air drying of CEB

After determination of mass, dimension, and green strength of freshly cast blocks, they were transferred to a temperature and humidity-controlled room for drying. It is important to recognise that the temperature and humidity have a strong influence on the strength development of earthen materials (Champiré et al., 2016; Lee et al., 2008), therefore it is necessary that samples are kept at a constant temperature and humidity environment. All blocks were dried for 14 days at 19 (±1) °C and 55(±2) % relative humidity. Unlike cement, there is no time-dependent hydration process in earthen materials and the properties are linked to their water content. 14 days was found to be a sufficient duration for drying and achieving a temporally constant mass. The mass and dimensions of all blocks were determined after drying them for 14 days. In the test series on the influence of pre-wetting or residual water content in the block on water-resistance behaviour, CEBs were dried for a period ranging from 8 hours to 67 days.

Out of every 9 blocks prepared for each mix, water resistance tests were conducted on 6 blocks and the remainder were tested for compressive strength.

4.4.3 Water resistance test

Immersion and drip tests were performed to access the water resistance of CEBs. A slightly modified version of the drip test was chosen that is relatively less intense than the immersion test and is suitable to access the performance of earthen materials in a non-extreme environment. Both the test setups to measure the water resistance of CEBs were custom made. It should be noted that both immersion test and drip test represent extreme conditions and may not necessarily reflect the long-term durability of unstabilised material at an architectural scale. However, they are useful in accessing the comparative performance of various CEBs in lab.

4.4.3.1 Immersion test

An immersion setup capable of providing clear visual information on the disintegration rate of earthen blocks was developed for understanding the response of water ingress in earthen blocks. The setup consists of a cylindrical jar and a removable platform assembly (with 3 decks) that can easily fit inside the cylindrical jar. Three earthen blocks were placed on individual decks and the whole assembly was lowered into the jar filled with tap water, as seen in Figure 4.6. The platform was lowered slowly such that the process of lowering the platform does not aid in the disintegration of blocks. It should be noted that the unstabilised CEB starts disintegrating as soon as it is in touch with water. The process of lowering the assembly and subsequent disintegration was recorded in a studio setting as seen in Figure 4.6. Images were captured with a digital camera (Canon 70D) at different intervals; 1-5 min (video),10min, 15 min, 20 min, 30 min and 1h. In exceptional scenarios when the earthen blocks were significantly water resistant, images were also captured at 2h, 4h, 6h, 9h, 12h, 24 hours and up to a maximum of 5 days.

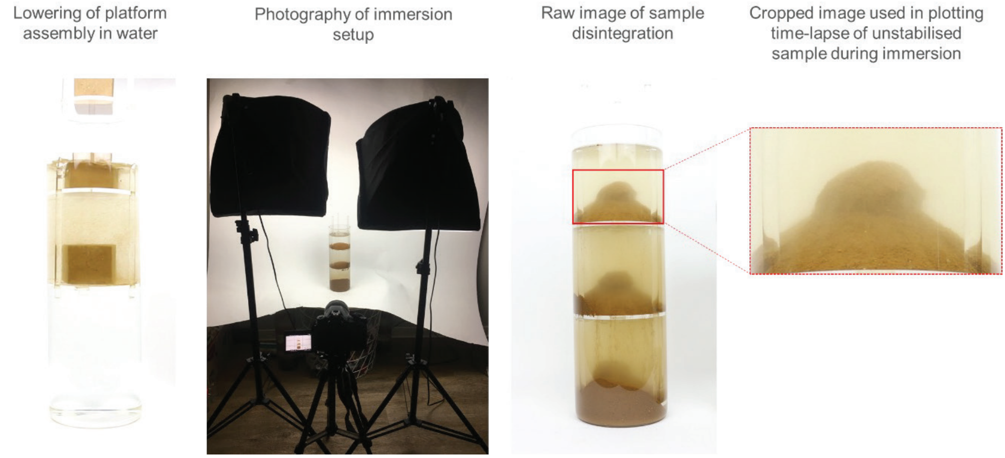

Figure 4.6: Immersion test setup and processing of image for plotting time-lapse of disintegrating blocks.

The raw images of disintegrating samples were processed by altering the brightness (only if required) and by cropping the image. The image of a block located on the upper deck was cropped and used in plotting the time-lapse. While the image of the middle deck is preferable over the top deck, the disintegration of unstabilised blocks is so fast that the samples in middle and bottom deck are often not clearly visible. In case of variations within the disintegration pace of 3 identical blocks (due to inconsistency arising from compaction or drying), the results were reported. In most instances, 3 immersion setups were used simultaneously (a maximum of 3 setups can fit in the frame of the camera).

4.4.3.2 Drip test

A drip test consists of water droplets falling from a height on earthen material at a low flow rate. However, a higher dripping rate was considered appropriate for testing the unstabilised (and stabilised) blocks produced in this thesis. The drip test assembly consists of water dripping from a showerhead (placed at a height of 30cm) above the block, which is oriented at 27° to horizontal (Figure 4.7). The blocks were placed on a removable platform as shown in Figure 4.7. The shower head was adjusted such that only one stream of water was falling in the centre of each block. The rate of flow of water was adjusted to be 50 ml/min per block based on the study by Aguilar et al. (2016) and Nakamatsu et al. (2017). The water head on the top surface of the block was measured to be approximately 1m. Before each test, the rate of flow of water from each nozzle was measured and adjusted to the selected values by varying the water pump pressure and by clogging or unclogging the nozzle of the shower head (the red wires stuck to the nozzle as can be seen in Figure 4.7). The water was continuously pumped to the shower head from a water tank located below the setup.

The mass loss from blocks (in %) was calculated at 2 and 10 min. In some test series, the mass loss in blocks was also calculated at 60 min. The mass loss at 2 min was measured by collecting the eroded mass of CEB in a tray which was placed underneath each block. This tray was then heated in the oven at 105°C to determine the solid mass loss and a correction was applied to get a reliable value based on the water content present in the block just before the testing (refer to Dataset 4Y3). The mass loss at 10 min was measured by weighing the mass of the eroded block. The blocks placed on a removable platform (Figure 4.7) were carefully transferred to an oven for the measurement of the dry mass of the sample. A correction, similar to the calculation of mass loss at 2 min, was applied for mass loss at 10 min. For samples that were tested until 60 min, the eroded mass of block was collected at 2 min and 10 min in trays placed underneath the block.

Figure 4.7: Modified drip test setup. The image on the left provides a visual of the setup. Erosion in an unstabilised block is shown in the figure on right.

Impact of Covid-19 on the execution of research

Covid-19 had a major impact on the experimental research conducted in this thesis. The limited opening time of the lab, limited access due to restriction on the number of people and multiple shutdowns of the lab resulted in adopting an alternative research approach. The limitation caused by Covid-19 has an impact on the overall investigation, especially on the choice of test. In fact, the existence of this chapter is credited to covid-19 as a study on unstabilised earthen material was not initially planned for the thesis. Test conducted on unstabilised CEBs were part of the chapter on cow-dung stabilisation of CEBs. The unstabilised CEBs were control test series to evaluate the comparative performance of cow-dung stabilised CEBs. However, the closure of the university restaurant forced us to drop a chapter on stabilisation with waste rice starch. Therefore, the time and energy were allocated in studying unstabilised earthen materials in depth. Some unexpected results during the preliminary testing stage also aided in pursuing detailed investigation on unstabilised CEB.

Covid-19 had a major role in the choice of the experiments, especially custom-made water resistance tests. One of the major advantages of the immersion test is that it can be conducted in low resource settings, such as a home. A small photography studio was set up in a corner of the living room and all immersion tests were performed at home. This also allowed the possibility to take images at regular intervals and observe the samples for almost 24h, which was especially useful for extremely water-resistant samples. The maximum duration for the drip test, i.e., 60 min, was also decided based on the restricted opening hours of the lab. The selection of test duration does not have a major implication on evaluating water resistance of unstabilised blocks but had an impact on testing of cow-dung stabilised blocks. The drip test was also designed and installed in a moving cart, such that the whole assembly (including water tank and pumps) could be transported easily.

4.4.4 Compressive strength test

The CEBs were tested in a compression testing machine (Model: E161PN114, Matest, Italy) set with the following loading parameters: loading rate = 0.5 kN/s and start load = 0.5 kN. The specimens were prepared and tested in triplicates and the results were expressed as average compressive strength. The geometry of CEBs is known to influence their tested compressive strength values (Aubert et al., 2013; Morel et al., 2007). Although the compression test was conducted without a confining pressure (unconfined), the friction along the interface of the specimen and the steel plate (of the equipment) confines the lateral expansion of the specimen. This increases the apparent strength of the block and provides an over-estimated strength value (Morel et al., 2007). The over-estimation of strength is significant in CEBs of low aspect ratio (ratio of the width to the height), such as those produced in this study (aspect ratio of 1). Hence, the compressive strength measured for CEBs is not indicative of their real-life performance. Although the compression test on these CEBs provides an over-estimated value, the results are useful in evaluating the comparative performance of earthen blocks, as long as a comparison is drawn between blocks of similar aspect ratio.

After testing each block, they were heated in an oven to measure the residual water content in the block (left after drying in the climatically controlled room). The residual water content and the water evaporated during drying in the climatically controlled room were used to re-calculate the compaction water content in each sample. Prior to water content measurement, a piece of the block (of approximately 20-30g) was taken and sealed in a plastic bag for the microstructural characterisation test. Care was taken in choosing a piece from the upper half of the block, away from the region of failure and unaffected by cracking due to compression.

4.4.5 Microstructural characterisation test - Mercury Intrusion Porosimetry (MIP)

Microstructural techniques have been extensively used to analyse the arrangement and distribution of aggregates, pores, their contact and connectivity in soils (Leroueil & Hight, 2013; Romero et al., 2011; Romero & Simms, 2008). A microstructural investigation was carried out through the Mercury Intrusion Porosimetry (MIP) technique. MIP, as the name suggests, is a technique where mercury (a non-wetting fluid) is forced into the pores of material by the application of external pressure. MIP was conducted on selected CEB samples using Autopore IV equipment (Micromeritics, US) to investigate the pore size distribution and porosity. This equipment is capable of measuring pore diameters in the broad range of 7 nanometers to 400 µm.

The results of the MIP test are sensitive to sample preparation. Samples of 1-1.5 cm^3 were extracted from selected CEBs with due care to avoid any damage to the samples. The water must be removed from the sample in order to start the test. The freeze-drying method was adopted over the oven drying method as it is known to cause minimal disturbance (no shrinkage) to microstructural fabric (Diamond, 1970; Romero & Simms, 2008). The freeze drying process used by Bruno et al. (2018) was followed to prepare the samples. Samples were immersed in liquid nitrogen (of -196°C) for a few minutes (until the boiling ceased) and the frozen sample was immediately transferred to a vacuum air cooler kept at sub-zero temperature. This process results in the sublimation of ice (transformation from solid to gas) without changing the microstructural fabric. All samples achieved a constant mass (full sublimation) within a week. The MIP test was conducted using the procedure described briefly in Appendix 4A. In the testing procedure, utmost care is required in operating the equipment, especially when closing high pressure chamber, to prevent error in measurement (more information in Appendix 4A). For a thorough overview of the MIP method, readers are referred to the article by Giesche (2006). Readers interested in further detail on the MIP test conducted for earthen material can refer to the thesis of Bruno (2016).

A contact angle of 141° and surface tension of 0.485 N/m were used for the calculation of pressure required for given pore diameter using Washburn equation, $P= [-4\ \lambda\ \cos\theta] / D$), where P is the applied pressure to the mercury, λ is the surface tension of the mercury, θ is contact angle between mercury and soil and D is pore diameter (Diamond, 1970). The contact angle value was assumed based on the information presented in the research of Diamond (1970) for smectite and illite mineral-rich clays. The results of the MIP test are often presented in a graphical form showing the relationship between log differential intrusion and pore diameter.

Although MIP provides a reliable quantitative characterisation of microstructure, it has some limitations which are described in the study of Romero & Simms (2008). Some of these limitations are 1. The mercury cannot enter pores which are surrounded by solid (closed pores), 2. Pores accessible through smaller pores are not detected until smaller pores are filled and,

3. Pores below 7nm and larger than 400μm are not detected in the MIP test. Therefore, there can be a slight discrepancy between the original microstructural fabric and the one indicated by the MIP test.

4.5 Results

4.5.1 Influence of compaction water content on water resistance and strength of unstabilised compressed earth blocks (CEBs)

The impact of the compaction water content on the strength and water resistance of CEBs is shown in Figure 4.8. The compressive strength increased from 2.4 MPa to 4.2 MPa with the increase in compaction water content from 8.6% to 12.6%. With further increase to 14.2%, the compressive strength decreased by 12%. A direct correlation between compressive strength and the dry density is observed (compare blue and orange lines in Figure 4.8(a)), which is in line with observations of Gerard et al. (2015) on unstabilised earthen materials.

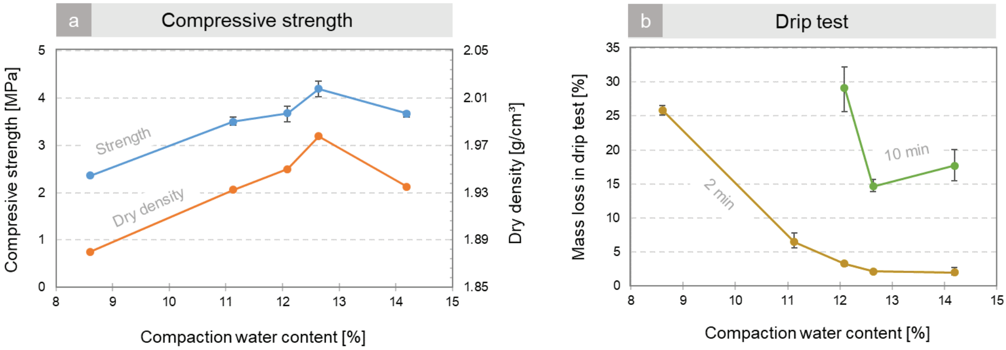

Figure 4.8: Influence of compaction water content on (a) compressive strength and dry density of CEBs, and (b) water resistance as measured through drip erosion test duration of 2 min and 10 min. All blocks were prepared with a compaction pressure of 2.5 MPa. The accompanying dataset is available in Dataset 4Y3. Note that the process of compaction results in the loss of water from the soil. Hence, the water content in CEBs just after compaction (referred to as compaction water content) was lower than the water content in the soil before compaction (more details in Appendix 4B).

The results of the drip tests are shown in Figure 4.8(b). With an increase in compaction water content, the mass loss in the drip test decreased and hence, CEBs became more water resistant. Mass loss measured after 2 min of drip test decreased from 26% to 2% with an increase in compaction water content from 8.6% to 14.2%. Further, the mass loss approaches a virtually constant value of about 2% mass loss when the compaction water content was above 12% (Figure 4.8(b)). Therefore, within this range (8.6-14.2%), a higher compaction water content is favourable for superior water resistance behaviour.

The results of 10 min drip test largely correspond with observation in 2 min, although only CEBs produced with over 12% compaction water content were able to survive the test duration. Increase in compaction water slightly (from 12.1% to 12.6%) decreased the erosion of CEBs by half. The mass loss in the strongest sample (4.2 MPa at 12.6% compaction water content) was found to be minimum, but still comparable to mass loss in CEBs produced with a higher compaction water content of 14.2%. Selected images of the eroded CEBs can be viewed in Appendix 4C.

The results of the drip test also correlated well with the immersion test results, shown in Figure 4.9. Similar to the drip test, the CEB with a low water content of 8.6% did not survive immersion beyond 2 min. With an increase in compaction water content, the water stability of CEBs improved. The CEBs prepared with 12.6% compaction water content survived immersion for 20 min. Whereas CEBs prepared at 14.2% compaction water content disintegrated slightly faster, which is in line with the observation in the drip test. This may be due to the lower dry density and higher porosity of CEB prepared at 14.2% compaction water content, indicating a slight impact of dry density on the water resistance.

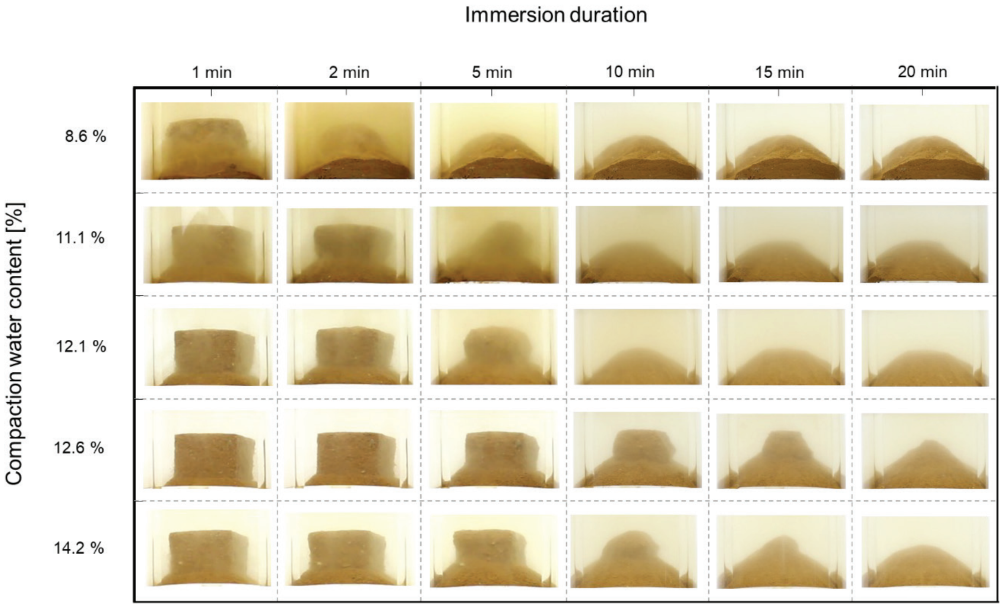

Figure 4.9: Time-lapse of disintegration of CEBs with varying compaction water content. All samples were prepared with a compaction pressure of 2.5 MPa.

Comparing the CEBs of similar dry density can provide information on the influence of compaction water content on water resistance without the interference of dry density. Comparing CEBs prepared at a compaction water content of 11.1% and 14.2%, which have a similar dry density of 1.93 g/cm^3 (and similar strength values), shows that CEBs with higher compaction water content (14.2%) is superior in performance in immersion test (Figure 4.9) and drip test (Figure 4.8(b)). In the drip test, the mass loss in CEB prepared with higher compaction water content (14.2%) was about one-third of the CEB prepared at lower compaction water content (11.1%). These results show that at the same dry density, better water resistance is observed for CEBs prepared with higher compaction water contents. Therefore, it is likely that microstructural fabric (distribution of pores facilitating water ingress) plays an important role. The role of microstructure in water ingress will be discussed in Section 4.6. Other parameters such as shrinkage and hardness of freshly casted CEBs were also measured and the results are described briefly in Appendix 4D, and accompanying data is available in Dataset 4Y3 (Kulshreshtha, 2022).

The experimental study on the influence of compaction water content (water content in CEBs immediately after compaction) shows that with an increase in compaction water content, the water resistance of CEBs increases. Moreover, at the same dry density, better water resistance is observed for CEBs prepared with higher compaction water contents.

4.5.2 Influence of compaction pressure on water resistance and strength of unstabilised CEBs

The influence of compaction pressure on CEBs was assessed by preparing samples with 1.25 MPa and 5 MPa compaction pressure and comparing them to CEBs prepared with compaction pressure of 2.5 MPa. The CEBs with 5 MPa pressure were prepared at the compaction water content of 8.90% and 11.1%. It was not possible to cast CEBs with a higher water content (>12%) at this compaction pressure as preliminary trials resulted in damage to the mould. Whereas samples prepared with 1.25 MPa compaction effort and low compaction water content (<12%) were insufficiently compacted (top half with good compaction, bottom half with bad compaction), therefore were discarded for the investigation.

The influence of compaction pressure on the dry density and strength of CEBs is shown in Figure 4.10(a). Solid line indicates results of CEBs compacted with 5MPa pressure, dashed line indicates CEBs with 1.25 MPa pressure. For CEBs compacted with 5 MPa pressure, the strength increased from 3.25 MPa to 4 MPa with an increase in compaction water content from 8.9% to 11.1%. Whereas in CEBs compacted with 1.25 MPa pressure, the highest strength of 3.25 MPa was achieved at 13.6% compaction water content (Figure 4.10(a)). Similar to the observation in Section 4.5.1, the compressive strength is co-related to the dry density of CEBs.

The results from the drip test shown in Figure 4.10 (b), reveal that a higher compaction effort results in better resistance to drip erosion. In CEBs prepared at 11.1% compaction water content (Figure 4.10(b)), increasing the compaction effort by 2 times (2.5 MPa to 5 MPa) resulted in a 60% reduction of mass loss (from 6.4% to 2.5%). Similarly, at about 12.5% compaction water content, an increase in compaction effort from 1.25 MPa to 2.5 MPa results in a 70% reduction of mass loss (from 7.4% to 2.1%.)

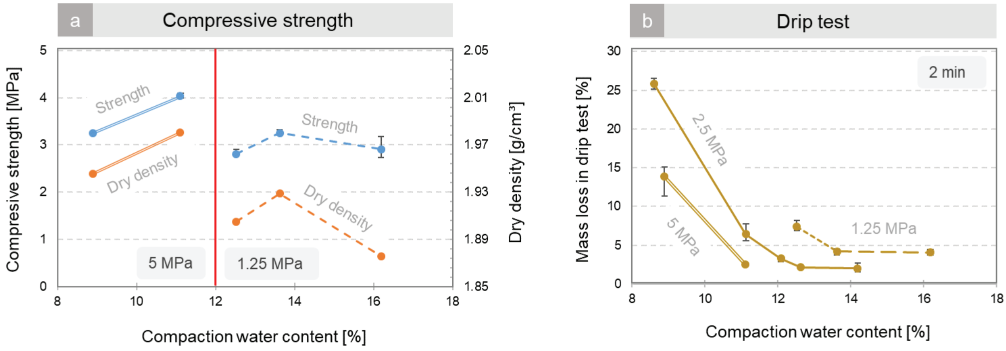

Figure 4.10: Influence of compaction pressure on compressive strength and mass loss in drip erosion test of CEBs. (a) Compressive strength data for compaction pressure of 5MPa and 1.25 MPa. (b) The drip test result for CEBs compacted with 5 MPa, 2.5 MPa and 1.25 MPa compaction pressure (duration: 2 min). The drip test results of 10 min are available in Appendix 4E. The complete dataset for plotting these results can be found in Dataset 4Y4 & 4Y5.

Figure 4.10(b) also indicates that the influence of compaction pressure reduces with a rise in compaction water content. For example, CEBs compacted with 5 MPa at 11.1% compaction water content lost 2.5% of their mass in 2 min drip test. Whereas the CEBs compacted with half the pressure effort (2.5 MPa) at 12.6% compaction water content had similar erosion (2.1%) in the drip test (see Figure 4.10(b)). Even in CEBs of similar strength, superior resistance to erosion was achieved using a higher compaction water content and less compaction energy. For instance, despite having similar compressive strengths, CEBs compacted with 1.25 MPa pressure (at 13.6% compaction water content) were more water resistant (mass loss of 4%) than CEBs compressed with 5 MPa (at 9% compaction water content, mass loss of 14%).

The trends seen in the drip test are also observed in the immersion test results. Figure 4.11 provides results of selected CEBs with similar water content and varying compaction pressure. The complete results of the immersion test for CEBs compacted with 1.25 and 5 MPa are available in Appendix 4F.

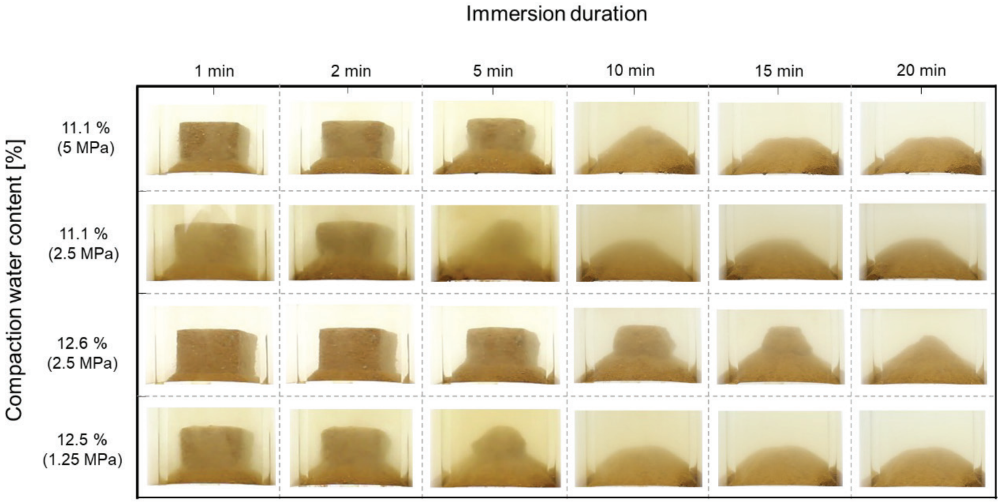

Figure 4.11: Time-lapse of disintegration of CEBs with varying compaction force (and similar water content).

4.5.3 Influence of residual or pre-wetting water content on strength and water resistance of unstabilised CEBs

The residual water content and pre-wetting water content refer to the water content in CEBs after (partially or nearly) drying them for a specific duration. In this thesis, pre-wetting water content is used in the context of water resistance, whereas residual water content is used in the context of strength. The terms 'degree of saturation', which means the extent of pores filled with water, is also related to residual or pre-wetting water content. An earthen material with a high residual or pre-wetting water content has a high degree of saturation.

Unlike testing of dried CEBs, the CEBs prepared for this test series had a higher water content at the time of testing. Therefore, this test series is most similar to the research in the field of unsaturated soil mechanics where compacted soil is tested at a relatively higher water content (moist). Preparation of CEBs for this test series was challenging due to the need for 9 identical sets of specimens, hence 91 identical CEBs (all prepared at 12.6% compaction water content). The required level of precision was challenging due to the inherent limitation of sample producing assemblies, resulting in some differences in the compaction water content of CEBs. However, the variation was found to be insignificant in most sets. Once the CEBs were produced, they were air-dried for specific durations, ranging from 0 hours to 67 days.

The influence of residual water content on compressive strength is shown in Figure 4.12. The result shows that the compressive strength of CEBs increases with an increase in drying duration and decrease in residual water content. Freshly cast CEBs were too soft for compressive strength testing, however, minor strength development was observed from 8 hours of drying (residual water content: 10.3%). Compressive strength of 1.7 MPa was measured after 24 hours of drying, which increased to 3.2 MPa in 3 days. The drastic improvement of strength in the first 3 days is a result of losing about 10% of water from the sample (Figure 4.12). The residual water content reduced from 2.3% to 1.7% in the next 11 days (between 3 to 14 days), reaching a compressive strength of 4.2 MPa in 14 days. The change in residual water content after 14 days was minimal and therefore, the strength increased slightly to 4.6 MPa after a drying period of 67 days. The residual water content measured in CEB after 67 days of drying was 1.5%. Even a slight variation in 0.2% water content (between drying duration 14 and 67 days) resulted in a gain of 0.4 MPa, reflecting the strong influence of residual water content variation on the compressive strength of CEBs.

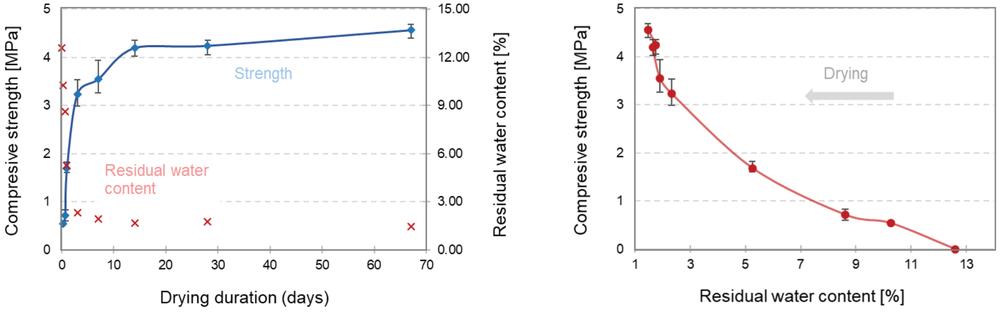

Figure 4.12: Influence of drying duration (left) and residual water content (right) on compressive strength of CEBs prepared at 12.6% compaction water content with 2.5 MPa compression. The complete dataset for plotting these results can be found in Dataset 4Y6.

The influence of pre-wetting water content on the stability of CEBs during immersion can be visualised in Figure 4.13. CEB immersed in water immediately after casting did not show any sign of disintegration in 20 min (Figure 4.13). The complete disintegration upon immersion was observed in 6 hours (time-lapse of CEB beyond 20 minutes can be found in Appendix 4G). The water resistance of CEBs decreased with an increase in drying duration or a decrease in pre-wetting water content. The rate of disintegration became almost consistent beyond 1 day (or 5.5% pre-wetting water content), as observed in Figure 4.13.

The results of the drip test shown in Figure 4.14 reinforces the observations of the immersion test that higher pre-wetting water content is favourable to water resistance of CEBs. The CEBs with higher pre-wetting water content (range of 8-13%) could survive 60 min test duration (with partial disintegration). However, CEBs with low pre-wetting water content (<8%) disintegrated much faster. The performance of CEBs with 12.6% pre-wetting water content was found to be about 6 times better than CEBs with less than 6% pre-wetting water content. Similar to the consistent rate of disintegration observed beyond 1 day of drying in the immersion test, the variation in mass loss in the drip test is insignificant after 1 day of drying (Figure 4.14). However, an exception to the trend is observed on 3 days of drying (or pre-wetting water content of 2.3%). This exception could be due to lower compaction water content (12.3%) than other CEBs (12.5-12.6%). As observed in Figure 4.8(b), a slight variation in compaction water content has a significant impact on erosion (the mass loss in 10 min drip test decreases from 29% to 15%%, by a mere increase of 0.5% compaction water content). This inconsistency is discussed further in Appendix 4H.

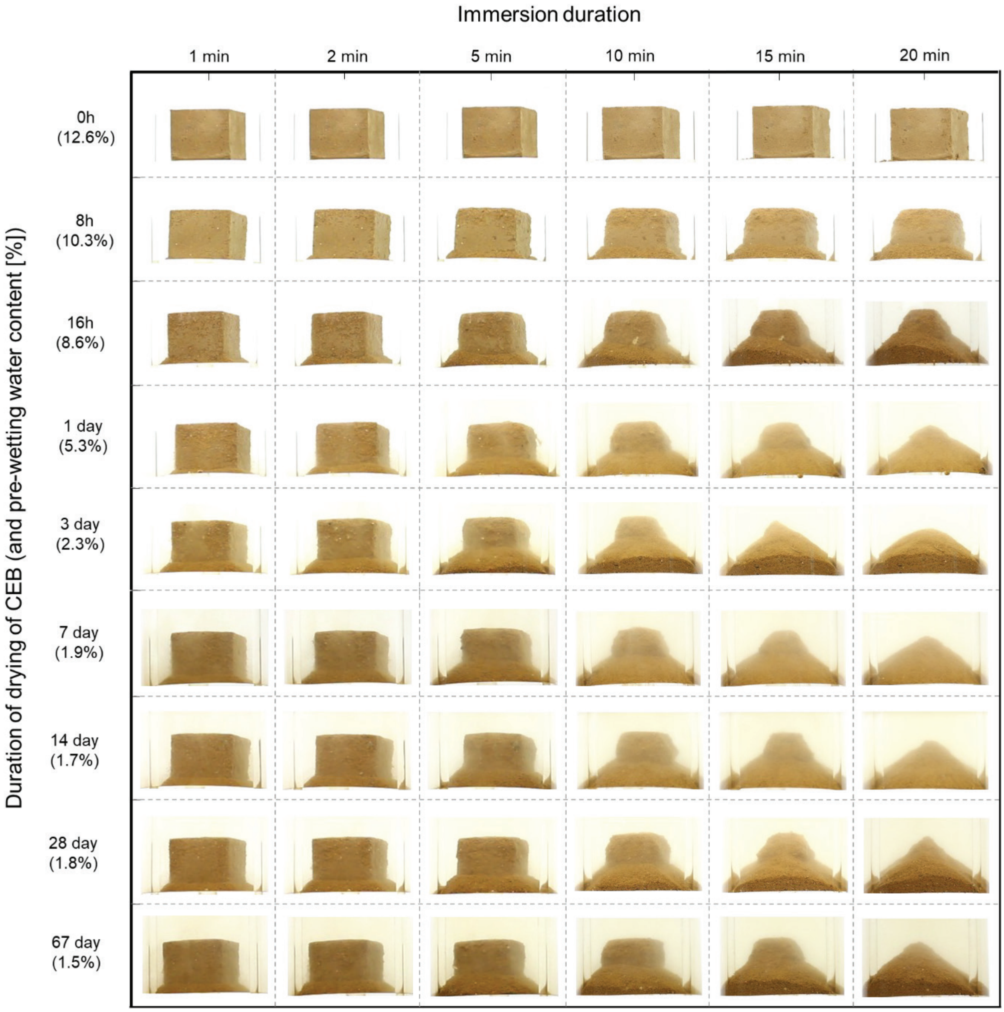

Figure 4.13: Time-lapse of disintegration of CEBs tested at different pre-wetting water content (which is dependent on the duration of drying). All the samples were prepared with 2.5 MPa compaction to reach the target compaction water content of 12.6%.

The influence of residual or pre-wetting water content on strength and water resistance is more significant than the influence of compaction water content and compaction pressure. Drying of CEBs results in loss of water, hence reduction in water content. CEBs with higher residual or pre-wetting water content (i.e., subjected to a short duration of drying) have low compressive strength but are more water resistant. Whereas CEBs with lower residual water content (i.e., subjected to a long drying duration) have good compressive strength, but are more susceptible to water-driven erosion. In earthen walls, residual (or pre-wetting) water content of an earthen wall is controlled by factors such as the ambient temperature, humidity, and rainfall. Hence, the strength and water resistance of the wall are never constant. Unlike compaction water content and compaction pressure, the pre-wetting water content cannot be controlled or optimised for practical applications. However, the pre-wetting water content is expected to play a dominant role in the durability of earthen walls, especially for preventing the erosion of walls in the event of rainfall. This would be further discussed in Section 4.6.

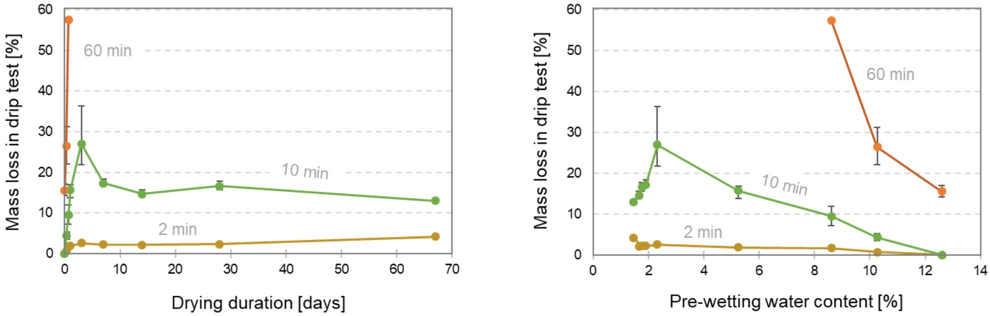

Figure 4.14: Influence of drying duration (left) and pre-wetting water content (right) on the mass loss of CEBs in the drip test. The mass loss was measured at 2,10 and 60 minutes. The sample was prepared with 2.5 MPa compression force to reach a target value of 12.6% compaction water content. The image of selected CEBs after the drip test is available in Appendix 4G. The complete dataset for plotting these results can be found in Dataset 4Y6.

4.5.4 Influence of compaction technique on water resistance and strength of unstabilised earthen materials

In addition to CEBs, Rammed Earth (RE) blocks were prepared by compacting the soil using a hand-held rammer. Due to low energy in hand compaction, the dry density measured for the rammed earth blocks was lower than CEBs compressed with 2.5 MPa compaction pressure (Figure 4.15). Irrespective of the lower densities, the highest compressive strength measured for the RE blocks were comparable to CEBs (4.1 MPa) (Figure 4.15). Compressive strength of RE blocks increased from 1.2 MPa to 4.1 MPa with the rise in compaction water content from 9% to 14.2% and then decreases to 2.6 MPa at 16.1% compaction water content. Similar to CEBs, a direct correlation between compressive strength and dry density is observed.

Comparing RE block and CEB of the similar compaction water content of 14.2% and similar dry densities (1.92 g/cm^3) in Figure 4.15 reveal a higher average compressive strength of RE blocks (4.1 MPa) than CEBs (3.7 MPa). The slightly higher strength of RE blocks (by 0.4 MPa) can be due to lower residual water content (1.25%) as compared to CEBs (1.5-1.7%) at the time of testing. While the difference of 0.25-0.45% residual water content seems insignificant, such variation in residual water content is known to influence compressive strength results (see Figure 4.12). The lower residual water content measured in RE blocks could be due to lower humidity levels (~53%) than usually recorded in the climatically controlled chamber during the sample drying period. This reinforces the sensitivity of earthen materials to their ambient humidity and temperature.

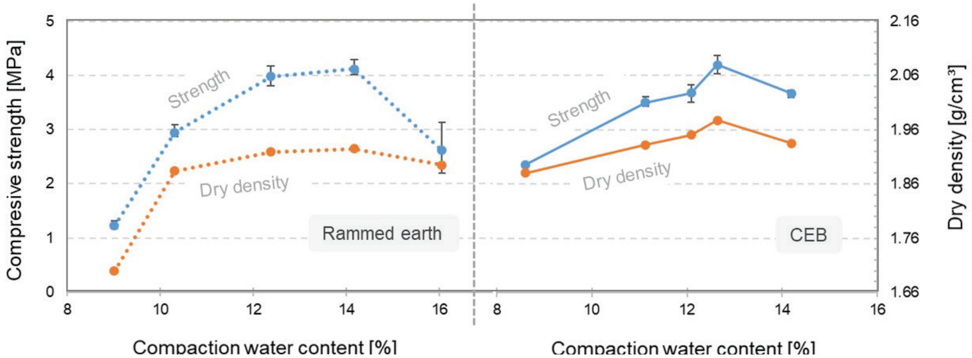

Figure 4.15: Compressive strength and dry density curve of rammed earth block compacted with a hand-held rammer (left) and CEBs (right). The complete dataset for plotting these results can be found in Dataset 4Y7.

The results of immersion test shown in Figure 4.16 reveal no variation between hand compacted rammed earth (RE) blocks and CEB irrespective of differences in dry density (and porosity) of CEBs and RE blocks. Immersion test results for all RE blocks can be seen in Appendix 4I.

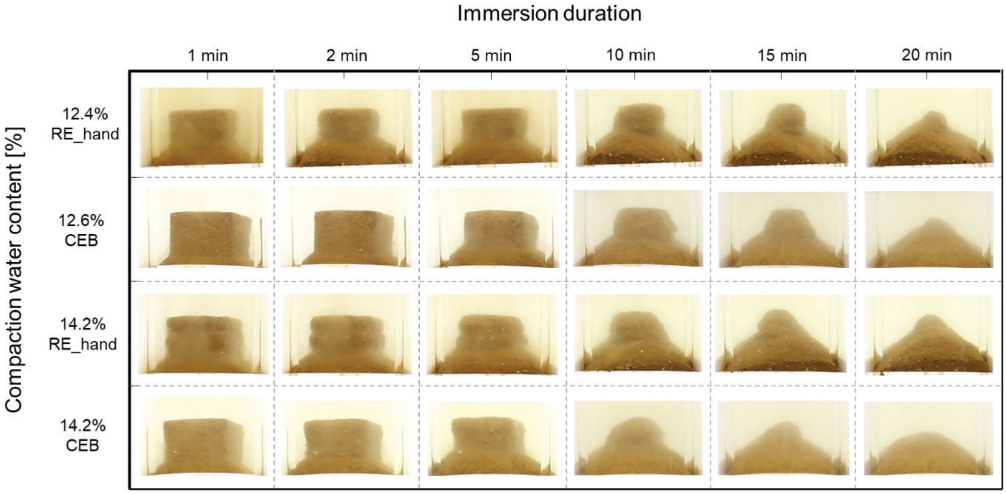

Figure 4.16: Time-lapse of disintegration of CEBs and rammed block with similar water content.

Similar to the immersion test, no significant variation in water-driven erosion was observed in the drip test (mass loss measured after 2 min), as shown in Figure 4.17. Some variation in mass loss between RE and CEB can be observed in 10 min drip test duration. The poor performance of RE blocks as compared to CEB (where mass loss recorded was low) could arise from the nonhomogeneous layers of RE blocks, where the upper region of each layer is more compacted than the bottom (as also visualised in Figure 4.16). While the top surface could resist erosion significantly well, the lower section could be susceptible to erosion due to a lower degree of compaction.

The results of immersion and drip tests indicate a minimal influence of the compaction technique on the short-term water resistance of earthen materials. Similar observations on the limited impact of the compaction method on wetting induced collapse of soil were found in the study by Lawton et al. (1989).

4.5.5 Influence of clay mineral on the water resistance of unstabilised CEBs

Due to the artificial preparation of soil mix with a single size range of sand (0.25-0.50mm), the strength of kaolinite and bentonite rich CEBs was quite low (0.1 MPa for kaolinite rich CEBs and 1.1 MPa for bentonite rich CEBs). Results obtained from both immersion and drip tests indicate that the bentonite clay rich CEBs outperformed the kaolinite clay rich CEBs by a huge margin. In the drip test, kaolinite rich CEBs did not survive beyond 2 min, whereas bentonite rich CEBs had a mass loss of less than 1% in 60 min (refer Dataset 4Y8). Figure 4.18 illustrates the contrasting difference in the immersion test result of bentonite and kaolinite rich CEBs. Kaolinite rich CEBs did not survive for 5 minutes, whereas the bentonite rich CEBs remained largely intact after 5 days of immersion. An increase in volume was also observed during the immersion of bentonite rich CEB, indicating the swelling nature of bentonite clays (Figure 4.18). The swelling of clay and its influence on water ingress will be discussed briefly in Section 4.6.2.

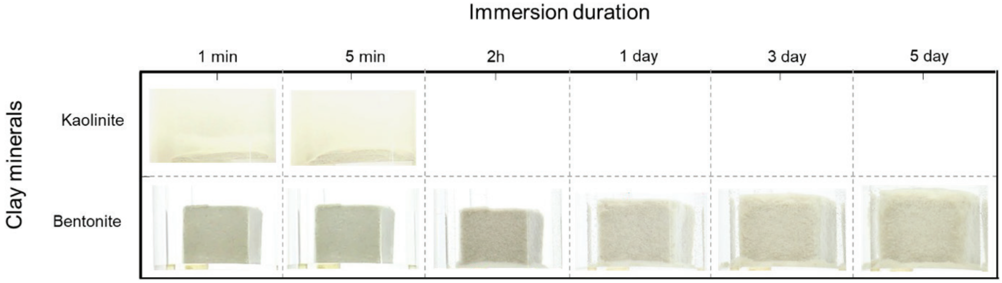

Figure 4.18: Time-lapse of disintegration of CEBs made with kaolinite and bentonite rich clay minerals at water content close to their plastic limit and compaction pressure of 2.5 MPa. The complete dataset is available in Dataset 4Y8.

4.6 Discussion

This section combines the insights from the experimental investigation in Section 4.5 with the microstructural characterisation test and theory on earthen materials (discussed in Section 4.2), to facilitate the discussion on the strength and water resistance of earthen materials.

4.6.1 Factors affecting the strength of unstabilised compressed earth blocks (CEBs)

As visualised in Figure 4.19, the strength of earthen materials depends on aggregate interlock, cohesion and capillary suction which is influenced by changing material composition, water content and density. These factors are discussed in the following sub-sections:

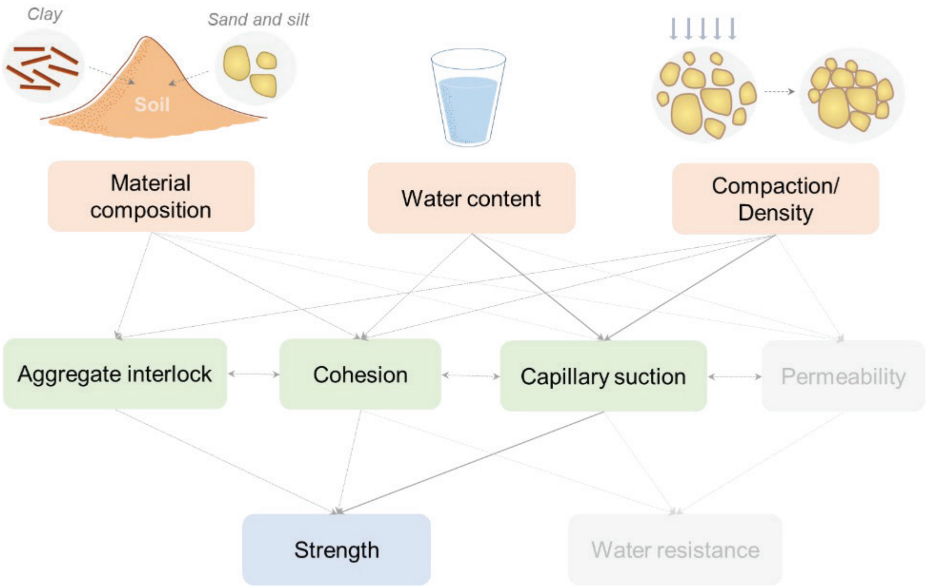

Figure 4.19: Parameters affecting the strength of unstabilised CEBs.

4.6.1.1 Material composition

Due to the use of same soil in most experiments, the material composition is a constant that does not influence the strength of CEBs investigated in this thesis. However, the influence of material composition could still be seen through the artificially created soil (see Section 4.5.5). CEBs produced from artificially created soils had a compressive strength of 0.1 MPa for kaolinite and 1.1 MPa for bentonite rich soil, which was comparatively lower than the strength measured for CEBs produced with well-graded natural Dutch soil (up to 4.2 MPa). The lower strength in these CEBs is expected due to poor aggregate interlock (no grading) and low cohesion (especially in kaolinite).

4.6.1.2 Water content

Water content in unstabilised earthen material is a key factor that influences the strength through the capillary suction (Bui et al., 2014; Champiré et al., 2016; Gerard et al., 2015; Jaquin et al., 2009). Unlike cement-based building materials, strength in unstabilised compressed earth blocks (CEBs) increases due to the process of drying. With an increase in drying duration, the residual water content in CEBs decreases. The decrease in water content increases the capillary suction which pulls the aggregates close to each other and thereby, increases the strength. The impact of water content on strength can be observed in Figure 4.12 (in Section 4.5.3), where a decrease in residual water content in CEBs from 8.6% to 1.5% (through air-drying) resulted in an increase of compressive strength from 0.7 MPa to 4.6 MPa.

4.6.1.3 Density/compaction

Capillary suction is dependent on the gaps between aggregates, where a smaller distance is favourable for strength. An increase in density decreases the gaps between the aggregates, hence improving the strength. A clear correlation between dry density and compressive strength was observed in all the CEBs. An increase in dry density can be achieved by compacting the soil with high compaction pressure. For example, increasing the compaction pressure from 1.25 MPa to 2.5 MPa (for CEBs prepared at a compaction water content of 12.5%) resulted in a 50% improvement of compressive strength, from 2.8 MPa to 4.2 MPa (Figure 4.5 and Figure 4.8 (Section 4.5)). The compaction of soil or earthen material is also dependent on its water content during compaction. Soil with low water content can be compacted easily, whereas soil with higher water content is difficult to compact due to the presence of virtually incompressible water. Hence, the impact of compaction effort on dry density and strength is more significant on soils with lower water content during compaction than on higher water contents.

4.6.2 Factors affecting water resistance of unstabilised compressed earth blocks (CEBs)

Similar to factors affecting the strength, material composition, water content and density have a strong influence on water ingress and therefore, water resistance of CEBs (Figure 4.20).

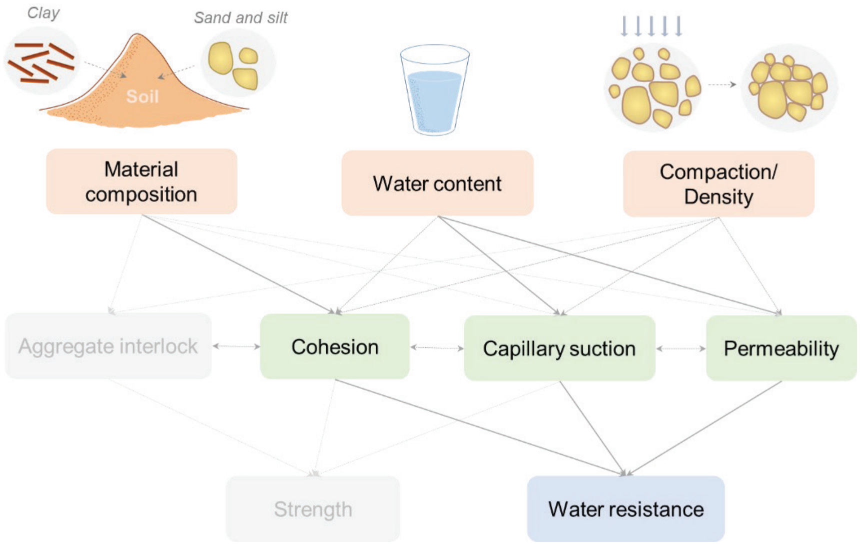

Figure 4.20: Parameters affecting the water resistance of earthen materials.

4.6.2.1 Material composition

The results presented in Section 4.5.5 show that the clay mineralogy has a significant impact on the water resistance behaviour of CEBs. Irrespective of similar clay content (amount of clay), the CEB produced with bentonite rich soil performed superior to CEBs produced with kaolinite rich soil and CEBs produced with natural Dutch soil. The superior water resistance performance of bentonite soil rich CEBs is likely due to the high swelling of the clay minerals, which clogs the pores and restricts the entry of water into the block. In fact, sodium bentonite clay used in this study is known to reduce the water permeability significantly (Yesiller & Shackelford, 2011). Although the natural Dutch soil contains swelling minerals, the overall swelling potential of the soil is quite low, as indicated by the low bulk cation exchange capacity of the soil (Table 2, Section 4.4.1).

4.6.2.2 Water content

Water content is one of the dominant factors that influenced capillary suction and permeability, and thus impact the water resistance of CEBs. The results presented in Sections 4.5.1-4.5.3 show that both compaction water content (water content in freshly compacted block) and pre-wetting water content (water content after drying) influence the water resistance of CEBs. The underlying reason behind the observed variations in water resistance of CEBs due to changes in compaction water content and pre-wetting content are discussed below.

(a) Compaction water content

An increase in compaction water content increases the stability of CEBs against drip erosion and immersion (see Figure 4.8 and Figure 4.9 in Section 4.5). To understand the role of microstructural fabric on the water ingress, MIP tests were conducted on CEBs produced with varying compaction water content. The results of the MIP test are shown in Figure 4.21.

Two trends in the microstructural fabric are observed by analysing the plot of log differential intrusion and pore size diameter in Figure 4.21; 1. The inter aggregate pore, hereinafter referred to as macro-pore, observed at 20-40 µm decreases with increasing compaction water content, 2. The smaller inter-aggregate pores, hereinafter referred to as meso-pores, observed in the range of 4-8 µm increase with increasing compaction water content. With an increase in compaction water content from 8.6% to 14.2%, the specific volume of macro-pores was reduced by 16 times, whereas the specific volume of meso-pores increased by 4.5 times (compare dark blue and orange lines in Figure 4.21).

As liquid water permeability of compacted soil is known to depend on the largest pores (Cuisinier et al., 2011; Romero, 2013), the water permeability is expected to be higher in CEBs with larger pore diameter and higher specific volume. A higher permeability means that more water can flow through the material and subsequently reduce the capillary suction holding the aggregate together, leading to disintegration. This proposition is consistent with observed results where CEBs with larger macro-pore size and specific volumes, such as CEBs with 8.6% and 11.1% compaction water content, did not survive the drip test and immersion for over 10 min. However, CEBs with over 12% compaction water content survived erosion for a longer duration, and up to 70% reduction in erosion was measured in the drip test (see Figure 4.8 and 4.9, Section 4.5.1). An increase in compaction water content beyond 12% results in the transformation of microstructural fabric from macro-pore dominated fabric to meso-pore dominated fabric, as shown through MIP result in Figure 4.21. The reduction in pore size and specific volume of largest pore reduces water permeability and rate of water ingress in the CEBs and therefore they take a relatively longer time to disintegrate. The specific volume of meso-pore does not seem to impact the rate of disintegration upon water ingress.

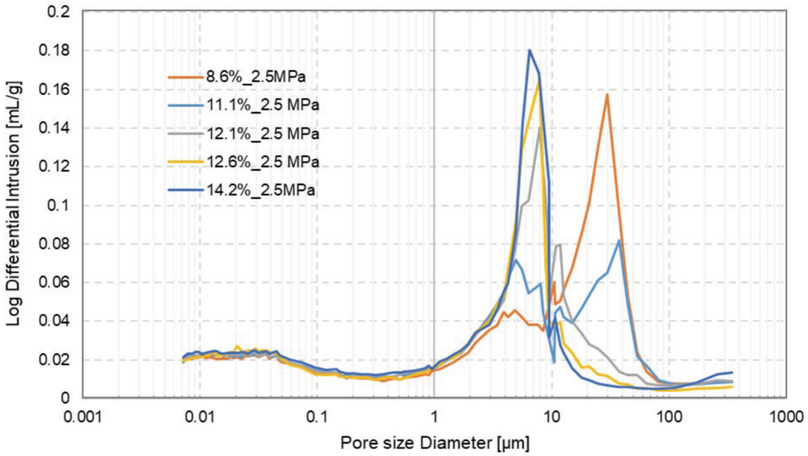

Figure 4.21: MIP test results showing the relation of log differential intrusion and pore size for CEB prepared at varying compaction water content with a compaction force of 2.5 MPa. The data used in plotting can be found in Dataset 4Y3. Additional information on consistency of MIP test can be found in Appendix 4J.

A comparison of CEBs with similar porosity (or dry density) provides a nuanced insight into the influence of compaction water content on pore size distribution. The porosity values of CEBs can be found in Appendix 4J and Dataset 4Y3 (Kulshreshtha, 2022). Comparing CEBs with similar porosity, such as those prepared with 12.1% and 14.2% compaction water content (Figure 4.21) and the ones shown in Figure 4.22, shows that while the volume of pores is similar, pore-size distribution is distinct and dependent on the compaction water content. For example, Figure 4.22(a) shows MIP test results on CEBs with a similar dry density of 1.88 g/cm^3 but varying water content and compaction pressure. With the rise of compaction water content from 8.6% to 16.2%, macro-pores of 20-40 µm transform into meso-pores of 5-10 µm (Figure 4.22(a)). The specific volume of macro-pores in CEB with lower compaction water content (8.6%) was 13 times more than that observed in CEB with 16.2% compaction water content. This shows that, CEB with lower water content had a higher water permeability and therefore, 6.5 times more erosion as measured in the drip test shown in Figure 4.10(b) (Section 4.5.2).The variation in microstructural fabric due to compaction water content is illustrated in Figure 4.23.

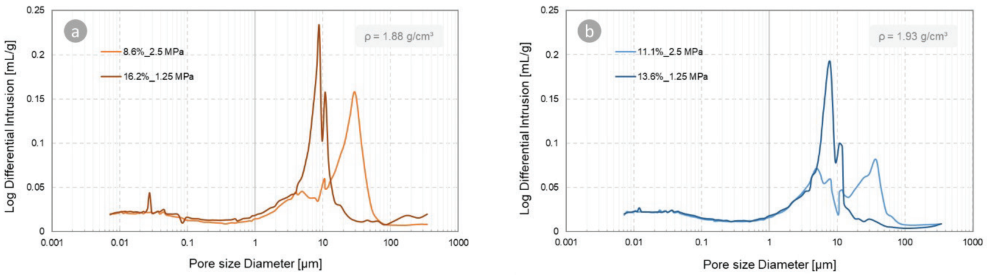

Figure 4.22: MIP test results showing the relation of log differential intrusion and pore size for CEB prepared at a similar dry density of (a) 1.88 g/cm^3 and (b) 1.93 g/cm^3. The legend shows the compaction water content followed by the compaction pressure used in preparing the CEBs.

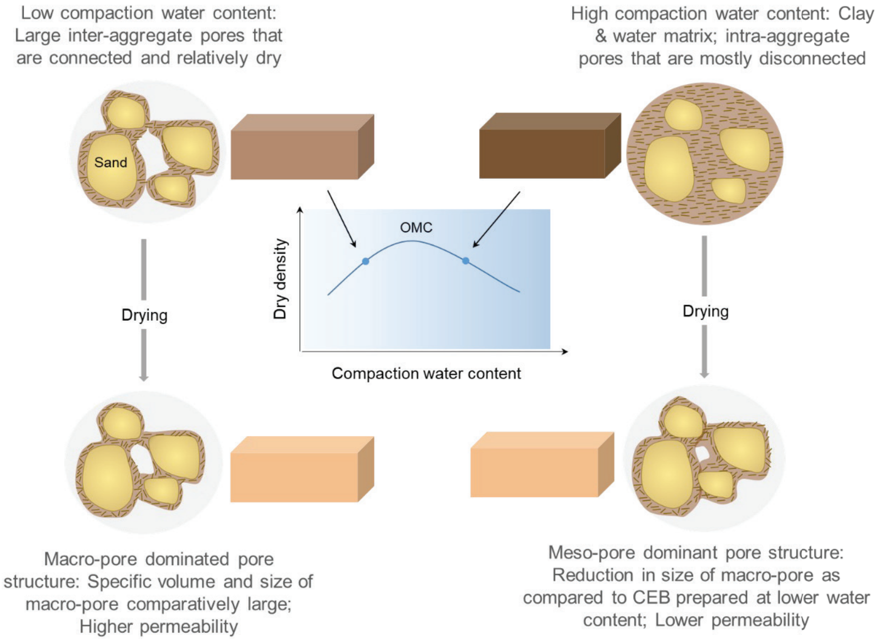

Figure 4.23: A visual representation of the influence of compaction water content on microstructural fabric, especially on pore size distribution.

(b) Pre-wetting water content

Water permeability is known to depend on the size of the largest pore and the degree of saturation of soil (refer Section 4.2.2). A higher degree of saturation means a higher pre-wetting water content and vice-versa. At high pre-wetting water content, low capillary suction in between the aggregates is expected to aid in faster erosion of CEBs, especially in the drip test where the falling water droplets impart energy on the aggregates. Contrary to this expectation, CEBs with higher pre-wetting water content (12.6%) performed 6 times better in drip test than CEBs with low pre-wetting water content (<6%) (refer to Figure 4.13 (section 4.5.3)). The superior performance of these CEBs can be attributed, amongst others, to hydraulic gradient.

Hydraulic gradient drives the flow of water into the pores of CEB, resulting in a decrease of strength (due to reduction in capillary suction) and possible volumetric expansion, leading to disintegration. Information on the hydraulic gradient is available in Section 4.2.2 and visualised in Figure 4.24 below. In a CEB where all pores are filled with water (100% saturation), the hydraulic gradient is negligible, and therefore, no water flows into the CEB hence, keeping them stable. In the superior performing CEB of pre-wetting water content of 12.6%, nearly half (about 46%) of the pores were filled with water (as estimated in Dataset 4Y6). The presence of water reduces the capillary suction, and thereby strength (as observed in Figure 14.2, Section 4.5.3), but also reduces the hydraulic gradient and flow of water into the material. Water can only flow through the pores filled with water (Fredlund et al., 2012) and the air has to move out of material to aid water ingress. Hence, the air in pore acts as an obstruction in the path of water ingress, thereby reducing the flow rate of water significantly. In the immersion test on CEBs with high pre-wetting water content, air bubbles were observed to get expelled out of the block, which enhanced disintegration. In the case of relatively dry CEBs (pre-wetting water content of 1.6%), only 5% of pores are filled with water. The high suction in the pores drives the water into the material, resulting in a reduction of suction and strength within a short duration of time.

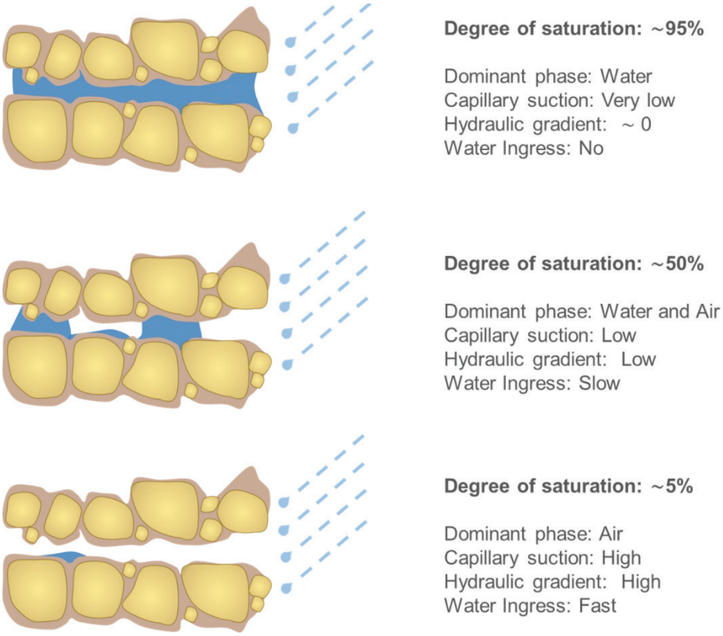

Figure 4.24: Influence of degree of saturation (or pre-wetting water content) on water ingress.

In parallel to the impact of hydraulic gradient, the volumetric expansion due to swelling of clays can also impact the water ingress. In the presence of water in pores, swelling of clays can reduce the size of macro-pore, thereby reducing the rate of flow of water or restricting its further access. However, such changes in macro-pore were not observed in CEB with high pre-wetting water content (refer Appendix 4K). Although when exposed to water, the swelling of clays can restrict further access to water. Based on the soil composition, the swelling of clays could provide further access to water or block it (as seen in bentonite rich CEBs).

4.6.2.3 Compaction/density

When comparing CEBs with similar compaction water content, an increase in compaction effort reduces the macro-pores. With an increase in compaction pressure, the aggregates get closer to each other thereby, reducing the inter-aggregate pores. By doubling the compaction effort during the production of CEBs at 11.1% compaction water content, the specific volume of macro-pores was reduced by half (Figure 4.25). The mass loss measured in the drip test was also reduced by 60% (Figure 4.10, Section 4.5.2). A similar observation of the impact of increasing dry density on microstructural fabric was observed by Xu et al. (2021) and Bruno et al. (2018). The reduction in macro-pores can also be achieved by increasing compaction water content. Hence, the influence of compaction on water resistance decreases with an increase in compaction water content, as shown in Figure 4.10, Section 4.5.2.

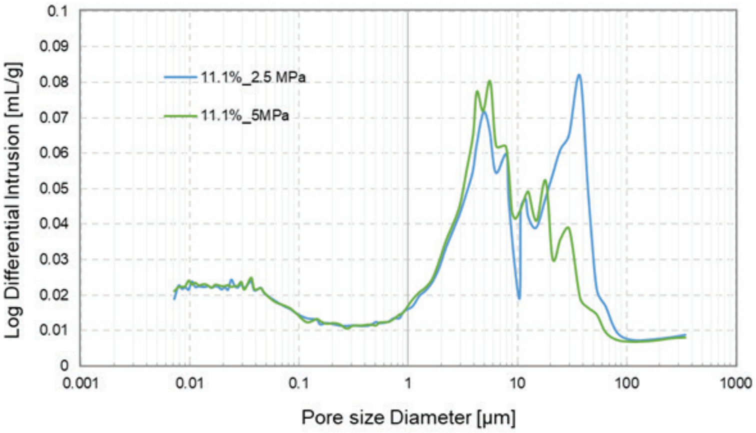

Figure 4.25: Influence of compaction pressure on pore size distribution, as measured by MIP. Comparison between CEBs prepared with compaction pressure of 2.5 and 5 MPa, at a compaction water content of 11.1%.

The influence of compaction technique on water resistance was insignificant in CEBs with higher water contents. Irrespective of lower densities, the water resistance comparable to CEBs was observed. This could be due to the similar size and specific volume of macro-pore in RE blocks and CEBs. However, a detailed microstructural investigation on impact of compaction technique is required to make any conclusions and should be explored as a future research topic.

4.6.3 Visualised factors affecting water ingress and subsequent water resistance in CEBs

Based on the newly gained insight on earthen materials, a visualised summary of factors that affect water ingress, and subsequent water resistance in CEBs is presented in Figure 4.26. These factors are also expected to be applicable to other earthen construction techniques. Some factors which are not investigated in this experimental study but are known to influence the characteristics of earthen material are also included in Figure 4.26 (based on the discussion in Section 4.2).

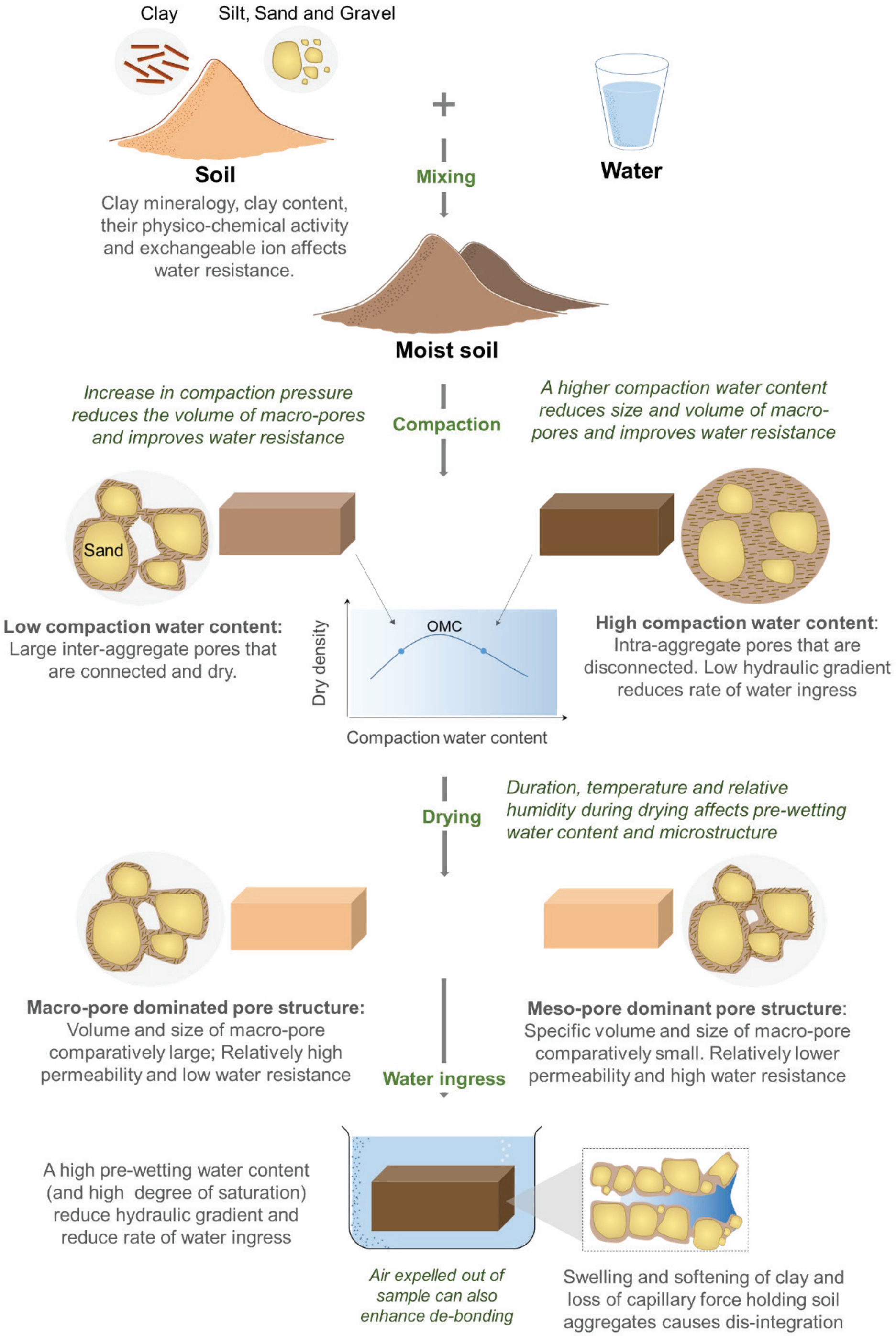

Figure 4.26: Factors affecting the microstructure fabric and water resistance of unstabilised CEBs. OMC in the image refers to an Optimum Moisture Content which corresponds to the maximum dry density.

4.6.4 Practical relevance of the research

The experimental investigation carried out in this chapter reveals the role of material composition, water content and compaction in enhancing the water resistance of unstabilised compressed earth blocks (CEBs). These insights could be valuable in improving the water resistance and durability of earthen houses.

The soil used in earthen construction projects is often modified by adding sand or clay to enhance the strength characteristics. Such modifications are rarely carried out to enhance water resistance. The lab results on clay mineralogy show the potential of swelling clay minerals and underline the need for further research on the possible beneficial contribution of bentonite clay in constructing water resistant earthen houses. While the bentonite CEBs performed well in the laboratory, the result may not be applicable at an architectural scale. Unlike laboratory tests, earthen structures often experience various wetting and drying cycles throughout their service life. The swelling and shrinking potential of bentonite could result in the appearance of cracks, as observed in a bentonite CEB exposed to an outdoor environment for a short duration of 1 week (Appendix 4L). Therefore, a full-scale test is necessary to evaluate if bentonite or any other swelling clay mineral rich soil is suitable for earthen construction.

The compaction water content value used in commercial production of unstabilised CEBs is often determined based on a compaction curve that provides a water content value corresponding to maximum dry density and strength. For instance, if a constructor would like to utilise the soil investigated in this research for commercial production of CEBs, the choice for water content would be 11% or lower (based on Table 4.2, Section 4.1). The new insights from this chapter suggest that while this compaction water content could provide optimal strength, it may not necessarily provide the optimal water resistance. To enhance the water resistance of CEBs with minimal influence on strength, it is better to adopt a slightly higher compaction water content (for example 12-13%). As observed in the experiments, an increase in compaction water content slightly (from 12.1% to 12.6%) decreased the erosion of CEBs by 50% (Figure 4.8, Section 4.5.1). Increasing the compaction water content (from 12.1% to 12.6%) also improved the compressive strength by 14% due to the design of compression setup used in this study which can compress relatively wet soils more easily. In commercial presses, relatively wet soil could not be compressed without the appearance of large cracks. Water is virtually incompressible and therefore, at a higher compaction rate, the water is unable to escape the mould. A compaction press with a slower compaction rate and gaps for the release of excess water could be designed to maximise water resistance and strength characteristics. This type of compaction press could be useful in making unstabilised blocks for low-cost housing projects, where the use of stabilisers is not economically viable.

At a slightly higher compaction water content, the need (and possibility) for high compaction effort also reduces and therefore fewer resources are required for construction. Extensive resources are required for techniques such as compressed earth block and rammed earth as the strength and water resistance characteristics in these techniques are predominately determined by the compaction process and the degree of compaction. Interestingly, several low resource intensive earthen techniques which use higher compaction water contents (such as cob, and wattle and daub) are often found in regions with high rainfall.

The disintegration of earthen material observed in laboratory conditions is extreme as compared to their performance in real climate, as noted by Beckett et al. (2020). This observation was also supported in the present study by analysing CEBs that were kept outdoors for several months. Moreover, as an additional project, a wall was also constructed using unstabilised CEB with slightly modified soil than used in this study (by adding some sand). If the laboratory results were the reflection of real performance, erosion on the wall should be visible in a few days of rain. However, minimal erosion due to direct rainfall was recorded in the wall for a period of up to 6 months. The wall has been exposed to outdoor conditions since November 24th 2021, and has experienced frequent rainfall and also a high-intensity storm (Figure 4.27). However, significant erosion up to 3 cm was measured on the bottom of the back wall (full height wall) due to frequent water splashing falling from the top of the wall. This reinforces the need for good architectural design such as long roof overhang and raised foundation to prevent erosion due to back splashing of falling water droplets.

Figure 4.27: Demonstration structure constructed with unstabilised CEB at The Green Village, TU Delft. The wall in front is exposed to rain whereas, the wall behind is protected with a roof. The bottommost layer of both walls is composed of lime stabilised earthen blocks to prevent direct contact with the concrete slab (and pooling water in the vicinity of the wall). It can be observed that the bottom region of the front wall is much wetter (via the darker colour), probably due to splashbacks or capillary rise (although a damp coat was applied over bottom-most blocks).

While the results of experiments presented in this chapter are not indicative of the performance of earthen material at an architectural scale, insights from the current study on pre-wetting water content could explain the possible reason behind the superior performance of the CEB wall as compared to laboratory samples. In an event of rainfall, the first drops fall on the face of wall and depending on their intensity may cause some erosion. Although, most rainfall is expected to penetrate the wall because the wall has a larger surface area and volume to dissipate the water. The water moves into the core and leads to the formation of a water content gradient through the section of the wall, as visualised in Figure 4.28. The outer face of the exposed wall is wetter than the core. The cross-section of the wall can be visualised as a series of small CEBs with varying water content. The higher pre-wetting water content and a higher degree of saturation on the face of the wall act as a barrier to water ingress. A visual and physical inspection of the CEB wall (by pressing the nail or thumb against the wall), as shown in Figure 4.27, indicated the presence of a high quantity of water, which could be responsible for resisting the water ingress. While this is just a hypothesis, a full-scale study could reveal the reasons behind the good water resistance performance of unstabilised earthen walls exposed to real climatic conditions.

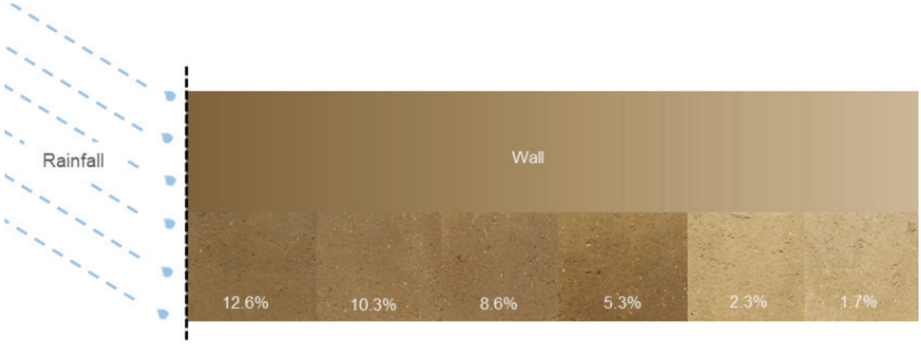

Figure 4.28: A conceptual cross-section of the unstabilised earthen wall with a higher pre-wetting water content on the face (due to prior rainfall/ higher relative humidity) which decreases through the section of the wall. The image of blocks from the experiment elucidated in Section 4.5.3 is shown with their corresponding pre-wetting water content. Higher pre-wetting water content in the earthen material act as a natural barrier to water ingress.

The strength of earthen material is often used as an indicator of durability (Beckett et al., 2020; Kinuthia, 2015). This investigation proves that strength is not necessarily related to water resistance (or durability). In CEBs with similar strength and dry density, the ones prepared with a higher compaction water content were found to be more water resistant. These tests were conducted on lab scale and there is a need for replication studies on a much larger scale (and real climatic conditions). These studies are required to evaluate the influence of compaction water content and other factors on water resistance of earthen material at an architectural scale.

The experiments carried out in the current study provide insight that could guide the soil selection, their modification, the use of higher compaction water content to enhance water resistance and the development of a new generation of compaction presses that could compress relatively wet soils. Moreover, the insights gained from the study on the influence of pre-wetting water content provide an explanation behind the good performance of earthen structures (at architectural scale) in real climatic conditions. There remains a need to verify the results obtained in this study at an architectural scale.

4.7 Conclusion

The tests conducted as part of this study re-emphasises the finding that the strength of unstabilised compressed earth block (CEB) is dependent on the dry density. However, the water resistance of CEBs depends not only on dry density but also on the soil composition and the water content, both during compaction and afterwards. The insights from this study provide recommendations to enhance the water resistance characterises of unstabilised CEBS which are listed below:

1. **Using a higher compaction water content for the production of CEBs:** A higher compaction water content results in better water resistance (also when comparing CEBs of similar dry density and strength)**.** An increase in compaction water content beyond OMC (11%) reduces the water-driven erosion. Increase in compaction water slightly by 0.5% (from 12.1% to 12.6%) decreased the erosion of CEBs by half. A microstructural investigation of CEBs revealed that compaction water content impacts the distribution of pores within the materials. With the addition of water, the pore size and the volume of the largest pores (macro-pores) decrease significantly. As the water ingress is known to depend on the size of the largest pores, the reduction in macro-pore size and volume improves the water stability of earthen blocks. In CEBs of similar dry density and porosity, the increase in compaction water content from 8.6% to 16.2% reduced the macro-pores volume by 13 times, resulting in 6.5 times better performance in resisting drip erosion. The result obtained in the study of compaction water content can guide the future development of compression press which not only maximises strength, but also water resistance.

2. **Using a higher compaction pressure for production of CEBs:** The influence of compaction pressure on water resistance is significant in drier mixes (dryer than OMC) but decreases with increasing compaction water content**.** An increase in compaction increases the dry density and reduces the volume macro-pores. By doubling the compaction pressure during the production of CEBs (at 11.1% compaction water content), the specific volume of macro-pores was reduced by half, resulting in improved water resistance and a 60% reduction of mass loss in the drip test. While the role of compaction pressure is significant, the compaction technique was found to have only a minor influence on the water resistance of earthen material.

3. **Potential of swelling clay minerals in resisting water ingress:** The clay mineralogy was found to have the most significant influence on water resistance behaviour. Blocks prepared with bentonite clay had less than 1% erosion in 60 min of drip test and could survive at least

5 days in immersion, while CEBs with kaolinite clay did not survive beyond 2 minutes in both the tests. Although the positive result motivates the use of bentonite clay in earthen construction, the swelling and shrinking of clays due to cyclic wetting and drying could lead to the formation of cracks, increasing the susceptibility of earthen materials to water ingress and structural failure. Thorough research is required to explore the potential of swelling clay minerals to produce earthen materials that are not susceptible to cyclic wetting and drying.

4. **High pre-wetting water content acts as a natural barrier to water ingress:** Pre-wetting water content has a major influence on the water-resistance behaviour. CEBs with higher pre-wetting water content (12.6%) performed 6 times better in the drip test than CEBs with low pre-wetting water content (<6%). Irrespective of their better water resistance, CEBs with high pre-wetting water content had low compressive strength. A higher pre-wetting water content (or a high degree of saturation) reduces the hydraulic gradient and therefore, reduces the rate of water ingress. These insights could provide explanation to the superior water resistance performance of CEB walls (of architectural scale) than laboratory tested CEBs. An earthen structure is always exposed to varying humidity, temperature, and rainfall. In an event of rainfall, the water falling on the face of the wall dissipates to the core but could gradually saturate with water and act as a natural barrier to water ingress (due to lowering hydraulic gradient). A detailed investigation into pre-wetting water content is required to confirm this hypothesis behind the good performance of unstabilised earthen material at an architectural scale.

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5

Water Resistance of Biologically Stabilised Earthen Materials

"Water is the element of change. Earth is the element of substance"

– Iroh, Avatar the Last Airbender (S2 E9)

The water resistance and strength of earthen materials are often improved by addition of chemical stabilisers. However, the wider debate around the negative environmental impact of chemical stabilisers has led to growing interest in biological stabilisers. While the strengthening mechanism of biological stabilisers is widely covered in scientific studies, information regarding their water-resistance performance is limited. Therefore, this chapter presents a review of a wide range of biological stabilisers (cow-dung, casein, chitosan, starch, guar gum, cactus mucilage, lignin, tannin and linseed oil, alginate, agar, carrageenan, xanthan gum and gellan gum) with a focus on mechanistic understating of the water resistance behaviour of biologically stabilised earthen materials. The response of biological stabilisers to water ingress and related physico-chemical and physical factors are discussed at microscale (stabiliser interaction with clay, sand) and macroscale (hydraulic conductivity of building blocks). Properties of stabilisers such as hydrophobicity, heat-induced modification or interaction with cations have a dominant effect on the overall response to water ingress. A technical, environmental, and economical assessment of biological stabilisers conducted on their feasibility in contemporary earthen construction reveals that most biological stabilisers are expensive and do not perform well in water resistance when compared to chemical stabilisers. However, stabilisers that can be extracted easily (such as cow-dung, cactus juice and tannins) are viable options for construction if they can be locally sourced and processed in required quantities. The study concludes with identification of the key gaps in the existing knowledge that needs extensive investigation for the full-scale adoption of biologically stabilised earthen materials.

Data accompanying Chapter 5 is available in Kulshreshtha (2022). Part of this chapter is published as Kulshreshtha, Y., Vardon, P. J., Du, Y., Habert, G., Vissac, A., Morel, J.-C., Rao, S. M., van Paassen, L., van Loosdrecht, M. C. M., Mota, N. J. A., & Jonkers, H. M. (2022). Biological stabilisers in earthen construction: A mechanistic understanding of their response to water-ilngress. 4th International Conference on Bio-Based Building Materials, 529–539. https://doi.org/10.4028/www.scientific.net/CTA.1.529

5.1 Introduction

Building with unstabilised earthen material is often affordable, although it may not necessarily be desirable (Chapter 3). While the desirability of earthen construction can be improved through its widespread use and support from the government, desirability is also linked to the material performance. The poor material performance coupled with a poor design of structure jeopardises the durability of earthen structures. Therefore, stabilisers (or binders) are often incorporated to enhance the strength and durability related technical performance of earthen material. The use of mineral binders such as Portland cement and hydraulic lime is common to enhance the compressive strength and water resistance of earthen materials. However, the use of mineral binders is widely debated due to their negative environmental impact (in particular, their high CO_2 footprint) and high cost (as discussed in Chapter 2). This debate has led to a growing interest in research into eco-friendly binders (Fabbri & Morel, 2016; Medvey & Dobszay, 2020; Ouedraogo et al., 2020; Van Damme & Houben, 2017). In this regard, research into biological stabilisers (also referred to as natural or organic stabilisers) is on the rise mainly due to their perceived better environmental performance, local availability, renewability of source, biodegradability and proven effectiveness in traditional earthen construction (Kulshreshtha et al., 2020; Şengör, 2019; Vissac et al., 2017). Moreover, biological stabilisers are expected to be a low-cost alternative to mineral binders, given their traditional and contemporary use in low-cost earthen housing in the Indian subcontinent and Africa.

The use of biological stabilisers in earthen construction dates back several centuries. Plant and animal-based stabilisers such as tree resins, arabic gum, agave juice, cactus juices, lignin, banana stem, fruit pods of locust beans, cow-dung, horse-dung, casein and oxblood have been used in earthen plasters and stuccos (Agarwal, 1982; Burroughs, 2001; Houben & Guillaud, 1994; Minke, 2006; Vissac et al., 2017). The traditional stabilisers and their recipe is well documented in studies by Vissac et al. (2017) and Paul & Changali (2020). In recent years, research into industrially produced biological stabilisers or biopolymers is on the rise. Multiple studies from the field of geotechnical engineering have reviewed these stabilisers for their effect on soil properties. Chang et al. (2020) reviewed the effect of stabilisers (such as agar gum, guar gum, gellan gum, xanthan gum, chitosan, starch, casein) on strength, hydraulic conductivity, plasticity, soil water characteristic and erosion of soil. Whereas, Jang (2020) reviewed the effect of biopolymers (xanthan gum, gellan gum, agar gum, guar gum, polyacrylamide) with a focus on the strengthening mechanism. Şengör (2019) reviewed the effects of xanthan, dextran, gellan and several other microbial biopolymers on their physical and mechanical impact on soil.

Although the positive influence of biological stabilisers in enhancing the strength and the strengthening mechanism was widely discussed in the aforementioned studies, the discussion regarding durability aspects such as water resistance was limited. Therefore, this chapter reviews the research from the field of earthen construction and geotechnical engineering with a focus on understanding the water-resistance of biologically stabilised earthen materials.

A wide range of traditional and industrial biological stabilisers derived from animals, plants, seaweeds and microbial fermentation are reviewed in this chapter. The insights from the reviewed literature are compiled to propose possible water resistance mechanisms of biologically stabilised earthen material. Thereafter, a technical, environmental, and economical assessment of biological stabilisers is conducted to evaluate their feasibility in contemporary earthen construction. The chapter concludes by outlining the key research gaps that could guide future research in the field of biologically stabilised earthen materials.

5.2 Water resistance of biologically stabilised earthen materials: A review

Although a broad range of literature is available on biologically stabilised earthen materials (and soils), only a limited number of studies cover a mechanistic understanding of how stabilisers impact the water ingress and subsequent water resistance of earthen materials. These studies are surprisingly rare in the field of earthen construction where erosion due to water ingress is a major concern. To understand the response of biological stabilisers to water ingress, peer-reviewed studies on water resistance aspects of earthen materials and compacted soils are selected using criteria such as:

1. Research work on the combination of more than one biological stabiliser is excluded due to the challenge in singling out the effect of each stabiliser.
2. Composite stabilisers (mix of biological and mineral binders) are also excluded due to challenge in singling out the effect of each individual stabiliser. However, chemicals or minerals added with the specific aim of transforming the characteristics of a biological stabiliser are included for some stabilisers.
3. Biological stabilisers such as beta-glucan and polyacrylamide are excluded as they have not yet been studied in the context of earthen construction.
4. Biological processes such as MICP (microbial induced calcite precipitation) are excluded in this research as it is widely covered in other reviews (Choi et al., 2020; Dejong et al., 2013; Rahman et al., 2020).
5. Biological fibres and aggregates (such as cereal straw, hemp fibres, wool, etc.) are excluded as they are comprehensively reviewed by other researchers (Hejazi et al., 2012; Jannat et al., 2020; Laborel-Préneron et al., 2016). It is worth noting that the effect of the fibre on the water-resistance of earthen blocks is unclear and based on the available literature, does not seem to result in a significant increase in water-resistance of earthen materials (Laborel-Préneron et al., 2016).
6. Studies which were published before January 2021 are only included in the review.

Based on the aforementioned criteria, the following biological stabilisers were selected for a review:

1. Stabilisers derived from animals: cow-dung, casein and chitosan
2. Derived from plants: starch, guar gum, cactus mucilage, lignin, tannin and linseed oil
3. Derived from seaweeds: alginate, agar and carrageen
4. Derived from microbial fermentation: xanthan gum and gellan gum

Table 5.1 (placed on the next page) provides a brief overview of the source, composition, factor affecting functional properties, common applications and characteristics of selected biological stabiliser. This compilation is expected to benefit researchers in identifying the various factors or variables to consider in an in-depth study of biological stabilisers on earthen construction. For example, the functional properties of starch is significantly affected by the botanical origin and can be transformed with heat-induced gelatinisation. Therefore, an in-depth study into starch stabilisation of earthen materials could investigate the variables 'starch botanical origin' and/or 'heating temperature' and find the best performing starch type and temperature for the chosen soil(s).

The interaction mechanisms reported in the literature for each biological stabiliser, including treatments for improved water resistance, are discussed below briefly. Most of the proposed and reviewed mechanisms were originally proposed for strengthening but are expected to also impact the water-resistance. A summary of strength and water-resistance related experimental data from the selected studies is presented in Table 5.2 (placed at the end of this section). This table summarises the technical information on dosage used, soil classification, compressive strength and water resistance. In addition, the proposed mechanism for strength gain and improved water resistance is also summarised for each study.

Table 5.1: The source, composition, factor influencing the functional properties, common applications and characteristics of various biological stabilisers

Biological stabiliser	Source/ Origin	Composition	Factors influencing composition or functional properties	Common applications	Characteristics	References
Cow-dung	Cow	Plant fibre, microbes, amine compounds, potassium, traces of sulphur, calcium, iron, magnesium, manganese, fragment of intestinal tissues	Cow-dung feed, breed	Fertiliser, fuel for cooking, source of biogas, bio-pesticide	High calorific value, rich in nutrients, antimicrobial	Garg & Mudgal (2007); Gupta, et al. (2016); Millogo et al. (2016); Kaur et al. (2017)
Casein	Mammal milks, milk-based products	Protein consisting of amino acids, prolines, apolar residues, calcium and phosphate ions. Types of casein: α_{S1}-, α_{S2}-, β- and κ-	Milk sources, environmental conditions like pH and ionic strength	Food ingredient, glues, painting, plastic, stabilizers, medical and dental uses	Amphiphilic (having both hydrophilic and hydrophobic parts), insoluble in water but soluble in alkaline solution, negatively charged at pH above 4.6	Detlefsen (1989); Fox (2003); El-Bakry (2011); Dalgleish & Corredig (2012); Vissac et al. (2013); Broyard & Gaucheron (2015); Sinaga et al. (2017); Fatehi et al. (2018a); Horne (2020)
Chitosan	(Discarded) crab or shrimp shells and cell walls of fungi.	Polysaccharide consist of N-acetyl-2-amino-2-D-glucopyranose and 2-amino-2-deoxy-D-glucopyranose Chemical formula :$C_{56}H_{103}N_9O_{39}$	Origin source (crab and shrimps based chitosan different than fungal), alkali concentration, degree of deacetylation	Thickener for food products, bio-pesticides, textile membranes, photography, cosmetic products	Good adsorption, highly basic, soluble in acidic environment, hydrophobic, insoluble in water (chitin), positively charged	Ravi Kumar (2000); Dash et al. (2011); Shukla et al. (2013); Cao et al. (2016); Chang et al. (2020); PubChem (2020a)

Biological stabiliser	Source/ Origin	Composition	Factors influencing composition or functional properties	Common applications	Characteristics	References
Starch	Plants and vegetables; Roots and tubers (potato, sweet potato, cassava, arrow-root), Cereal grain (wheat, corn, rice, sorghum, quinoa, sago), legume (pea, mung beans)	Polysaccharide made of amylose (linear chain) and amylopectin (branched chain), Chemical formula $(C_6H_{10}O_5)n$	Botanical origin: granule shape and size, amylose and amylopectin ratio; non-carbohydrate fractions such as protein, minerals (phosphorus) and lipid	Food application: viscosity modifier, emulsifier, thickener, encapsulating material, Non-food applications: Adhesive, biodegradable thermoplastic, papermaking, binder in pharmaceutical etc.	Heat induced gelatinisation, soluble in hot water, viscous, adsorption properties, negatively charged	Husband (1998); Wang, et al. (1998); Hoover (2001); Tester et al. (2004); Ma & Bruckard (2010); Avérous & Halley (2014); Shrestha & Halley (2014); Chang et al. (2016b); Britannica (2020)
Guar gum	Seeds of Guar plant (Cyamopsis tetragonoloba), a member of Leguminosae family	Polysaccharide composed of Galactose and Mannose	Molecular weight of the galactomannan, chain length, degree of polymerisation	Food, paper making, pharmaceuticals, paper, textile, explosive, oil well drilling and cosmetics industry	Hydrophilic, thicker, water blocking properties, shear thinning, soluble in cold water, stable over large pH range, uncharged	Chudzikowski (1971); Bouazza et al. (2009); Mudgil, et al. (2014); Sharma et al. (2018)
Cactus mucilage	Cactus (Opuntiaficus Indica)	Contains water, polysaccharide (arabinose, rhamnose, galactose, galacturonic acid, xylose), fat and proteins	Cactus type, fermentation process, climate (temperature, rain)	Food product, admixture for earthen plasters, Purification of drinking water.	Viscous, water-holding capacity, negatively charged	Amin et al. (1970); Heredia Zavoni et al. (1988); Chandra, et al. (1998); Sáenz, et al. (2004); Ravi et al. (2016)
Lignin (derivatives)	By-products of paper, timber and bioethanol industries	The structural unit of lignin is phenyl propane. lignin by-products are mainly classified into hydrolyzed lignin,alkali lignin and lignosulfonate	Source of plant biomass, pulping and extraction process- degree of sulfonation.	Lignosulphonate: Manufacturing of chemicals, additive in construction materials, bio-oils	Amphiphilic, Lignosoluphonate: possess many active functional groups, surfactant property, dispersant, negatively charged	Flatt & Schober (2012); Duval & Lawoko (2014); Zhang et al. (2020)

Biological stabiliser	Source/ Origin	Composition	Factors influencing composition or functional properties	Common applications	Characteristics	References
Tannin	Tea, grape skins and seed, oak tree, chestnut, plant galls	Polyphenols. Types of tannins: Gallotannins, ellagitannins, complex tannins, and condensed tannins	Plants species, habitat place, plants parts and growth time	Tanning, food ingredient, pharmaceutical applications, dyeing, drilling dispersant, wood adhesives	Metal ions chelating, proteins precipitation, biological antioxidant, negatively charged	Khanbabaee & Ree (2001); Pizzi (2008); Barbehenn & Peter Constabel (2011); Sieniawska & Baj (2017); Huang et al. (2018); Clausell et al. (2020); Kumar Das et al. (2020)
Linseed oil	Seeds of the flax plant (Linum usitatissimum).	Lipids rich in fatty acids such as α-linolenic acid, linoleic acid, oleic acids	Composition, crosslinks, temperature, additives	Pigment binder in oil paint, varish in wood finishing, plasticizer and hardener in putty	Insoluble, durable, oxidative polymerisation	Mallégol et al. (2000); Vissac et al. (2013); Adekunle (2015); Orlova et al. (2021)
Alginate	Brown seaweed of Macrocystis, Laminaria, and Ascophyllum species	Polysaccharide made up of mannuronic acid (M) and guluronic acid (G)	Spices, M/G ratio, chain length and distribution, cation type and concentration	Food application: emulsifier, thickener Non-food application: Wound dressing, packaging, drug delivery, nano-composite films	Hydrophilic, water holding capacity, gelation at room temperature, negatively charged	Benli et al. (2011); Burey et al. (2008); Dove et al. (2016); Draget et al. (1994); Funami et al. (2009); Galán-Marín et al. (2010); Quastel & Webley (1947); Venugopal (2011)
Agar	Marine red algae species such as Gracilaria and Gelidium of the class Rhodophyceae	Polysaccharide composed of agarose (neutral) and agaropectin (charged)	Species, environmental conditions, physiological factors	Bakery and dairy products, microbiological and pharmaceutical products, bacteriological cultural medium	Thermo-reversible gelation, hydrophilic, thickener, inert (support bacteriological media), soluble above 80°C	Araki (1956); Duckworth & Yaphe (1971); Sutterer et al. (1996); Venugopal (2011); Chang et al. (2015a)

Biological stabiliser	**Source/ Origin**	**Composition**	**Factors influencing composition or functional properties**	**Common applications**	**Characteristics**	**References**
Carrageenan	Red seaweed such as Gigartina, Chondrus, Eucheuma, and Furcellaria (class Rhodophyceae)	Sulfated polygalactan polysaccharides rich in ester sulfate . Carrageenan is classified into types such as λ, κ, ι, ε, μ.	Algal source, season of harvest, extraction procedure, ester-sulfate content	Milk products, processed meats, toothpaste, cosmetics, skin preparations, laxatives	Thickening, gelling, water-soluble, loss of functionality at high temperature and low pH, negatively charged	Venugopal (2011); Necas & Bartosikova (2013); PubChem (2020b)
Xanthan gum	Bacterium Xanthomonas campestris found on cabbage plants	Polysaccharide composed of D-mannose (β1,4) D-glucuronic acid (β1,2) and D-mannose.	Strain of Xanthomonas, fermentation conditions.	Food additive, cosmetics, toiletries, water-based paints, used in drilling fluid for oil recovery	Thickening and viscosity modification, hydrophilic, stable over a broad range of temperatures, pH and salt concentration; negatively charged	Katzbauer (1998); Rosalam & England (2006); Petri (2015)
Gellan	Produced by the bacterium Sphing omonas elodea	Polysaccharide consisting of β-1,3-D-glucose, β -1 ,4-D-glucuronic acid, β -1 ,3-D-glucose, α-1,4-L-rhamnose	Species, phase of growth, composition of growth medium and growth temperature of bacteria	Bakery and confectionary, dairy product, water-based gels, microbiological cultural media, cosmetic products	Stable over wide pH range (2-10), hydrophilic, high compatibility with other biopolymer, thermo-reversible gel, negatively charged	Yuguchi et al. (1993); Chandrasekaran & Radha, (1995); Giavasis et al. (2000); Morris et al. (2012)

5.2.1 Stabilisers derived from animals

5.2.1.1 Cow-dung

Cow-dung is a commonly used traditional stabiliser in developing countries that is known to improve the water-resistance of earthen materials. While studies have shown improvement in strength and water-resistance of earthen materials (Millogo et al., 2016; Ngowi, 1997; Vilane, 2010), only Millogo et al. (2016) have proposed a mechanism for strength gain and water-resistance. In their study, the enhanced performance of stabilised blocks was attributed to cementing through an insoluble compound formed by reaction between amine compounds (present in cow-dung) with fine quartz (in soil) under alkaline conditions (measured in this study to be pH 12). The mass loss due to disintegration through water absorption was observed to be 5.6% (at 3 wt.% stabilisation) as compared to unstabilised blocks which completely disintegrated. The high alkaline condition of cow-dung reported in their study seems unrealistic to have occurred solely due to biological processes and significantly higher than pH values reported in other literature related to cow-dung (Huang et al., 2017; Rao et al., 2017; Whalen et al., 2000). Therefore, there is a need for further clarification through a comprehensive study to provide insight on water-resistance of cow-dung stabilised earthen materials. The role of extracellular polysaccharide secreting bacteria, as suggested in a recent study by Rao et al. (2021) could also be explored to further understand the water-resistance of cow-dung.

5.2.1.2 Casein

Casein, a protein extracted from milk, has been used as a plastering material in several ancient earthen buildings (Beas, 1991; Vissac et al., 2017). Casein is known to have both hydrophilic and hydrophobic groups (Horne, 2020). The hydrophilic groups are hypothesised to adsorb onto the clay while the hydrophobic groups are exposed to the environment, thus forming a surface that resists water ingress (Anger & Fontaine, 2009; Vissac et al., 2013). The performance of casein can be improved by treating it in an alkaline medium with cations (such as calcium and sodium) and heating, facilitating edge ionic interaction with clays. For example, stabilisation with casein (6.6 wt.%), which was heated after dissolving in calcium hydroxide was shown to prevent the disintegration of earthen blocks immersed in water for 24 hours, resulting in a wet compressive strength of 0.75 MPa (Chang et al., 2018). Similarly, sodium treated casein was shown to improve the strength of stabilised dune sand as compared to untreated casein (Fatehi et al., 2018).

5.2.1.3 Chitosan

Chitosan is a polysaccharide obtained from (discarded) crab or shrimps shells. Stabilisation of soil with chitosan is known to reduce permeability (Khachatoorian et al., 2003) and provide resistance against water and wind erosion (Kavazanjian et al., 2009; Nakamatsu et al., 2017; Orts et al., 1999). The water-resistant properties of chitosan can be linked to its hydrophobicity (Aguilar et al., 2016) and electrostatic interaction between positively charged chitosan with negatively charged clay particles (Hataf et al., 2018). Chitosan-coated earthen samples (prepared by dipping them in liquid with 0.5-3 wt.% of chitosan dissolved in 1% acetic acid solution) survived drip erosion for 10 min (test limit) whereas, uncoated samples disintegrated in 1 minute (Aguilar et al., 2016). A water drop contact angle of 140° was measured for chitosan-coated sand particles showing their hydrophobic behaviour (Donayre et al., 2018). Hataf et al. (2018) extracted chitosan from shrimp shells and formed a viscous solution (0.02-0.16 wt.% chitosan) that was used to stabilise the soil. Their study found that at optimum moisture content, the chitosan solution was distributed throughout the matrix and formed bridges with negatively charged clay particles, thereby increasing the mechanical strength of the soil.

5.2.2 Stabilisers derived from plants

5.2.2.1 Starch

Starch is one of the most produced biopolymers that has gained popularity due to its gelation property and its ability to produce materials with different functional properties (Taggart, 2004). Studies have shown that stabilisation with starch results in improvement of mechanical strength and reduction of permeability in both sandy and clayey soils (Ayeldeen et al., 2016; Khatami & O'Kelly, 2013; Kulshreshtha et al., 2017). Starch is known to adsorb onto clay through hydrogen bonding (Husband, 1998; Xie et al., 2015; Yan et al., 2005). However, improvement in strength and water-resistance is significant when starch is heated during or after mixing. The heat-induced transformation of starch results in the formation of a gel matrix that binds the soil aggregates together. Alhaik et al. (2017) added hot starch solution to quarry fines heated at 120°C. The heat-treated samples (containing 1 wt.% starch) could withstand high humidity up to 7 days without significant disintegration. Heat-induced gelatinization through microwave and oven heating (105°C) was also utilised in a study by Kulshreshtha et al. (2017). In their study, sand stabilised with completely gelatinised corn starch (16.7 wt.%) survived up to 7 days of immersion in water. The water resistance was found to relate to the extent of gelatinisation of starch, which depends on the heating process.

5.2.2.2 Guar gum

The potential of guar gum for soil stabilisation was identified in the early 1980s (Weaver, 1984). The use of guar gum has proven to lower the hydraulic conductivity (Bouazza et al., 2009), reduce permeability (Ayeldeen et al., 2016; Khachatoorian et al., 2003) and increase cohesion and strength of soils (Ayeldeen et al., 2017; Soldo et al., 2020; Sujatha & Saisree, 2019; Toufigh & Kianfar, 2019). Guar gum forms a hydrogel film over soil aggregates and results in filling up of pores between aggregates (Muguda et al., 2017; Sujatha & Saisree, 2019). Guar gum is also known to form a highly linked hydrogel network with clays through hydrogen bonding (Ma & Pawlik, 2007; Nugent et al., 2009). Toufigh & Kianfar (2019) found that the addition of guar gum (2.5 wt.%) improves the performance of rammed earth, especially its sensitivity to a humid environment. Muguda et al. (2020) studied guar gum stabilised compressed earthen blocks (2 wt.%) and observed that the stabilised blocks lost only 1% mass in the dip test (partially submerged for 10 minutes) as compared to 18.5% for unstabilised samples. Formation of hydrogel and higher osmotic suction was found to be responsible for better aggregation. Similarly, in a study on gaur gum stabilised silty soil, Sujatha & Saisree (2019) found an improvement of 2.5 times as compared to unstabilised samples, measured through dry and wet cycle tests. Pore filling and hydrogel formation were considered responsible for the better performance of guar gum.

5.2.2.3 Cactus mucilage

Cactus mucilage is a traditionally used plastering and coating material for earthen walls (Beas, 1991; Vissac et al., 2013). It is known to improve the surface texture of stabilised soil through pore-filling (Akinwumi & Ukegbu, 2015). While a few studies have investigated the strength improvement in soil by adding cactus mucilage (Akinwumi & Ukegbu, 2015; Ayobami et al., 2017; Gardiner et al., 1999), only one study by Heredia Zavoni et al. (1988) explored its water-resistance properties. In their study, stabilised panels performed up to 25 times better (in spray erosion test) than unstabilised panels during wetting and drying tests. The viscous solution of cactus mucilage was prepared by soaking chopped cactus stalks in water for different ageing durations. Higher erosional resistance was found in samples made with the solution aged between 14 and 25 days. While the research show promising improvement through the processing of cactus mucilage, further comprehensive research is needed to understand the water-resistance mechanism of cactus mucilage thoroughly.

5.2.2.4 Lignin

Lignin is by-product of the paper and bioethanol industry that has been extensively researched. Stabilisation with lignin improves strength (Ceylan et al., 2010; Y. Liu et al., 2020; Zhang et al., 2018) and water-resistance (Santoni et al., 2002; Ta'negonbadi & Noorzad, 2017; Tingle & Santoni, 2003). Significant information on soil stabilisation with lignin is covered in the comprehensive review by Zhang et al. (2020). Lignin consists of hydrophilic and hydrophobic groups and improves water-resistance through various mechanisms such as pore filling, ionic interaction and cation exchange (Zhang et al., 2020).

Yang et al. (2018) studied the stabilisation of clayey sand with lignin-rich biofuel co-products (12 wt.%) and observed that the stabilised samples resisted 7 days of immersion without disintegration. In comparison, unstabilised samples disintegrated in 4 hours. Improved strength and water resistance were also observed by Zhang et al. (2020). In their study, all stabilised samples survived 1 day of immersion and samples stabilised with higher dosage performed well in drying and wetting tests. In both these studies, the improvement in strength and water-resistance was hypothesised to occur though aggregation of soil particles and pore-filling. Similar physical bonding mechanisms in lignin stabilised soil has been suggested and validated by several authors (Liu et al., 2020; Zhang et al., 2015, 2018).

5.2.2.5 *Tannin*

Tannins have been used as a stabiliser in traditional earthen construction for its water-resistance properties. Although, there is a lack of research on water-resistance, one study from Guihéneuf et al. (2020) and a dataset from Banakinao et al. (2016) show evidence of improved water-resistance of tannin stabilised earthen blocks. Studies on strength improvement through tannin stabilisation suggest that the formation of an insoluble tannin-iron complex, due to polymerisation or oxidation of tannin, could be responsible for enhanced strength (Keita et al., 2014; Sorgho et al., 2014). Thus, this insoluble complex could also be the reason behind increased water-resistance of tannin stabilised earthen materials.

5.2.2.6 *Linseed oil*

Linseed oil has been widely used as a water proofing coating for earthen floors and walls (Agarwal, 1981; Vissac et al., 2013). It is known to be rich in unsaturated fatty acids which are hydrophobic (Orlova et al., 2021; Vissac et al., 2013). There is a lack of study into the details of the water-resistance mechanism of linseed oil stabilised earthen material. A study by Guihéneuf et al. (2020) showed that the addition of 1-2 wt% linseed oil resulted in an over 2 times decrease in rate of absorption of water. The improved water-resistance was proposed to be governed by hydrophobicity of linseed oil. While the effects of linseed oil were prominent, the added oil included a small quantity of hexametaphosphate which was added to improve the workability of soil. This addition was observed to impact the water-resistance properties of stabilised soil and therefore the efficacy of both individual components needs to be elucidated in further studies.

5.2.3 Stabilisers derived from seaweed

5.2.3.1 *Alginate*

Alginate is gaining popularity as a stabiliser in field earthen construction due to its gelation at room temperature, which is desirable in practice as heating would not be required. Alginate improves water retention and soil aggregation capacity (Emerson, 1956; Quastel & Webley, 1947), reduces hydraulic conductivity (Bouazza et al., 2009; Karimi, 1998) and improves mechanical behaviour of soils (Arab et al., 2019; Soldo et al., 2020; Wen et al., 2019). Application potential of alginate is also explored in advanced earthen construction technology such as 3D printing of earth-based material (Perrot et al., 2018) and poured earth construction (Pinel et al., 2017).

Sodium alginate gel is soluble in water, but when exposed to a calcium-rich environment, it forms a water-resistant gel. Calcium or other polyvalent ions act as cross-linking compounds that link alginate monomers to form polymers, leading to increase in water resistance (Rhim, 2004). This cross-linking is reported to depend on ion concentration and time (Pavlath et al., 1999). This property is often used by researchers to improve the mechanical and durability related properties of earthen materials. Wen et al. (2019) utilised calcium chloride solution as an ionic crosslinking agent with sodium alginate to form calcium alginate gel that cemented the sand particles, thereby improving the water-resistance significantly. The stabilised sand (0.4 wt.%) sample could survive 12 cycles of wetting and drying, where each cycle consisted of 24h of immersion. Dove et al. (2016) investigated stabilisation of soil with sodium alginate and found favourable strength improvement in soil with higher calcium content. However, the improvement in water resistance was found to be limited.

5.2.3.2 Agar gum

Agar gum has been investigated for its potential to reduce the likelihood of liquefaction of sand (Smitha et al., 2019), and its reversible gelation properties has been exploited for its potential to enable collection of undisturbed sand samples (Sutterer et al., 1996). Agar gum is known to form a gel network after cooling from elevated temperature, known as cold-set gelation (Burey et al., 2008) and is therefore often heat-treated before use. In a study by Chang et al. (2015a) on clayey soil and sand, agar gum was mixed in hot water before adding to the soil. Both stabilised soils resisted 7 days of immersion and resulted in a wet compressive strength (compressive strength after immersion) up to 0.5 MPa in clayey soil (3 wt.% agar gum) and 0.06 MPa (1 wt.%) in the sand. Pore filling was observed in stabilised samples, and it was hypothesised to be the mechanism responsible for improved wet strength. Aggregation and pore-filling was also observed in the study by Smitha & Sachan (2016). In contrast to the study by Chang et al. (2015a), Lee et al. (2008) found no significant improvement in water immersion behaviour of heat treated agar (5 wt%) stabilised blocks.

5.2.3.3 Carrageenan

Carrageenan is a stabiliser that could be modified into water stable gel (Venugopal, 2011), however, its potential to improve water resistance is yet to be explored. In a study by Nakamatsu et al. (2017), carrageenan coated compacted clayey soil proved to be effective against water erosion as the material survived 10-minute drip erosion test. In comparison, unstabilised samples failed in 5 minutes. The contact angle of coated samples was found to be in the range of 101°-104°, showing its hydrophobic nature. However, when exposed to outdoor environment for 95 days, the coating degraded significantly.

Carrageenan can form a gel network via an ionotropic gelation mechanism (as observed in alginate) coupled with a cold-set mechanism (as observed in agar gum) (Burey et al., 2008). Therefore, in addition to heating and cooling, the addition of ions improves the stability of carrageenan gels. For example, addition of potassium ions to κ- Carrageenan results in a gel that is insoluble in cold water (Venugopal, 2011). These characteristics of carrageenan could be further explored to develop water-resistant earthen materials.

5.2.4 Stabilisers derived from microbes

5.2.4.1 Xanthan Gum

Xanthan gum is a widely researched stabiliser that is known to improve strength and durability of earthen materials and soils (Ayeldeen et al., 2017; Cabalar et al., 2018; Cabalar & Canakci, 2011; Chang et al., 2015b; Chang et al., 2015c; Chang et al., 2015d; Chen et al., 2019; Guihéneuf et al., 2020; Muguda et al., 2020; Qureshi et al., 2017; Soldo et al., 2020). Xanthan gum stabilisation has shown to reduce hydraulic conductivity or permeability (Ayeldeen et al., 2016; Bouazza et al., 2009; Karimi, 1998; Khachatoorian et al., 2003; S. Lee et al., 2019; Ng et al., 2020; Wiszniewski & Cabalar, 2014). It is an effective stabiliser for expansive soil (Singh & Das, 2020) and peat (Latifi et al., 2016). In addition, It has been also suggested as a low-cost alternative binder for earthen construction in developing countries (Chang et al., 2015c).

Chang et al. (2015b) studied the stabilisation mechanism of xanthan gum and found that the improvement in performance of xanthan gum stabilised soil is due to the formation of thick gel (via hydrogen bonding) that coats the soil particles and results in pore filling. In the study by Qureshi et al. (2017) stabilised sand (2 wt.%) resisted multiple drying and wetting cycles. Muguda et al. (2020) studied xanthan gum stabilised compressed earthen blocks (2 wt.%) and observed that the stabilised blocks lost 1% mass in a dip test (partially submerged for 10 minutes) as compared to 18.5% for unstabilised samples. Significant increase in durability was also observed in a study on stabilised sample exposed to outdoor environment (Soldo et al., 2020).

5.2.4.2 Gellan gum

Gellan gum has been researched for ground improvement (Chang et al., 2015a; Chang et al., 2016b, 2017a; Ferruzzi et al., 2000), liquefaction potential reduction (Im et al., 2017), reduction of gas permeability (Ng et al., 2020) and as an alternative binder for earth buildings (Chang et al., 2015b). Similar to carrageenan, the properties of gellan gum can be modified through heat treatment and by adding cations. The addition of divalent cations such as calcium and magnesium is known to improve the strength properties of gellan gum gel (Giavasis et al., 2000). Furthermore, the addition of Gellan gum in soil is reported to result in pore filling, thereby enhancing strength and water resistance (Chang et al., 2015; Ng et al., 2020).

In the study by Chang et al. (2015a), gellan gum was mixed in hot water before being added to the soil. Stabilised soils resisted 7 days of immersion and resulted in wet compressive strength up to 0.5 MPa in clayey soil (3 wt.%) and 0.05 MPa in sand (1 wt.%). Pore filling was observed in stabilised samples and it was proposed that the wet strength is governed by the behaviour of gellan gel in water. In other related studies, the gellan gum stabilised sand survived 24h in water (test limit) and resulted in a compressive strength up to 0.34 MPa (2 wt.%) after 10 wetting-drying cycles (Chang et al., 2016b, 2017).

Table 5.2: Strength and water-resistance of earthen material stabilised with various stabilisers. The table includes research that performed at least one durability test in accordance with tests mentioned in the study by Beckett et al. (2020). The dosage of stabiliser (or stabiliser content) is based on the mass percentage of stabiliser to dried soil until unless specified. (*) indicates the values retrieved from figures in the published studies. For studies conducted on multiple soils, a maximum of two soils are included in the table.

Stabiliser	**Dosage [wt.%]**	**Soil classification**					**Compressive strength**			**Water resistance**				**Note**	**Reference**
		Clayey soil					**Stabilised [MPa]**	**Unstabilised [MPa]**	**Mechanism**	**Test**	**Stabilised**	**Unstabilised**	**mechanism**		
		Clay [%]	*Silt [%]*	*Sand [%]*	*Classification*	*Predominant clay mineral*									
		Sandy soil													
		Size [mm]	*Cc*	*Cu*		*Predominant mineral*									
Cow-dung	1-3	36	17.5	43		Kaolinite	2.45-2.8 (1-3%)	2.1	High pH resulting in solubilisation of sand and forming insoluble siliceous amine organic compound	Water absorption (mass loss)	Mass loss [%]: 6.4- 5.65* (1-3%)	Disintegrate	Same as strength	Adobe blocks prepared by adding dried cow-dung to soil followed by 72h fermentation.	Millogo et al. (2016)
Casein	2.0-6.6				Low plastic silt (ML)		2.65.-5.63 (2-6.6%)	1*	Casein coating on soil particles forming soil-casein conglomerates	Wet compressive strength (24h)	0.48-0.75 MPa (2-6.6%)	0.025 MPa	Inter-particular binding strength is stronger than swelling pressure during saturation	Commercial casein powder dissolved in Calcium hydroxide by heating at 70°C.The soils were mixed in 1:1 mass ratio.	Chang et al. (2018)
		0.2-2	1.14	1.35	Poorly graded sand (SP)	Quartz									

Guar gum	0.5-2	6	38	56	Highly compressible silt clay (MH-CH)	-	0.2-0.42 (0.5-2%)	0.19	Hydrogel of guar gum fill voids and holds the particle together. Adhesive force arising due to hydrogen bonding.	Wetting and drying cycles-12 (5h in water and 42h at 70°C)	Mass loss [%] : 8-4 (0.5-2%)	Mass loss [%] 10%	Reduction in strength due to breakage of structural bond.	Strength at 28 days (1-90 days) With increasing concentration, thicker gel formation that fills void.	Sujatha & Saisree, (2019)
Guar gum	0.5-3	16	4	70	Low plastic clay (CL)	Kaolinte	1.6-4.3 (0.5-3%)	0.4	Combination of higher osmotic suction and formation of hydrogel (through hydrogen bonding) that result in better aggregation	Dip test (partially submerged for 10min)	Mass loss in Dip test: 1% (2%) *	Mass loss in Dip test:: 18.5% *	Same as strength	No sign of cracking or swelling in other durability test: contact , suction (moisture absorption). Guar gum performed poor than xanthan gum	Muguda et al. (2017), (2020)
										Geelong drip test (60 min)	Depth of erosion in Geelong test: 2.5mm *	Depth of erosion in Geelong test: 7.5mm*			
Chitosan	0.5-3% (mass to volume of liquid)	36	43	20	Low plastic clay (CL)	Muscovite-illite	3.8* (3%)	2.1	Strong chitosan matrix binding clay particles leading to increase in strength	Contact angle	With coating: 94° (1%), 85° (3%) ; Matrix: 65° (3%)	-	Hydrophobicity of chitosan responsible for water resistance (coating). Increase in volumetric stability	Chitosan in powder form was mixed with 1% (v/v) acetic acid to form chitosan solution. Solution used for making adobe blocks	Aguilar et al. (2016)
										Drip erosion test (10 min)	All samples passed 10 min limit (0.5% chitosan mixed with soil had localize erosion)	Failed in 1 min			
Starch	16.60%	0.125–0.25				Quartz	26.6	-	Heat induced transformation (gelatinisation) of corn starch and bonding with sand.	Immersion test (7 days)	Disintegration within 3 h(oven heated) to partial disintegration in 7 days (microwave heated at higher Wc)	-	-	Samples dried at 105°C for 24 h or heated in microwave oven for 5 minutes.	Kulshreshtha et al. (2017)

Cactus solution	-	34		66	Low plastic clay (CL)	-	-	-	-	Accelerated erosion test of panel: 20 cycles of simulated rain (3 h rain, 21h drying)	Water flowed easily on surface ; Mass loss: 18g (9 cycle)	excessive damage observed within 30 min, Mass loss: 620g (9 cycle.	Viscosity of cactus solution and smoothness of surface (hydrophobicity)	Viscous Solution prepared by soaking equal proportions (by weight) of the chopped cactus stalks in water for different aging durations (1-60 days)	Heredia Zavoni et al. (1988)
Lignin	12%	38		54.9	Clayey sand (SC)	-	0.88 (type A)	0.28*	Biofuel co-products (BCPs) cement and bond soil particles together and fills pore space resulting in better strength and less void for water replacement , thus low expansion.	Water immersion (7 day)	BCP A: Does not disintegrate in water for 1 day and a small crack after 7 days	Disintegrates in 4 hour	Same as strength	Results presented for a soil specimens made at one type of soil at OMC. Biofuel co-products (BCPs) A has 25% lignin, and BCP B has 5% lignin	Yang et al. (2018)
							0.7 (type B)				BCP B: Disintegrate partially after 1 day and completely in 7 days				
Lignin	2-15%	9.7	81.2	9.1	Low plastic silt (ML)		0.25-0.7* (2-12%)	0.13	Soil particle coated with the stabilisers and pore volume reduction	Wet compressive strength (1day)	0.1-0.4 MPa (2-12%) ; All sample were intact in water after 1 day	-	Same as strength. Reduction of suction and dissolution of lignin-based cementing materials upon wetting resulted in reduction in strength	The number of cycles in wetting-drying test was based on termination criteria (mass loss>30% or fracture)	Zhang et al. (2020)
										Wetting-drying cycles: 1 day submerged, 2 day 30 °C	Specimens: Intact upto 4 cycles except specimens with low lignin content (2% and 5%) which disintegrated after 1 cycle.				

Linseed oil	1-2%	30*	50*	20*	Low plastic silt (ML)*	kaolinite, illite	5.9-6.1* MPa	6.2*	No effect of LO addition	Capillary absorption (based on AFNOR french standard)	200	500	Hydrophobic properties of linseed oil responsible for water-resistance	Soils were mixed with sodium-hexametaphosphate (HMP) (0.0425%) to improve dispersion of clays. It is assumed that HMP does not interact with stabiliser; Oven dried samples	Guihéneuf et al. (2020)
										Contact angle	67-96° (2%)	12°			
Alginate	0.1-0.5	31	45	24	Low-plastic clay (CL)	Kaolinite	1.7* (0.1%)	1	Crosslink of Ca ion present in soil with Na-alginate resulting in interparticle bridging	Modified capillary absorption test ((partially submerged for 1min)	Mass loss [%] : 0.75*% (0.1%)	1.7*%	-	3 types of soil and 4 varieties of alginate used in study.	Dove et al. (2016)
Alginate	0.1-0.4		2.05	1.21	Sand	-	0.15-0.26 *(0.1-0.4%)	-	$CaCl_2$ solution used as ionic crosslinking agent with Na-alginate to form calcium alginate gel that cement the sand particles.	Wetting and drying cycles-12 (24h in water and 34h at 50°C)	UCS: 0 cycle: 0.44 MPa, after 12 cycles-0.24 MPa* (0.4%,50°C)	-	Significant increase in water resistance due to formation of water stable ca-alginate gel.	Na-alginate mixed with sand and kept in 0.5M $CaCl_2$ solution for 1-28 days at 25-100°C curing temperature.	Wen et al. (2019)
							0.44* (0.4%, 50°C)								
Carrageenan	0.5-2% (mass to volume of liquid)	36	43	20	CL (low plastic clay)	Muscovite-illite	3.8* (2%)	2.1	Anionic interaction with cations (present in soil) resulting in effective binding	Contact angle	Coating: (0.5-2%): 101°-104° ; Matrix: None	None	Hydrophobicity of carrageenan responsible for water resistance	Extraction from red algae in 0.1M NaOH (4h), followed by precipitation in 2-propanol, and drying at 50°C for 24 h. Powder mixed with distilled water to make solutions	Nakamatsu et al. (2017)
										Drip erosion test (10 min	1 and 2% (Matrix and coating) passed 10 min limit.	Disintegration in 5 min			
										outside exposure (95 days)	The coating was degraded and ineffective	Not tested			

Agar gum	1-4	60		40	Low-plastic clay (CL)	Kaolinite	3.2-9.2* (1-3%)	1.05	Soil-biopolymer coagulation via gelation. Hydrogel matrices increasing inter-particle resistance.	Wet strength (7 days)	0.19-0.53 MPa (1-3%)	-	Strength governed by gel strength in immersed situation	Agar powder dissolved in hot water and added to pre-heated soil. Included multiple curing conditions	Chang et al. (2015a)
		0.02-2*	0.92	3.02	Poorly graded sand with silt (SP–SM)		0.8-2.4* (1-3%)	-	Coating on sand, pore filling and increase particle to particle contact area.		0.06-0.07 MPa (1-3%)	-			
Xanthan gum	1-mei		0.8	1.8	SP	Quartz	1.1 MPa (1%),1.7 MPa (2%), 0.75 MPa (3%), and 1 MPa (5%)	-	Formation of thick and high tensile hydrated gel of xanthan gum between sand grains	Wet and drying cycles (Slake durability tests)- 4	Mass loss [%]: 75-30 (1-3%)*	-	Xanthan gum hydrogel links are hydrated, yet keeps the particles together during saturation.	Dessert sand used in the study.	Qureshi et al. (2017)
Xanthan gum	0.5-3	16	4	70	CI	Kaolinte	2.1-4.3 (1-3%)*	0.4	Combination of higher osmotic suction and formation of hydrogel (through hydrogen bonding) that result in better aggregation	Dip test (partially submerged for 10min)	Mass loss in Dip test: 1% (2%) *	Mass loss in Dip test:: 18.5% *		No sign of cracking or swelling in other durability test: contact, suction (moisture absorption)	Muguda et al. (2017), (2020)
										Geelong drip test (60mins)	Depth of erosion in Geelong test: 2mm *	Depth of erosion in Geelong test: 7.5mm*			

Xanthan gum	1-4		1.5	10	Silt with low plasticity (SW-SM)	-	3.3-7.1 (1-4%)	1.2	Mass surrounding the sand particle was created by interaction of xanthan gum and fines which resulted in bonding, causing increase in cohesion.	Exposure to real environment for 30 days	Strength loss [MPa]: 63% (recalculated)* strength decrease from 5.9MPa to 2.2 MPa	Disintegrated	-		Soldo et al. (2020)
Gellan gum	0.5-2	0.2-1*	1.09	1.94	SP (poorly graded sand)	-	0.13-0.44* (0.5-2%)	-	Formation of stiff and strong inter-granular hydrogel matrix between sand grain	Wetting and drying cycles-10 (24h in water and 28days at 20°C)	Dried strength [MPa] : 0.09-0.34* (0.5-2%)	-	Gel swells due to hydrophilic water absorption upon wetting	-	(Chang et al., 2016b, 2017)
										Immersion 24h	Wet strength [MPa] : 0.01-0.05* (0.5-2%)				
Gellan gum	1-3	60		40	Low plastic clay (CL)	Kaolinite	4.7-12.6* (1-3%)	1.05	Soil-biopolymer coagulation via gelation. Hydrogel matrices increasing inter-particle resistance.	Wet strength (7 days)	0.21-0.52 MPa (1-3%)	-	Strength governed by gel strength in immersed situation	Gellan powder dissolved in hot water and added to pre-heated soil. Included multiple curing conditions	Chang et al. (2015a)
		0.02-2*	0.92	3.02	Poorly graded sand with silt (SP–SM)		0.6* (1%)	-	Coating on sand, pore filling and increase particle to particle contact area.		0.05 MPa (1%)				

5.3 Response of biological stabilised earthen material to water ingress in earthen material

The addition of a biological stabiliser modifies the material composition of the stabilised soil mixture and therefore, affects the water resistance of biological stabilised earthen materials through transforming parameters such as cohesion, capillary suction, and permeability (Figure 5.1). Although the water content and compaction effort are expected to influence the water resistance of biologically stabilised earthen materials to a certain extent, their role is not covered in scientific literature. Nevertheless, the discussion in Section 5.2 points toward the dominant role of material composition in influencing the strength and water resistance characteristics of biologically stabilised earthen material.

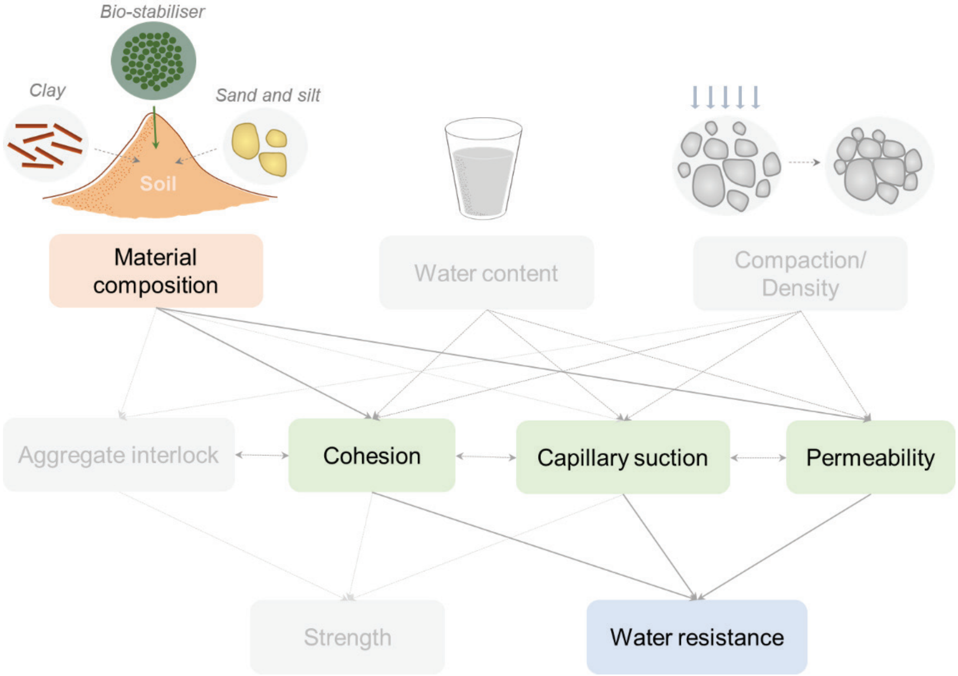

Figure 5.1: Parameters affecting the water resistance of biologically stabilised earthen materials.

As discussed previously in Section 4.5 (Chapter 4), the water permeability in earthen material is dependent on the size of the largest pore (inter-aggregate or macro-pore). In studies related to various gums, cactus and lignin, the microstructural fabric was observed to be modified through pore-filling, a physical process that reduces the size of inter-aggregate pores, and therefore reduces water ingress and subsequent erosion. Reduction in water permeability was measured in several studies with the increase in stabiliser content, such as alginate (Wen et al., 2019), gellan gum (Chang et al., 2016b) and guar gum (Sujatha & Saisree, 2019). Reduction in a specific volume of pores and size of largest pores was also observed (through the MIP test) in lignin stabilised compacted soil by multiple authors (Liu et al., 2020; Zhang et al., 2015). It should be noted that other stabilisers could also lead to pore filling, but the scientific literature referred to here has not tested nor proposed this specific mechanism.

The water ingress in biologically stabilised earthen material could reduce capillary suction which is expected to depend among other parameters on the physico-chemical characteristics of clays and biological stabiliser, which also governs cohesion. The physico-chemical properties of clay are already discussed in Section 4.2.3 (Chapter 4) and therefore, the subsequent paragraphs discuss the physico-chemical characteristics of stabilisers that enhance the overall water stability of stabilised earthen material.

Hydrophobicity is a physico-chemical characteristic reported for chitosan, linseed oil and carrageenan that improves the water repellence of the overall earthen material (otherwise, a water-attracting or hydrophilic material), and therefore, decreases the interaction of water with the soil. The hydrophobic stabilisers are effective when used as a surface coating (as found in chitosan and carrageenan) but lose their characteristics slightly when mixed in the matrix of soil (Aguilar et al., 2016; Nakamatsu et al., 2017). However, when added to the mix in adequate quantities, they can still be effective, as observed for linseed oil (Guihéneuf et al., 2020).

The properties of native (non-modified) stabilisers are often inadequate for resisting water ingress. Instead, they can be modified through a heat treatment process or by adding cations. This processing results in enhanced water resistance. The heat-induced modification has been utilised to modify casein, starch, agar gum and gellan gum (Chang et al., 2015a; Chang et al., 2018; Kulshreshtha et al., 2017). Heating of these stabilisers in presence of water (temperature in a range of 70-105°C as noticed in all studies) transforms their physical structure into a relatively water stable material. For example, the heat-induced modification of starch resulted in the transformation of starch grains (~ 15μm diameter) into a continuous gel phase that hardens upon cooling and binds with soil aggregates (Kulshreshtha et al., 2017). This process is referred to as gelatinisation and improves the water stability of the starch stabilised soils. The effect of heat-induced modification could be highly significant as shown in a study by Chang et al. (2015a). They found that heat-treated gellan gum-stabilised clayey soil resisted immersion for over 28 days, whereas non-heat-treated samples disintegrated completely in a day. There is potential for heat-induced modification of carrageenan which is yet to be sufficiently explored for application in earthen materials.

Exposing stabilisers to a cationic medium, especially containing divalent cations, as observed in casein, alginate and gellan gum, can also improve the water resistance properties significantly. For example, sodium alginate is soluble in water but exposing it to a calcium-rich environment results in a water stable form of alginate. This characteristic was utilised by Wen et al. (2019) to prepare sodium alginate stabilised sand specimens that were exposed to calcium chloride. The resultant specimens resisted multiple cycles of wetting-drying. The combination of both heat processing and cation addition could further improve the durability related characterises of stabilisers such as casein, carrageenan and gellan gum. While the study by Chang et al. (2018) explored the combined heat processing (70°C) and cation addition (calcium) to enhance water resistance of stabilised blocks, research exploring the combined treatment is yet to be conducted for gellan gum and carrageenan.

The addition of biological stabilisers modifies the physico-chemical interactions of the soil with water. The physico-chemical characteristics of stabiliser are expected to dominate the overall response to water ingress, unless clay minerals are present in the soils (which are usually present in earthen materials). In stabilised soils without clays (i.e., sandy soil), the characteristics of stabiliser and the interfacial properties of sand-stabiliser are responsible for resisting the water ingress. Disintegration could happen if and when the stabiliser starts de-bonding (or solubilising) due to the flow of water, reducing its capacity to hold the aggregates together. Multiple studies show the dominant impact of stabiliser and its treatment on the water resistance of stabilised sandy or non-cohesive soils (Chang et al., 2015a; Kulshreshtha et al., 2017; Qureshi et al., 2017; Wen et al., 2019).

The presence of clay in soil makes the interaction with stabilisers complex, as clay aggregates are more sensitive to water ingress. Irrespective of the sensitivity of clay aggregates to water ingress, their presence is necessary to provide strength to earthen material. Although a high quantity of stabiliser can sometimes provide the required strength, its use will be uneconomical for practical purposes. Addition of a stabiliser could limit the interaction of clays with water and reduce the susceptibility of earthen material to disintegration upon water ingress. Stabilisers can also form chemical bonds (such as hydrogen bonds and ionic bonds) with the clay aggregates and result in the formation of composite materials of enhanced water resistance.

Hydrogen bonding is a commonly proposed reaction mechanism of water with clays (and sand) which is weaker than ionic bonding and is sensitive to ions present in the water. Starch, xanthan gum, guar gum and gellan gum are proposed to form hydrogen bonds with clays (Alhaik et al., 2017; Chang et al., 2015a; Muguda et al., 2017) however, their role in improving the water resistance is still unclear. An ionic bond is formed by the electrostatic attraction between oppositely charged ions in chemical compounds. The negatively charged surface of the clay particles is proposed to form ionic bonds with positively charged stabilisers such as in chitosan stabilised samples (Hataf et al., 2018). The ionic interaction between stabiliser and clay minerals could be facilitated through a change of pH and ionic strength (measure of concentration of ions in solution). For example, in the study by Ma & Bruckard (2010), the adsorption between starch and kaolinite (clay) increased with decreasing pH. At pH lower than 7, the edge charge of clay particles was found to be positive, thereby leading to electrostatic attraction between negatively charged starch and positively charged edges of clay particles. In the same study, the interaction (adsorption) increased with increasing ionic strength (using NaCl). Therefore, based on the charge of the stabilisers, providing a suitable acidic or alkaline environment can facilitate interaction or adsorption. A lower pH is preferable for negatively charged stabilisers, whereas a higher pH could be favourable to positively charged stabilisers. The presence of exchangeable cations in the soil and stabilisers is also proposed to improve the bond strength. Cation exchange was proposed for strengthening lignin and alginate stabilised earthen materials (Dove et al., 2016; Zhang, Yang, et al., 2020). Like hydrogen bonding, the role of ionic bonding and cation exchange in enhancing the water resistance is unclear.

When an earthen block is immersed in water, water moves through the macro-pores and interacts with the surrounding material of the pores. Biological stabilisers are likely to transform the physical and surface characteristics of the pores and consequently, affect the physio-chemical interactions with water. However, when the ions present in water interfere with the stabiliser-soil aggregate bond, they may cause swelling and softening of stabiliser, and provide a route for water to interact with the clays. The swelling of clay can create micro-cracks in the matrix facilitating the further movement of water. The softening of the matrix, coupled with reduced capillary suction due to the presence of water is expected to result in de-bonding of aggregates.

The water ingress and its subsequent effects in biologically stabilised earthen material is a coupled process, where more than one mechanism affects the flow of water through the earthen material. And therefore, it is possible that a stabiliser modifies the pore structure by pore-filling, forms ionic bond with clay particles and transforms into a water stable form by addition of heat or cations. All the interactions would collectively determine the water-resistance. Understanding of interaction mechanisms could guide the researchers to use an appropriate approach to improve the properties of biologically stabilised earthen materials. The interaction mechanism proposed in the reviewed literature are compiled in Figure 5.2. Additional information on the response of biological stabiliser to water ingress can be found in Kulshreshtha et al. (2021)

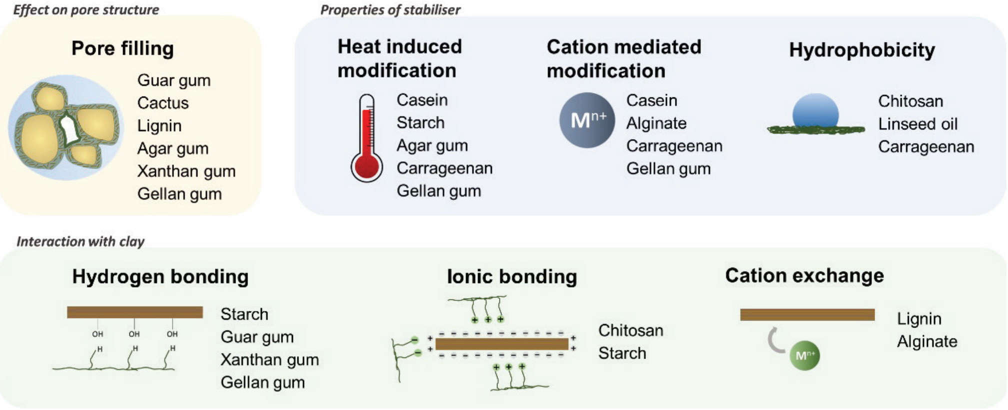

Figure 5.2: Proposed interaction mechanism facilitating water-resistance of biologically stabilised earthen material. Interaction with clay illustration after Du et al. (2019)

5.4 Assessment of biological stabilisers in earthen construction

Biological stabilisers are gaining popularity as ecological alternatives to conventional stabilisers such as Portland cement. Although biological stabilisers are receiving a lot of attention in the field of materials science, the same does not apply to practice of earthen construction. If and when a biological stabiliser could replace a conventional stabiliser depends on multiple factors. The adoption of biological stabilisers strongly depends on its technical performance (such as durability and strength) and cost. Further, biological stabilisers are perceived as environmentally friendly; however, it is important to gain insight into their environmental performance before claiming eco-friendly properties. Therefore, a brief assessment is conducted on technical, economic, and environmental performance of biologically stabilised earthen material to judge its suitability in contemporary earthen construction, especially its feasibility in decreasing the housing shortage.

5.4.1 Technical performance

The technical performance of biological stabilisers is a subject of debate due to lack of in-depth knowledge on these stabilisers. This section offers a brief insight into important technical parameters such as water-resistance and compressive strength, with some minor discussion on moisture buffering capacity and biodegradation.

5.4.1.1 Water-resistance

The variability in raw material (soil), sample preparation (construction method) and the testing method make comparison of biological stabilisers on the parameter of water resistance challenging. Moreover, the significant variations in stabiliser content, stabiliser quality and their treatment could make a comparison unreliable. While it is interesting to know which stabiliser amongst the selected biological stabilisers is most water-resistant, there remains a lack of studies and reliable information to make a fair comparison. However, it is still possible to compare some biological stabilisers which were part of the same study and make a rough qualitative assessment on their relative performance.

In studies involving stabilisation of soil with various biological stabilisers, Chang et al. (2018) found that that stabilisation with either 1% agar gum or 1% gellan gum are more effective in resisting water than 1% xanthan gum. In their study, casein (5%) was found to be most effective, however information on lower and comparable dosage to other stabilisers is missing. Muguda et al. (2020) found that xanthan gum (2%) was slightly more water-resistant than guar gum (2%). In the study of Chang et al. (2015a), heat modified agar gum (1-3%) and gellan gum (1-3%) showed excellent water-resistance performance. Calcium-alginate (0.4%) stabilised sand was also found to be water stable (Wen et al., 2019). Similarly, both starch and lignin stabilised samples were found to be significantly water resistant, but a high dosage of stabiliser (>8%) was used and therefore, it is challenging to extrapolate the effects of lower dosage.

Chitosan, carrageenan and linseed oil have been shown to improve the surface hydrophobicity but how long their surface could resist water ingress is a question which needs further investigation. The water resistance performance of cactus mucilage was good, however more research is needed to explore the potential of cactus as a stabiliser. Cow-dung is traditionally used as a water-resistant stabiliser. However, studies did not reveal any extraordinary water resistance performance even though it was reported by dweller of the survey (Chapter 3) that cow-dung contributes significantly to it. Therefore, in depth studies are required to understand the water resistance of cow dung stabilised earthen materials.

In most studies, the water-resistance of cement stabilised earthen material was significantly higher than biologically stabilised materials. It is also known from practice that cement stabilisation of 5-12% is enough to make water stable earthen materials. However, exceptions were observed in studies of Qureshi et al. (2017) where xanthan gum (2%) stabilised sand could resist drying and wetting cycles with smaller loss of mass as compared to cement stabilised sand (10%).

Based on the studies reviewed in this chapter, it can be concluded that for most stabilisers, a modification (either heating or addition of cations) was a primary cause for better water-resistance performance. Agar gum, gellan gum, starch and alginate are some of the examples of these stabilisers. Several missing gaps have been identified which makes a fair comparison between the performance of biological stabiliser challenging and this is addressed in Section 5.5.

5.4.1.2 Compressive strength

In comparison to studies on water-resistance, significantly more studies are available which target improvement of compressive strength through application of biological stabilisers. In order to draw information on the comparative compressive strength performance, strength data of biologically stabilised earthen material was collected from 33 research articles and is compiled in Dataset 5X1 (Kulshreshtha, 2022). All biological stabilisers are included except cactus juice for which no information of effect on compressive strength is available in literature.

As is the case with comparing water-resistance performance, a comparison on compressive strength is challenging mainly due to variability of raw materials (both soil and stabiliser). However, in order to draw a qualitative conclusion on strength performance, compressive strength hierarchy from various studies is compiled in Table 5.3.

Analysis of Table 5.3, in conjunction with Dataset 5X1, with focus on strength increases per unit stabiliser, reveals that xanthan gum provides the maximum strength improvement followed by guar gum, gellan gum, agar gum, starch, tannin, alginate, casein and carrageenan (the precise order is subjective and was based on qualitative judgement). Cow-dung, lignin and linseed oil are found to have minimal effect on strength (taking into account strength increase per unit stabiliser). The effect of lignin is still appreciable in clayey soil but not much in silty soil.

In multiple studies, xanthan gum and guar gum performed better than cement stabilisation. Strength upto 6MPa was measured for stabilisation with 1% xanthan gum (Chang et al., 2015c). Significantly high compressive strength were also observed in case of Gellan gum (12.6 MPa at 3% stabilisation) and Agar gum (9.2 MPa at 3% stabilisation), which were both heat treated to modify the properties of stabilisers (Chang et al., 2015a).

Table 5.3 Strength hierarchy of stabilised earthen material acquired from available literature. Unless specified, all stabilised samples have higher compressive strength in comparison to unstabilised samples

Literature	Clay [%]	Silt [%]	Sand [%]	Compressive strength Hierarchy
Ngowi (1997)	14.5	22.5	63	Cement (5%-15%) > Lime (5%-15%) > Unstabilised > Cow-dung (10%-20%)
	48	25	27	
Vilane (2010)	10	5	85	Cement (5%-20)> Cow-dung (10%)
Soldo et al. (2020)	8		92	Xanthan Gum (1-5%) > Gaur Gum(1-5%) > Alginate(1-5%) > Chitosan (1-5%)
Toufigh & Kianfar (2019)	5		95	Cement (2.5-10%) > Guar Gum (2.5-7.5%)
Chang et al. (2015a)	60		40	Gellan gum(1-3%) > Agar Gum (1-3%)
			100	Agar Gum (3%) > Gellan Gum (1%) > Agar Gum(1%)
Chang et al. (2015c)				Xanthan Gum (1%) > Cement (10%) >= Guar Gum(1%)
Ayeldeen et al. (2016)	15	63	20	Guar gum (0.5-2%) > Starch (0.5-2%) > Xanthan gum(0.5-2%)
Muguda et al. (2017)	16	4	70	Guar Gum=Xanthan Gum (2-3%) > Cement (8%)
Lee et al. (2019)		18	82	Xanthan Gum (1-2%) > Cement (7%)
Qureshi et al. (2017)			100	Xanthan Gum (2%) = Cement (10%) > Xanthan Gum (3-5%)
Chang et al. (2016b)	60		40	Gellan Gum (1%)> Agar Gum (1%)> Xanthan Gum (1%)> Cement (10%)
			100	Cement (10%)> Xanthan Gum (1%)>= Agar Gum (1%)> Gellan (1%)
Chang et al. (2018)				Xanthan (1%)> Gellan (1%)> Casein (5%)> Agar Gum (1%)> Cement (10%)
Fatehi et al. (2018)			>95	Xanthan (1%)> Agar (1%)> Gellan (1%)> Sodium Caseinate (1%)> Casein (1%)> Lignin (5%)

5.4.1.3 Others

Earthen materials offer several advantages as compared to concrete and fired bricks (as discussed in chapter 2). One of its major benefits is its moisture buffering capacity, which is its potential to regulate temperature and humidity thereby providing a comfortable indoor living environment. While the impact of biological stabilisers on moisture buffering is not investigated for most stabilisers, recent studies on xanthan gum and guar gum stabilised samples shows an increase in moisture buffering capacity (Muguda et al., 2020). Both xanthan and guar gum stabilised earthen materials showed a higher moisture buffering as compared to cement stabilised and unstabilised earthen material (Muguda et al., 2020).

Biodegradation of biological stabilisers is an often discussed and debated characteristic. Biodegradation is desirable when occurring after demolition of a building but undesirable during its service life. The biodegradation is expected to be severe when the earthen material is in contact with water. Wen et al. (2019) hypothesised that biodegradation was responsible for decreasing stability of calcium alginate stabilised sand that was submerged in water (Wen et al., 2019). Biodegradation of biologically stabilised earthen material is a topic which is not yet scientifically investigated but quite important for understanding its feasibility in practical application.

5.4.2 Economy

Cost is an important parameter that governs the choice of a stabiliser in any given earthen construction project. Unfortunately, the cost of all biological stabilisers is significantly higher than that of Portland cement at present. Figure 5.3 reveals these differences in cost of stabilisers in context of India. The cost calculation in the context of Europe or Netherlands is available in Dataset 5X2-3.

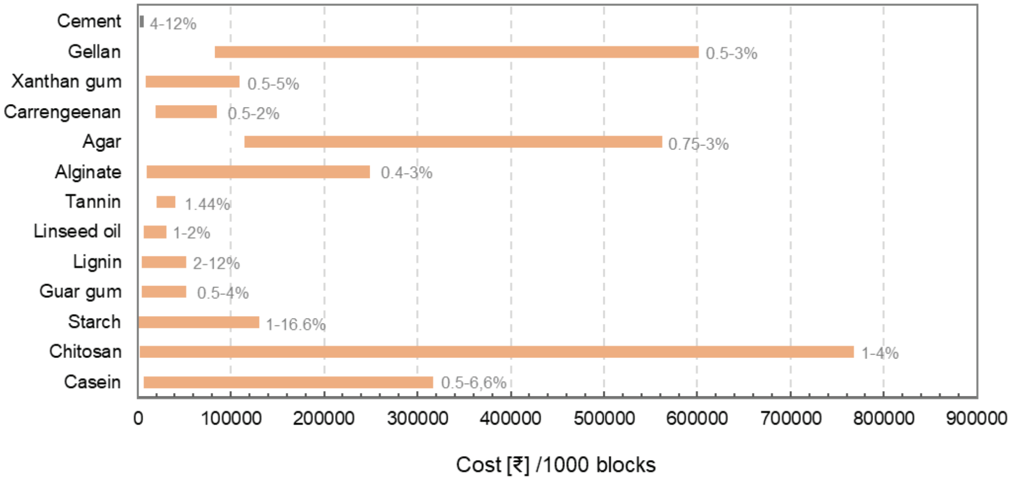

Figure 5.3. Estimated cost for stabilisation of earthen blocks with biological stabilisers (in Indian Rupees). The details of cost calculation can be found in Dataset 5X2-3. The horizontal bars represent the cost range for stabiliser calculated for the minimum and maximum dosage (available through literature) and minimum and maximum price of stabilisers acquired from the website of Indiamart. The dosage used for cost calculation are shown next to each bar.

The cost is dependent on the dosage and a higher dosage of biological stabiliser is impractical to use from an economical point of view. A lower dosage of most biological stabilisers (apart from gellan gum, agar gum, chitosan) can still be cost competitive if a user wants to apply it for benefits such as moisture buffering capacity, biodegradability or perceived environmental performance. However, it must be noted that stabilisation with cement even at higher dosage (12%) is more economical than biological stabilisation and is expected to provide strength and durability performance far superior to biological stabilisers. Therefore, biological stabilisers cannot compete economically with Portland cement at present, especially when comparing them on similar strength and durability performance.

The information presented in Figure 5.3 and the following discussion may discourage researchers and practitioners in investigating or applying biological stabiliser in earthen construction practice from an economic point of view. However, it should be noted that most of these biological stabilisers are currently produced in small scale for food and medical applications (refer Table 5.1). Therefore, the quality of these products as required for construction applications could possibly be lower, and thereby cheaper than the product available in the market now. Moreover, while biological stabilisers are not yet cost effective, introduction of mass production and expanded application is expected to decrease prices (Chang et al., 2016a). According to Chang et al. (2016a), increases in commercialisation of xanthan gum in the past 3 decades has led to about a 9 times reduction in the cost of stabilisation with xanthan gum. The growing support and awareness on bio-based economy is also expected to further push down the cost of biological stabilisers.

The cost of stabilisation with biological materials can also be reduced if these stabilisers can be sourced locally. The information on cow-dung and cactus is missing from Figure 5.3 as these stabilisers are often sourced locally and are not industrially produced or stored. Therefore, apart from expenses in collection, transportation and processing, these stabilisers are often available free of cost. Using waste stream to extract stabilisers locally can also reduce the cost of construction significantly as possible in case of cow-dung (when present in excess), chitosan (extracted from shrimp waste), lignin (low-quality lignin which has no commercial value) and starch (extracted from biomass or rice cooking waste).

5.4.3 Environmental performance

Biological stabilisers are touted and perceived as environmentally friendly alternatives to conventional stabilisers, however there are no studies which evaluate the environmental performance of the biological stabilisers especially in context of earthen construction. The lack of data on most biological stabilisers in environment database repositories also adds to the complexity in assessing their environmental footprint. Another challenge is that the biological stabilisers and mineral stabilisers do not have similar effects on earthen materials and therefore, a comparison on similar technical parameters can be unreliable. The lack of information restricts making strong comments and conclusions on the environmental performance. However, it is worthwhile to discuss the extraction and production process of biological stabilisers briefly to gain insight into energy and material requirement in the process.

Table 4.4 provides a summary of extraction and production processes of various stabilisers. It can be observed that most of the stabilisers require complicated processes, significant energy-, chemical-and water usage. Traditional biological stabilisers such as cow-dung, cactus, tannins, linseed oil and caseins are relatively easy to extract when compared to industrial biological stabilisers. Cow-dung is the only stabiliser that can be used directly without processing.

Most of the industrial stabilisers are presently used in food and drug industry, therefore their use in construction sector can create competition with food, which is undesirable. Industrial biological stabilisers such as chitosan can be extracted in a small-scale setting, however, extraction of large quantities can be quite challenging. Lignin and its derivatives are by-products of paper and timber industry and therefore their ecological footprint can be expected to be low.

Table 5.4 Summary of the extraction and production process of various biological stabilisers

Biological stabiliser	**Extraction and production process**
Cow-dung	Used directly
Casein	Acidification, ultracentrifugation, precipitation by salts or ethanol, rennet coagulation (Fox, 2003)
Chitosan	Production of deacetylated chitosan from shrimp shells requires treatment with HCl and NaOH, nitrogen, process water and cooling water. Chitosan can also be produced through enzymatic hydrolysis in presence of chitin deacetylase (Ravi Kumar, 2000; Shukla et al., 2013)
Starch	Extraction through dry-milling or wet-milling(popular). The starch is steeped, pulped, milled, separated, centrifuged, sieved, dried and ground in wet-milling process. Steeping process use sulphur dioxide and lactic acid. Need of 50°C temperature for a prolonged period of time (48 h). (Liu et al., 2018; Singh et al., 1997)
Guar gum	The seeds of Cyamopsis tetragonolobus are broken and processed (separating of hull and germ from the endosperm, polishing) to obtain refined guar splits. These splits are milled into fine particles and packaged. The guar gum can be further processed (dissolution in water, precipitation and recovery with ethanol or isopropanol) into purified or clarified guar gum. (Chudzikowski, 1971; Mudgil et al., 2014; Sharma et al., 2018)
Cactus juice/ mucilage	Chopped cactus stalks are soaked in water, (1:1 or 1:3 by weight), optionally heated at 65 ºC, and stored for several days at room temperature in a sealed container. A viscous fluid or gel is obtained by the end of the process (Heredia Zavoni et al., 1988)
Lignin and derivatives	Lignin derivatives are by-products of paper, timber and bioethanol industries and are extracted as liquid and often used directly or stored in powder form (Zhang et al., 2020)
Linseed oil	Extracted by pressing and/or heating the dried flex seeds (Dixit et al., 2012)
Tannin	Dynamic and static maceration assist with different methods, like microwave, ultrasound, infrared (for industrial production). The solvent used are usually water, methanol, ethanol or acetone (Aires, 2020; Sieniawska & Baj, 2017)
Alginate	The extraction involves use of solvent such as $\mathrm{Cacl_2}$,$\mathrm{Na_2Co_3}$. There is need of stirring, temperature upto 70 °C and filtration (Mian & Percival, 1973; Rioux et al., 2007)
Carrageenan	Extraction is carried out in alkaline aqueous medium (calcium or sodium hydroxide) followed by precipitation of isopropyl alcohol, and drying at 50 °C (Nakamatsu et al., 2017).

Agar gum	The seaweed is blended and extracted in boiling water by heating for 4-10 hours at the pH range of 5-6 (adjusted by sulphuric acid). A bleaching agent (e.g., hypochloride, hydrosulfite, bisulfite) is also added to the boiling water. The supernatant is strained and the residue is boiled again for 10 h. The liquor is poured in trays to cool and gellify. The gel is cut into small pieces and subjected to repeated freezing and thawing for 3-6 days. The impurities are drained off and the final extract is dried for 15-30 days (Venugopal, 2011).
Xanthan gum	Produced from the fermentation of glucose (aerobic, T =28–30 °C, pH ~ 7) using Xanthomonas campestris. After fermentation, the broth is pasteurised to kill the bacteria and the xanthan gum is recovered by precipitation with isopropyl alcohol or ethanol (Petri, 2015; Rosalam & England, 2006)
Gellan gum	In the pre-treatment step, Fermentation broth (prepared with glucose, $K_2HPO_{4,}$ MgS04, NH_4NO_3, $NaMoO_{4,}$ yeast extract, $MnCl_2$, $Zncl_2$, $CoCl_2$ and other chemicals) is heated to 100°C and then cooled to 85°C. The pH is increased to 10 using NaOH and then neutralised to 7 using sulphuric acid. Finally, the cells are removed through centrifuge and Gellan is precipitated using propanol (Giavasis et al., 2000).

There is a potential in extracting stabilisers from waste. For example, Chang et al. (2018) discussed the potential to use dairy waste in producing casein of lower environmental footprint. Similarly, waste starch from cooking of rice can be extracted and used in stabilisation of earthen material. A major challenge in extracting waste is the requirement of extensive collection and storage infrastructure.

In comparison to production processes of biological stabilisers, the production of cement and hydraulic lime requires intensive mining and heating at high temperature. It can be expected that the carbon footprint of biological stabilisers is significantly lower than cement or hydraulic lime. However, a thorough investigation is needed before claiming their environmental performance. In the study of Kulshreshtha et al. (2017), the environment footprint of corn starch stabilised sand (16.7% starch) was unexpectedly higher than that of concrete (of similar strength). It was found that particularly the fertilisers used in growing maize were responsible for the higher footprint. Therefore, parameters such as energy and resources required before harvesting can contribute to higher impact of some plant based biological stabilisers.

5.4.4 Feasibility of biological stabilised earthen materials in contemporary housing

The assessment of this chapter reveals important gaps in technical and environmental aspects of biological stabilisers. However, it appears that economic considerations, i.e., the high cost of stabilisers, is a major barrier to its contemporary application. Unlike cement, biological stabilisers are not yet produced at a large scale and are therefore expensive. Use of most biological stabilisers in contemporary mass housing initially therefore seems unfeasible. However, it is expected that the prices will go down (significantly) in the future.

Traditional stabilisers such as cow-dung, cactus juice, tannins, casein and linseed oil can be viable options if they are locally sourced and processed. One of the main requirements of a housing project is the large quantity of raw materials required for construction. Therefore, stabilisers such as cow-dung, cactus and tannin seem to be promising given their simple extraction process and wide availability in some locations. The successful application of these stabilisers will depend on a robust collection and storage system. Valorisation of stabilisers from waste streams (for casein and starch) could also reduce the cost and improve environmental performance.

Based on the limited research conducted on biological stabilisers, their technical performance (especially water resistance) does not compare well with cement as a stabiliser. However, biological stabilisers offer other benefits such as moisture buffering capacity or biodegradation after demolition. Another aspect which is a barrier for application in modern earthen construction is lack of standards supporting use of unstabilised and biologically stabilised earthen materials.

The growing interest of researchers in biological stabilisers is motivated by its apparent eco-friendly behaviour. The same motivation also holds for practitioners who might be willing to use them provided enough evidence proving their performance is available. As discussed in Chapter 2, stabilisation is not always required and should be done only when necessary, especially as providing sufficient architectural details and design elements can prevent use of stabiliser. However, good design cannot be guaranteed in many projects (especially low-cost housing projects). Moreover, unstabilised earthen material suffers from a low image (refer to Chapter 2). Therefore, some stabilisation that can convince people of safety and the reliability of earthen structures is advantageous. Rather than approaching biological stabiliser as an alternative to cement or hydraulic lime, approaching them as a light stabilisation to improve performance of unstabilised materials could support its widespread use and acceptance.

Interest in biological stabilisers is growing in India!

The choice and use of stabilisers for earthen construction in India is governed by its local availability, knowledge, and traditions. While the use of Portland cement and hydraulic lime in earthen construction is currently widespread, there is a resurgent interest in biological stabilisers. The rising interest is partly due to concerns about the negative environmental impact of modern building materials (such as concrete) which is drawing ecologically inclined people towards traditional building materials and techniques. The trust of people in biological stabilisers also stems from its use in traditional earthen houses in India. Stabilisers such as cow-dung are widely used, with cow dung used due to its perceived water-resistant characteristics. Several food-based stabilisers such as Terminalia Chebula (also known as Kadukkai or Haritaki), jaggery (unrefined sugar) and starch are also used in traditional as well as newly built earthen houses. Although these stabilisers have shown their effectiveness in traditional earthen houses, there are no scientific evidence of their exact performance in improving the strength and/or water resistance of earthen material. Therefore, these stabilisers at present cannot be 'engineered' and research is required to understand their role in improving earthen materials. Due to their unclear role, they are often used in combination with hydraulic lime for the construction of modern earthen houses. There use is earthen construction in India is now merely symbolic (especially food-based stabilisers) as it is expected that hydraulic lime overpowers the function of biological stabilisers in improving earthen material's performance. Nevertheless, the 'image' of biological stabilisers is positive in India and hence, favours its widespread acceptance.

5.5 Gaps in the study of biologically stabilised earthen materials

One of the outcomes of this study is identification of potential gaps in the research of earthen construction. These gaps are opportunities that are not just interesting but necessary for thorough understanding and full-scale adoption of biologically stabilised earthen materials. Here is a brief compilation of research gaps identified and discussed in this study:

- Research on biological stabilisation so far has mainly focused on strength development, whereas it is known that earthen structures usually fail due to durability related aspects. There is a lack of good quality research focusing on water-resistance of biologically stabilised earthen materials. Studies looking into a mechanistic understanding of water-resistance are also generally absent, except for a few stabilisers such as lignin.
- Specific attention is required on the research of traditional stabilisers such as cow-dung, cactus, tannins. These low-cost stabilisers are still used in rural areas developing countries, and comprehensive research could benefit several earthen house dwellers. While all these stabilisers are known or have shown to enhance water resistance, there is lack of comprehensive studies that provide insight into their behaviour. The wide availability and acceptance of cow-dung makes it an interesting stabiliser to explore in India. Therefore, detailed investigation on cow-dung stabilised earthen block is carried out in Chapter 6.
- While the potential of chitosan, carrageenan and linseed oil is explored in some studies, more research is required on the water resistance properties of these stabilisers.
- Possibility to extract starch and casein from waste and using it as stabiliser should be explored.

- A fair comparison between biologically stabilised earthen materials on the characteristic of water-resistance is challenging due to lack of standard tests to measure water resistance of earthen material, especially unstabilised material. The study by Beckett, Jaquin and Morel (2020) can act as starting point for much needed discussion on standard water-resistance tests that can be performed even in labs with moderate resources.
- Another challenge in comparing various study is variability in raw material (soil and stabilisers). There is a need for standard soils (which is commercially available and can be purchased from anywhere in the world) and standard test equipment (and parameters) for conducting research which is reproducible and comparable.
- None of the published scientific research has investigated the biodegradability aspect of biologically stabilised earthen material. Biodegradability impacts durability of earthen structure and it can act as a positive characteristic if triggered after demolition. However, if biodegradation occurs during the service life, the earthen construction will require frequent maintenance. A thorough understanding of biodegradation is required for practical feasibility of biological stabiliser.
- Only a single study has investigated the moisture buffering capacity of stabilised earthen material, in that case for xanthan gum and guar gum stabilisation (Muguda et al., 2020). Similar studies on other biological stabilisers can provide insights necessary for promotion of biologically stabilised earthen materials.

Although biological stabilisers are gaining popularity as eco-friendly alternatives to conventional stabiliser, there is no study evaluating the environmental impact of biologically stabilised earthen material. In fact, there is a lack of data to use to perform environmental assessments. Research is required to prepare a database which provides useful information in conducting life cycle assessment of these stabilisers.

5.6 Summary and conclusions

Building with earth offers several benefits. However, its water resistance performance is a concern for its widespread application in India and elsewhere. This limitation is often solved by adding chemical stabilisers (or mineral binders) such as Portland cement and hydraulic lime. The widespread debate around the use of chemical stabilisers has led to growing interest in biological stabilisers which are renewable, perceived eco-friendly and have proven their effectiveness in traditional earthen construction.

While the strengthening mechanism of biological stabilisers is widely covered in scientific studies, data regarding their water-resistance performance is limited. Therefore, this chapter reviewed a wide range of traditional and industrial biological stabilisers derived from animals, plants, seaweeds, and microbes. An attempt was made to explain the possible mechanisms responsible for the water-resistance behaviour of biologically stabilised earthen materials. The response of biological stabiliser to water ingress and related physico-chemical and physical factors was discussed at microscale (stabiliser interaction with clay, sand) and macroscale (hydraulic conductivity of building blocks). Properties of stabilisers such as hydrophobicity, heat induced modification or interaction with cations have a dominant effect on the overall response to water ingress.

A technical, environmental, and economical assessment of biological stabilisers was conducted to evaluate their feasibility in contemporary earthen construction. Some studies on biological stabilisers (such as on xanthan gum) have shown significant improvement in strength when compared to cement stabilised earthen material. However, biological stabilisers have not been able to perform comparatively well in water resistance tests. The cost and local availability of the stabilisers are also important criteria affecting the application of a specific stabiliser. At present, the cost of most biological stabilisers is significantly higher than cement and hydraulic lime, even though lower quantities of the material are required for stabilisation. In this regard, traditional stabilisers such as cow-dung, cactus juice and tannins can be viable options for construction if they can be locally sourced and processed in required quantities. While biological stabilisers are perceived environmentally friendly, a clear assessment through life cycle analysis is required to reveal their ecological impact. Extraction of industrial biological stabilisers involves significant energy, chemical and water usage, which can increase their environmental impact. Stabilisers that can be extracted from waste (such as cow-dung, casein, starch) could be explored further as an eco-friendly alternative.

To assess the overall performance of biologically stabilised earthen material, a fair comparison should be made with unstabilised and cement/lime stabilised earthen material on parameters such as durability, strength, environmental friendliness, moisture buffering behaviour, recyclability, long term field performance, bio-degradation, availability, acceptability and economy. A fair comparison could motivate a faster adoption of biologically stabilised earthen material, especially in the current scenario where reduction of greenhouse gases is a universal mission.

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6

Insights into the Water Resistance Behaviour of Cow-dung Stabilised Compressed Earth Blocks

“Never underestimate the stink”

– Mechanist, Avatar the Last Airbender (S1 E14)

The water-resistance characteristic of cow-dung has made it a widely used stabiliser in traditional earthen structures. However, scientific insights on its water resistance characteristics are missing. This chapter investigates the water-resistance behaviour of cow-dung stabilised compressed earthen blocks (CD-CEBs) through an extensive experimental programme to evaluate the influence of cow-dung and soil related factors and to identify and characterise the components of cow-dung responsible for its water resistance. While cow-dung ageing and compaction force have minimal impact on the performance of CD-CEBs, the ageing of a cow-dung soil mixture (up to 14 days) and a higher compaction water content improves both strength and water resistance. It was found that the small-sized microbial aggregates (SSMA) present in cow-dung are responsible for enhanced water resistance of CD-CEBs. SSMA are negatively charged aggregates (mean size 2.7 μm) of low specific surface area that are hydrophobic, rich in fatty acids and stable upon wetting. The insights gained from these experiments are compiled to recommend strategies for further improvement in the performance of CD-CEBs. The use of wet cow-dung is advised over dry cow-dung as it provided over 80 times better water resistance. Adopting a higher compaction water content (by 3%) improved the water resistance by over 40 times. Moreover, the water resistance of CD-CEBs was improved over 30 times by using a low-swelling clay mineral such as kaolinite rich soil.

Data accompanying Chapter 6 is available in Kulshreshtha (2022). A part of this chapter is published as Kulshreshtha, Y., Vardon, P. J., Meesters, G., van Loosdrecht, M. C. M., Mota, N. J. A., & Jonkers, H. M. (2022). What makes cow-dung stabilised earthen block water-resistant? 4th International Conference on Bio-Based Building Materials, 540–548. https://doi.org/10.4028/www.scientific.net/CTA.1.540

6.1 Introduction

Cow-dung is a commonly used stabiliser in traditional earthen structures. Cow-dung stabilised earthen structures are widespread across Asian and African countries such as India, Ethiopia, Uganda, Burkina Faso, Ghana, Swaziland and Botswana (Agarwal, 1981; DHS, 2022; Kulshreshtha et al., 2020; Millogo et al., 2016; Ngowi, 1997; Vilane, 2010; Yalley & Manu, 2013). According to the global Demographic and Health Surveys programme, multiple countries such as Ethiopia and Uganda have over 10% of households using dung as a flooring material (DHS, 2022). More information on the DHS database on households with dung flooring is available in Appendix 6A.

Cow-dung is often applied as a coating to earthen walls and floors with or without mixing it with soil. The addition of cow-dung in soil is known to repel insects, reduce cracks in soils, and improve cohesion and plasticity of soils (ITDG, 1999; Katale et al., 2014; Ngowi, 1997). However, the use of cow-dung in traditional earthen construction is primarily motivated by its water resistance characteristics (ITDG, 1999; Lekshmi et al., 2020; Millogo et al., 2016; Ngowi, 1997; Vilane, 2010). Yet, only limited scientific research has explored this characteristic in depth. While most scientific research on cow-dung stabilised earthen construction has presented strength and water resistance results, these studies were conducted with a focus on optimisation of strength characteristics. A summary of these studies is highlighted in Table 6.1.

Table 6.1: Scientific studies on cow-dung stabilised earthen materials. The compressive strength and water resistance test results are summarised from each study. In studies that investigated stabilisation of multiple sources of soils, only one of them is selected. (*) indicate values determined from a plot.

Reference	Construction technique	Cow-dung content	Compressive Strength results	Water resistance test and results	Other tests conducted
Ngowi (1997)	CEB	10-20 % (wet dung)	1.8 MPa (10%), 1.4 MPa (20%) Unstabilised 1.8 MPa	Immersion test: Disintegration in 12-24h as compared to unstabilised samples which disintegrated immediately	-
Vilane (2010)	Rammed block	5-20 wt.% (dry dung)	1.8 MPa (5%), 2.2 MPa(10%), 0.8 MPa (20%) Unstabilised: 2 MPa*	Wet compressive strength (7 days submerged in 10mm of water) comparable to unstabilised (0.3 MPa)	-

Yalley & Manu (2013)	CEB	15-30% (dry dung)	4.7 MPa (15%), 5.8 MPa (20%), 5.1 MPa (25%), 4.6 MPa (30%) 4.6 MPa (unstabilised)	Wet compressive strength (immersed in water for 10 min): 0.85 (15%), 2.8 MPa (20%), 2.3 (25%), 1.9% (30%), 0 MPa (unstabilised)	Abrasion, water absorption
Millogo et al. (2016)	Adobe	1-3 wt.% (dry cow dung mixed with soil and left for 72h fermentation)	2.45-2.8 MPa (1-3%) 2.1 (unstabilised) *	Mass loss through water absorption [%]: 6.4- 5.65* (1-3%) Unstabilised: complete disintegration	Flexural strength, SEM, video microscopy, Linear shrinkage, XRD
Bamogo et al. (2020)	Earth plaster	2-6 wt.% (dry cow dung mixed with soil and left for 72h fermentation)	1.2-2.4 MPa (2-6%) 1.8 MPa (unstabilised) *	Water absorption coefficient [kg/m^2/s$^{1/2}$]: 0.29-0.22 (2-6%), unstabilised: 0.47 Mass loss in spray test [%]: 6-2 [2-6%], 14 (unstabilised)	SEM-EDS, moisture absorption, linear shrinkage, thermal conductivity, abrasion resistance, flexural strength
Lekshmi et al. (2020)	Mud mortar (adobe)	10-20 wt.% (dry dung)	3.5 MPa (10%), 2.9 MPa (20%) 4 MPa (unstabilised)	Capillary absorption test: Sorptivity [mm/√h] 14.8-17.7 (10-20%) 6.8 (unstabilised)	Water absorption test, linear shrinkage
Pachamama et al. (2020)	Earth plaster	10-20 wt.% (dry dung)	0.9-0.5 MPa (10-20%) 0.5MPa (unstabilised)	-	Linear shrinkage
Darshan et al. (2021)	Rammed earth	2-8 wt.% (dry dung)	2.5-1.3MPa (2-8%), 1.23 MPa (Unstabilised)	-	-

Cow-dung stabilised earthen material in most studies was prepared by mixing dry cow-dung in soil at a dosage ranging from 1%-30%. The addition of cow-dung was seen to increase the compressive strength in most soils, with exception of research by Ngowi (1997) and Lekshmi et al. (2020) who reported a reduction in compressive strength. The strength increase in most studies was insignificant as compared to improvement observed by adding chemical stabilisers (such as Portland cement). In all studies, the incorporation of cow-dung to an unstabilised earthen matrix resulted in the improvement of water resistance characteristics. However, the variability in the test method and raw materials makes it challenging to quantitatively compare water resistance characteristics between studies.

While multiple studies have shown the positive impact of cow-dung addition on the water-resistance performance of earthen materials, none of them provide solid evidence on the actual mechanism that was responsible for improved water resistance. In their study, Millogo et al. (2016) proposed that the chemical reaction between cow-dung (rich in amine compounds) and soil (quartz) under an alkaline condition results in the formation of an insoluble compound that glues the soil aggregate together simultaneously improving strength and water resistance. However, this compound remained undetected in their characterisation study. Moreover, the alkaline condition (pH of 12) reported to result from the fermentation of cow-dung is significantly higher than the pH range of 6.5-9.5 reported for cow-dung in other studies (Huang et al., 2017; Rao et al., 2017; Whalen et al., 2000; Zhang et al., 2013). Thus, there remains a need to verify their hypothesis. In a study on the utilisation of cow-dung for ground improvement, Rao et al. (2021) found that extracellular polymeric substances (EPS) present in the cow-dung are responsible for binding soil aggregates, resulting in improvement of mechanical strength. While their study was limited to strengthening mechanism, the EPS in cow-dung could also be responsible for improved water resistance of cow-dung stabilised earthen materials. hence, understanding the various components of cow-dung could be an essential step to understand its water resistance characteristics.

Cow-dung is known to be composed of undigested plant fibres (consisting of cellulose, hemicellulose and lignin), microorganisms, amine compounds, potassium, fragments of intestinal tissues and traces of sulphur, calcium, iron, magnesium, and manganese (Garg & Mudgal, 2007; Graham, 2004; Gupta et al., 2016; Millogo et al., 2016). A recent investigation on cow-dung by Rao et al. (2021) revealed the presence of cellulose, hemicellulose, lignin, fatty acids and esters, polysaccharides and aldehydes, glucuronic acid and galacturonic acid, amine and alkylhalides. Although water resistance of cow-dung is anecdotally attributed to the fibres present in cow-dung (refer Chapter 5), the mechanism of how fibres cause improvement of the water resistance is unclear (Laborel-Préneron et al., 2016). Therefore, a thorough investigation into the role of various components of cow-dung may provide insights into the mechanism responsible for water-resistance improvement of cow-dung stabilised earthen blocks.

This chapter therefore investigates the water-resistance behaviour of cow-dung stabilised compressed earth blocks (CD-CEBs) through an extensive experimental programme to identify and characterise the components of cow dung responsible for its water-resistance. The obtained insights are then used to lay out practical recommendations and guidelines that would be valuable for practitioners building earthen structures stabilised with cow-dung.

6.2 Preliminary study

The parameters and variables selected for experimental investigation were developed through a series of preliminary studies conducted to explore the potential of cow-dung in stabilisation of earthen materials. The insights from each preliminary study were useful in determining variables to explore in the next preliminary study. The key activity and results from each preliminary study are presented in the sub-section below.

6.2.1 First preliminary study

The first preliminary study was conducted with cow-dung collected in January 2019. This study was conducted on hand compacted blocks stabilised with dry and wet (or fresh) dung. Although most scientific literature on cow-dung stabilised earthen material uses dry cow-dung, it was decided to use wet cow-dung for all of the following investigations motivated by multiple reasons: 1. Results showed better performance of soil stabilised with wet or fresh cow-dung than the soil stabilised with dry dung, 2. The cow-dung was collected in a wet state from the farm and therefore, it was more convenient to use the wet dung directly for the investigation, 3. The soil used in the study was supplied in dried form and therefore, it was convenient to use wet dung directly to reach the desired consistency, 4. Inaccessibility of outdoor and indoor space for drying cow-dung without creating the nuisance of smell.

The first trials on component separation were also conducted, and the cow-dung was separated into fibres and microbial biomass using a sieve of size 63μm. Each component was individually mixed with soil to prepare samples that were dried for a week and later submerged in water. The variation in water resistance of these samples aided in extending the research into understanding role of individual components of cow-dung.

6.2.2 Second preliminary study

The second preliminary study was conducted on wet cow-dung collected in October 2019. In this study, the compressed earthen block making setup was prepared and optimised. Over 50 samples of cow-dung stabilised compressed earth blocks (now on referred to CD-CEB) were prepared to find the compaction parameters required for producing replicable earthen blocks. Water resistance tests were also developed and optimised.

One of the main outcomes of this study was the selection of cow-dung content. The cow-dung content in CD-CEBs was fixed to be equivalent to 2% mass of dry dung in dried soil. Therefore, solid content in the wet cow-dung was measured before sample preparation and the amount of wet dung was (re)calculated and mixed with soil to reach the desired cow-dung content and consistency. Thus, the amount of wet dung added to the soil ranged from 16-20 wt.%. For example, if the wet cow-dung was composed of 10% solids and 90% liquid, then 200g wet cow-dung was added to 1000g dried soil to reach the target value of 20g solid cow-dung, which corresponds to 2 wt.% cow-dung in dried soil.

The choice of cow-dung content of 2% was motivated by the desired consistency of soil for compaction. The addition of wet cow-dung corresponding to 1% dry cow-dung content in the soil resulted in a relatively dry mix. Whereas, the addition of wet cow-dung corresponding to 3% dry dung in the soil resulted in mix of fluid consistency. The chosen content of cow-dung is also in line with wet cow-dung content used by Ngowi (1997) and dry cow-dung content used by Millogo et al. (2016). During this study, the successive trials to separate components of cow-dung lead to further separation of microbial biomass into small and medium-sized aggregates. These microbial aggregates are discussed in Section 6.4.2.3.

6.2.3 Third preliminary study

The third study from the cow-dung collected in March 2020 was planned to be the final and main experimental series. However, it was interrupted by the Covid lockdown and restrictions and only a few experiments such as pH variation in cow-dung (and components) were conducted. While soil cow-dung mixes were prepared on the day of collection, it was not used for casting samples due to restrictions. The long term observation (1 month) of this mix revealed no growth of fungus. In some mix, fungus was observed after 2 weeks but it disappeared in time and did not re-occur. This provided insights into the long shelf life of soil cow-dung mix and motivated the study on the influence of ageing of cow-dung soil mix on strength and water resistance of CD-CEB. It was also observed that the wet-cow dung stored for over a month had a thin layer of fungus growing on the surface of exposed dung, but the entire volume had no fungus. This observation motivated the study on the influence of cow-dung ageing on the strength and water resistance of CD-CEBs. Microbial biomass was extracted from cow-dung and its volume and density were determined. Fibres were also extracted from the wet cow-dung and used in future experiments.

6.3 Experimental design

Based on the observations of preliminary studies, an extensive experimental programme was prepared and performed with cow-dung collected in August 2020. Table 6.2 provides a summary of the experimental programme, including the objective of the test series, the variables involved and the test conducted. In test series A, the influence of including cow-dung in CEBs was investigated. In test series B, the influence of various choices involved in the manufacture of CD-CEBs were systematically tested. Tests on the ageing of cow-dung (B1 test series in Table 6.2) and ageing of cow-dung soil mixture (B2) were also included. In addition, the influence of compaction water content (B3), compaction pressure (B4) and drying duration of CD-CEBs (B5), were evaluated (similar to variables influencing unstabilised CEBs in Chapter 4). Extensive tests were conducted to understand which component of cow-dung was particularly responsible for water resistance of CD-CEBs (C). Several other variables were also evaluated to improve the CD-CEBs further and to evaluate their feasibility in the practice of earthen construction (test series D-I). It should be noted that when the whole cow-dung batch (collected in August 2020) was consumed in the experiments, a new batch of cow-dung was collected in December 2020 and used in test series G.

Table 6.2: Summary of experimental design

Objective	Variable	Definition	Test series code	Test conducted
To evaluate the improvement with cow-dung stabilisation	cow-dung content	Mass of cow-dung relative to the mass of dry soil.	A	Compressive strength, immersion test, drip test
To evaluate the factors influencing strength and water resistance of cow-dung stabilised earthen blocks CD-CEBs	Ageing of cow-dung	Duration of storage after collection of fresh cow-dung	B1	Compressive strength, immersion test, drip test
	Ageing of soil and cow-dung mixture	Duration of storage after mixing soil and dung	B2	
	Compaction water content	Water content in the earthen block immediately after compaction	B3	
	Compaction pressure	Amount of pressure applied during compaction of soil cow-dung mixture into CD-CEBs	B4	
	Drying duration of CD-CEBs	Drying period of CD-CEBs after casting (in days)	B5	
To identify and characterise the component of cow-dung which makes CD-CEBs water resistant	Components of cow-dung	Various components separated from cow-dung: fibres, small-sized microbial aggregates (SSMA) and medium-sized microbial aggregates (MSMA)	C	Compressive strength, immersion test, drip test , particle size analysis, zeta potential measurement, electron microscopy, contact angle test, surface area measurement, mercury intrusion porosimetry, and gas chromatography- mass spectrometry.
To optimise the CD-CEBs for better water resistance	Components of cow-dung (their combinations)		D	Compressive strength, immersion test, drip test
To understand the variation between dry cow-dung or wet cow-dung stabilised CEBs	Wet and dry cow-dung		E	Compressive strength, immersion test, drip test, particle size analysis
To evaluate the influence of batch of cow-dung on performance of CD-CEBs	Batch of cow-dung	Cow-dung collected from the same source but in different time of the year(s)	F	Compressive strength, immersion test, drip test
To understand the role of soil type on performance of CD-CEBs	Soil type	Natural and artificially created soil (with different clay minerals)	G	Compressive strength, immersion test, drip test, electron microscopy
To evaluate the reusability of CD-CEBs	Recycled CD-CEB		H	Immersion test
To evaluate the performance of CD-CEBs compared to conventional mineral stabilisers	Stabiliser	Portland cement and hydraulic lime as binder in stabilised CEBs	I	Compressive strength, immersion test, drip test

6.4 Materials and methods

The materials and methods used in the study of unstabilised earthen materials (in Section 4.4, Chapter 4) were also used in the investigation of cow-dung stabilised compressed earthen blocks (CD-CEBs). Therefore, to prevent the duplication of information, repeated materials and methods are summarised in a few sentences.

6.4.1 Soil selection

The soil used in the investigation of cow-dung stabilised earthen material is the same as the one used in the study of unstabilised earthen material. The complete characterisation of the soil is available in Section 4.4.1, Chapter 4.

6.4.2 Cow-dung

6.4.2.1 Collection of cow-dung

Fresh (wet) cow-dung was collected from the biological farm 'Hoeve Biesland' located in Delfgauw, Netherlands. The dung was collected from the concrete floor as shown in Figure 6.1(a). The quality of cow-dung was found to be consistent between different batches. This might be due to automated straw and protein feeding system installed in the farm that reduces the variability in diet (Figure 6.1 (b-c)). The farm is equipped with an automated cow-dung wiping system which pushes excreted cow-dung in an underground storage space (Figure 6.1 (d)). Detailed information on the cows, feed and cow-dung collection system can be found in Appendix 6B. The dung was collected in plastic buckets (with an airtight lids) and stored at room temperature until its usage.

6.4.2.2 Properties of cow-dung

The solid content in the freshly collected cow-dung (mass of dry dung relative to the mass of wet dung) was measured to be 10.8%. The solid content measured for the same dung at different time durations was in the range of 9.5-11.7%. The solid content in all batches of cow-dung collected during 2019-2020 was measured in the range of 9.5-12.2%, which is in line with the measured values in the research of Lorimor et al. (2004). Details of the solid content measurement in cow-dung are available in Appendix 6C. The density of fresh cow-dung was measured to be equivalent to the density of water (1g/cm^3). The low density of cow-dung is a result of low solid content and the presence of low-density fibres in suspension state.

The pH of cow-dung (without any dilution) was measured to be 7.55, using a pH meter (model: 827 pH lab, Metrohm, Switzerland). The pH was found to decrease in time possibly due to the formation of fatty acids due to ongoing microbial fermentation of organic matter in cow-dung (as also observed by Rao et al. (2017)). The pH of cow-dung initially decreased to 6.2 in first 5 days of storage but subsequently increased to 6.9 until day 14. After 30 days of storage, the pH was measured to be

7.5, the same as the pH of freshly collected cow-dung. A similar trend of pH variation was also measured in cow-dung collected in preliminary study 3 (dung collection March 2020), which can be seen in Appendix 6D, with a supporting database available in Dataset 6X1 (Kulshreshtha, 2022).

Figure 6.1: Collection of cow-dung from farm 'Hoeve Biesland'. (a) manual collection of dung in buckets, (b) Robot feeding protein meal to cows, (c) Straw cutting and dispersing system installed on the roof, (d) Automated cow-dung wiping system installed on the concrete floor. The underground cow-dung storage capacity in the farm is ~750 m^3.

6.4.2.3 Components of cow-dung

The components of fresh cow-dung were separated into fibres and microbial biomass (or microbial aggregates) through wet sieving. The wet sieving was performed by adapting the method in ISO 17892-4 (2016) recommended for fine soils. 88g of wet cow-dung (stored for 10 days in a bucket) was poured over the sieve stack (2mm, 1mm, 0.5mm, 0.25mm, 0.125mm, 63μm) mounted on a 5L measuring jar and washed up with tap water thoroughly. The sieving process was carried out manually for 30 minutes using about 1.2 L water, in steps of 100 mL water. The water was added to the sieve unless the fibres on each sieve were clean (bright coloured) and non-pungent. The addition of water was followed by carefully squeezing the cow-dung mass (initially placed on the 2mm sieve) in order to force the separation of the component parts of the cow-dung. The washed mass, assumed to be mainly consisting of microbial biomass and water, was collected in the 5L bucket and was further separated through centrifugation at 5000 rpm for 10 mins using a centrifuge (Model: Heraerus megafuge 16, ThermoFisher, Germany).

The centrifugation process resulted in settling of heavier mass microbial biomass, termed medium-sized microbial biomass (MSMA), leaving supernatant liquid termed small-sized microbial aggregates (SSMA), as shown in Figure 6.2. The MSMA had a consistency of thick slurry whereas SSMA had a consistency closer to water. All the sieved components were carefully collected in aluminium trays and heated in an oven to 105°C to determine the solid mass content. The amount of dry dung was calculated to be 8.4g, representing 9.5% solid content in wet dung. The solid mass of fibres, MSMA and SSMA were found to be 42%, 24% and 34% respectively. The cow-dung collected for this study was thus composed of 42% fibres and 58% microbial biomass. The particle size distribution of MSMA and SSMA were determined with the laser particle size analyser method (discussed in Section 6.4) giving a range and mean size of 1-63 μm and 19.8 μm respectively for MSMA and 0.5-7 μm and 2.7 μm for SSMA. The data of the sieve analysis can be found in Dataset 6X2.

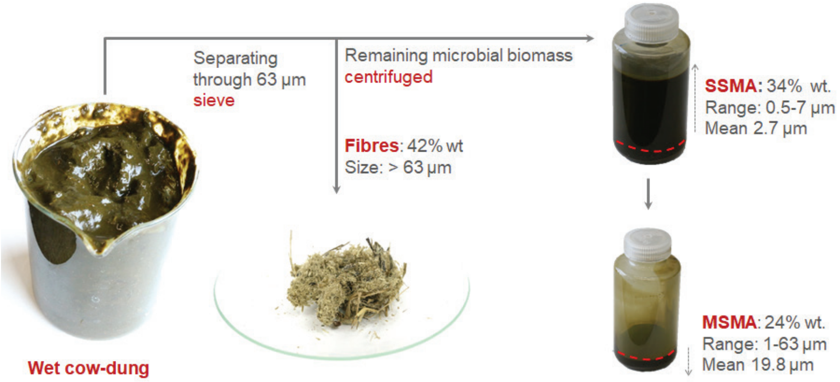

Figure 6.2: Separation of components from wet cow-dung. The SSMA and MSMA stands for small-sized microbial aggregates and medium-sized microbial aggregates respectively.

pH measurements were also carried out on SSMA and microbial biomass (SSMA+MSMA) before drying and without any further dilution. The pH of microbial biomass and SSMA was measured to be 7.7 and 7.3, respectively. The values of both samples were found to be in line with pH measurements of the cow-dung (see also Appendix 6D and Dataset 6X1).

6.4.3 Production of Cow-Dung stabilised Compressed Earth Blocks (CD-CEBs)

The production of cow-dung stabilised compressed earth block (CD-CEB) was carried out following the protocols described in Section 4.4.2 (Chapter 4).

6.4.3.1 Preparation and storage of soil cow-dung (soil-CD) mixtures

A number of specific soil and cow dung (and components) mixtures were prepared (see Table 6.3 for an overview of mix designs). A standard mixing procedure and its slight variations were adopted for various mixtures. In the standard mixing procedure, wet cow-dung was added to soil gradually and mixed manually for a total duration of 5-10 minutes. The amount of cow-dung added to soil was equivalent to 2% dry cow-dung in dried soil (by weight). The solid content in cow-dung and natural water content in soil was determined prior to the mixing by heating the materials at 105˚C for 24h in an oven. As sufficient water was already available in cow-dung no additional water was required for sample preparation to reach the desired water content (17-19%) in the mixture. The desired water content in all mixtures was above the optimum water content (OWC). It should be noted that the age of cow-dung used in most mixtures was 1 day, unless specified differently in Table 6.3.

After preparation of the soil cow-dung mixtures, they were stored in a metal container (tightly sealed with plastic film as shown in Appendix 6E) for a duration of 5 days at room temperature before using them in casting stabilised CEBs (standard mixture storage procedure). Based on the preliminary studies, it was found that storing soil-CD for over 3 days results in the elimination of pungent odour. Therefore, a duration of 5 days was found to be suitable and feasible for most mixtures. pH values and water content of all the mixes were determined before casting.

For the test series on components of cow-dung (C1), the number of separated components of cow-dung (Fibres, MSMA and SSMA) added to the soil was determined by their respective proportions in cow-dung. For example, SSMA represents 34% of the solid mass of cow-dung. Therefore, the corresponding amount of SSMA added in soil was equivalent to 0.68% (34% of 2%) dry mass of SSMA. Similarly, mixtures were prepared with 0.84% fibres and 0.48% MSMA.

For test series on soil type (G1), the 'manufactured soil' samples were prepared with commercially available kaolinite (Sigma-Aldrich), bentonite clays (Sigma-Aldrich) and river sand (0.125-0.25 mm). Kaolinite clay rich soil was prepared by adding 14.8% mass of kaolinite (equivalent to clay content in the natural soil) to sand (0.125-0.25 mm). Similarly, bentonite rich soil was prepared by adding 14.8% bentonite to the sand.

The information on mix design, especially information on slight variation in standard mixing and storage procedure for various mixtures is summarised in Table 6.3.

Table 6.3: Summary of mixing procedure and mixture storage. CD referred in the table stands for cow-dung.

Test series code	Test series/ Variables	Mixing procedure and variations	Mixture Storage and variations	Note
A	Cow-dung content	Standard	Standard	-
B1	Ageing of cow-dung	Standard	Standard	CD stored for 1, 8, 15, 30 days before mixing with soil
B2	Ageing of soil and cow-dung mixture	Standard	CD- soil mixture stored for 1,5,14, 28 days after mixing	-

B3	Compaction water content	Drying of mixtures was necessary to reach the desired water contents (12-15%).	Standard	Drying achieved with a temperature-controlled air blower set at 60°C.
B4	Compaction pressure	Standard	CD- soil mixture stored for 14 days	
B5	Drying duration of CEBs	Standard	Standard	-
C1	Components of cow-dung (Fibre, MSMA, SSMA)	In addition to a higher water content, mixtures with components of cow-dung were prepared at optimum water content (OWC). Hence, drying of mixtures was necessary. As compared to standard 2% stabilisation, the % of components used were different. Fibre: 0.84%, MSMA: 0.48%, SSMA: 0.68%	Fibres soil mixture was stored for 1 day	OWC values were obtained through the Harvard miniature compaction test (Appendix 6F and Dataset 6X3). CD stored for 13 days before separating components.
D	Components of cow-dung (their combinations)			
D1	SSMA+MSMA (1.16 wt.%)	Similar to procedure used in C. Stabiliser content of 1.16%.	standard	CD stored for 20 days before separating components.
D2	SSMA+MSMA (2.32 wt.%)	Similar to procedure used in C. Stabiliser content of 2.32%.	Mixture stored for 24h before casting days	Short storage due to appearance of fungus in mixture in 2 days (image in Appendix 6G). CD stored for 27 days before separating components.
E	Wet and dry cow-dung	2% dry cow-dung soaked in a pre-determined amount of water and mixed with soil	Mixture stored for 24h before casting days	Appearance of fungus in mixture in 2 days (image in Appendix 6G).
F	Batch of cow-dung	Standard	Standard	-
G	Soil type			CD from December batch
G1	Soil 1: Natural Dutch soil	Standard	Standard	-
G2	Mix 2: Kaolinite rich soil + CD	Standard	Standard	
G3	Mix 3: Bentonite rich soil + CD	Water was added to reach the desired water content close to their plastic limit (34%).		

G4	Mix 4: Sand (0.125-0.25 mm) + CD	Standard	Standard	-
G5	Mix 5: Sand + SSMA	Similar to procedure used in C. Stabiliser content of 0.68%.	Standard	-
H	Recycled CD-CEB	No mixing procedure required. Disintegrated CD-CEBs after immersion test were dried and used directly	Mixture cast immediately	-
I	Stabiliser (Portland cement, hydraulic lime)	Soil mixed with cement powder (2%,5%) or hydraulic lime (2%) and water just before casting to prevent hardening due to the hydration process.	Mixture cast immediately	Natural Hydraulic lime: grade 3.5, Portland cement: Grade 42.5 The curing process for stabilised CEBs described in Section 6.4.3.3

6.4.3.2 Casting of stabilised CEBs

The same compaction equipment and pressure used in casting unstabilised CEBs (see Section 4.4.2.2, Chapter 4) were used for the production of stabilised CEBs. A pre-determined amount of stabilised soil mixture was filled in individual spaces of the mould. The amount of mixture put in the mould was calculated based on the information obtained from the Harvard miniature compaction apparatus (Dataset 6X3) for the desired outcome of 40 × 40 × 40 mm block size.

The same procedure used for casting unstabilised CEBs (see Section 4.4.2.2, Chapter 4) was used here for the manufacturing of CD-CEBs. No releasing agent (e.g. oil) was used in the mould as it may influence the results of the water resistance test. All stabilised CEBs were prepared with a compaction pressure of 2.5 MPa per block, with the exception of Test series B4 where mixture was compressed with 1.25 MPa per block. After finishing the compaction process and demoulding, the CEBs were weighed (precision 0.01g). Three CEBs from each series were randomly picked and their dimensions were measured accurately using a digital Vernier calliper scale. The dimension and mass measurements were used to determine the bulk density of the fresh CEBs. In order to get a rough estimation of the comparative green strength (strength of freshly casted stabilised CEB) of different blocks, an Equotip hardness test was conducted. These measurements were skipped for extremely soft CEBs in Test series G2, G4 and G5.

The mixture of cow-dung and sand (Test series G4 and G5) could not be produced with machine compaction as the resultant blocks were too soft to demould and these were therefore hand compacted in 3 layers. Each layer was compacted with 15 blows from a hand-held metal rammer (base area 2 x 2 mm) and samples were demoulded only after 14 days.

6.4.3.3 Drying of stabilised CEBs

After determination of mass and dimensions of freshly cast blocks, they were transferred to a temperature and humidity controlled room. All cow-dung stabilised blocks were dried for 14 days at 19 (±1) °C and 55 (±2)% relative humidity, with the exception of CEBs with kaolinite and bentonite minerals (Test series G2 and G3) which were dried for 21 days. Cow-dung stabilised sand blocks and SSMA stabilised sand blocks were also dried for 28 days as they were too soft to be removed from the moulded in the first 14 days (Test series G4-G5). The CEBs stabilised with Portland cement and hydraulic lime were stored in a sealed bag for 14 days (to prevent loss of water and facilitate hydration), followed by 14 days of drying in the air (Test series I). The influence of drying duration on the characteristics of CD-CEBs was tested in the Test series B5. The mass and dimensions of all blocks were determined after their respective drying period.

Out of every 9 sample blocks prepared for each test series, water resistance tests were conducted on 6 samples and the rest of them were tested for compressive strength.

6.4.4 Water resistance and compressive strength tests

Immersion and drip tests as described in Section 4.4.3 (Chapter 4) were conducted on all CEBs. Both these tests are known to be reliable for assessing the efficacy of stabilisers (Beckett et al., 2020).

The immersion test was conducted using setup shown in Figure 4.6 (Chapter 4). Unlike unstabilised CEBs, most stabilised CEBs take time to disintegrate. Therefore, in addition to capturing images at 1-5 min (video), 10min, 15 min, 20 min, 30 min and 1h as done for unstabilised CEBs (see chapter 4), images were captured at 2h, 4h, 6h, 9h, 12h and 24 hours. In exceptional cases, images were also captured on 2, 3, 5, 7 and 10 days. The raw images of disintegrating samples were processed by altering the brightness (only if required) and by cropping the image.

The drip test was conducted using the setup shown in Figure 4.7 (Chapter 4). The rate of flow of water in the drip test was adjusted to 50 ml/min per block (similar to the rate used for unstabilised CEBs). Mass loss from blocks (in %) was calculated at 2 and/or 10 and 60 min.

In addition to immersion and drip tests, a few samples of CD-CEBs were also exposed to an outdoor environment for 135 days (Nov 2020-Mar 2021) to get insights into their performance in a natural environment. The initial mass and final mass after outdoor exposure were measured to determine the mass loss from the block (in %). Information on rainfall (precipitation) and temperature variation during the exposure period are available in Appendix 6H and Dataset 6X4.

The compressive strength test on stabilised CEBs was carried out following the procedure as described in Section 4.4.4 (Chapter 4). After testing each block, they were heated in an oven to measure their residual water content. The residual water content was used to re-calculate the compaction water content in each sample. Prior to water content measurement, a piece of selected blocks (of approximately 20-30g) was taken and sealed in a plastic bag for additional microstructural characterisation.

6.4.5 Characterisation tests

6.4.5.1 Particle size analysis

Particle size analysis was conducted on microbial biomass (SSMA and MSMA) samples to determine the mean size and size range of aggregates. The samples were taken 10 days after the collection of the cow dung. The particle size analysis was conducted using the particle size and shape analyser DIPA 2000 (Donner technologies / Ankersmid, Netherlands). One of the advantages of this technique is that it is not influenced by the optical or physical characteristics of the material. Moreover, no pre-knowledge of the material is required for the analysis. For each material, the test was repeated three times and the mean diameter and the size range was reported.

6.4.5.2 Specific surface area determination

The gas adsorption test was selected to measure the specific surface area of selected microbial aggregates. The absorption of nitrogen gas (N2) in combination with applying the Brenauer Emmett Teller (BET) equation is the used (Pennell, 2016). The analysis was carried out using Gemini VII 2390 gas adsorption analyser (Micromatrics, US). A small amount of powdered sample (<1g) was filled in a glass tube which was then connected manually to the equipment. The powder was prepared by heating the microbial biomass at 80°C for 48h in an oven and grinding the dry mass in a ball mill. The test was repeated three times to ensure the accuracy of the results. The gas adsorption test was conducted on microbial biomass samples obtained from cow-dung batches collected in March and August 2020).

6.4.5.3 Mercury intrusion porosimetry (MIP)

The MIP test was conducted on selected stabilised CEBs using the procedure as described in Section 4.4.5 (Chapter 4).

6.4.5.4 Environmental scanning electron microscopy (ESEM)

The microstructure of the cow-dung, its components and their composites with various soil minerals, were characterized using a Quanta F650 environmental scanning electron microscope (ThermoFisher, Germany). ESEM is a qualitative technique that is commonly used in the understanding microstructure of geo-materials , especially for studying the porosity changes due to wetting and drying of the material (Romero & Simms, 2008). Therefore, along with imaging of dried samples, imaging of samples during wetting and drying cycle were conducted using a Peltier cooling/heating system on a selected sample to understand the response of increasing relative humidity on the microstructural fabric.

ESEM equipped with a concentric back scattered (CBS) detector was used to capture images of dry samples at 10 or 15kV under vacuum. CBS is a high efficiency back scattered electron (BSE) detector composed of multiple rings which is especially valuable in acquiring topographical information of the sample. A Gaseous secondary electron detector (GSED) was used in capturing images during wetting and drying cycles. The principle behind GSED and its application for geo-materials can be read in Romero and Simms (2008).

ESEM characterization was carried out on 3 different sets of samples each with different sample preparation methods.

ESEM/CBS at 10 kV was used to study the microstructure and morphology of cow-dung and its extracted components (Fibres, MSMA, SSMA), which were heated at 80°C for 24h in an oven and stored in a sealed plastic bag prior to analysis. An X-ray energy dispersive system (EDS) was used together with ESEM for element chemical analysis of these samples. Images were captured at 125x, 500x,1000x, 5000x,10000x and 20000x magnifications.

The composites material composed of mixed microbial biomass and soil minerals (kaolinite, bentonite, silica rich sand) were studied by ESEM/CBS at 15 kV. The aim was to visualise the physical interaction between microbial biomass and soil minerals. The clay minerals and sand were individually mixed with microbial biomass (in liquid form with a solid concentration of 3.5%) in the proportion of 3:1 (clay: microbial biomass). The mixture was then heated at 60°C in the oven for 48h. For sand and microbial biomass composite, proportions of 1:10 (microbial biomass:sand) and 1:20 were used. Images were captured at magnification in the range from 125x-20000x.

6.4.5.5 Zeta potential measurement

Zeta potential measurements were conducted on microbial biomass extracted from cow-dung to study the stability of colloidal solutions and to provide information on surface charge and its relation with pH. Detail information on the zeta potential and its measurement can be found in the manual by Malvern Instruments (2013). Zeta potential measurements were conducted using a Zetasizer Nano ZS (Malvern, UK). The microbial biomass suspension was extracted from the cow-dung 3 weeks after the collection of fresh cow-dung. As Zeta potential is known to be influenced by pH, conductivity, and concentration of solids in the suspension (Malvern Instruments, 2015), tests were conducted to clarify the effect of each.

To understand the effect of concentration on zeta potential, the microbial biomass suspension was diluted with demineralised water to obtain samples in the range of 0.008 to 0.3% dry weight. For each concentration, tests were conducted in triplicates. The diluted microbial suspension was filled in the instruments sample cell (folded capillary cell- DTS1070) and the cell was inserted into the instrument. The image of the folded capillary cell with microbial solution is shown in Appendix 6I. The equipment runs 10 analyses per sample, thereby giving an averaged value of the zeta potential, mobility and conductivity. A concentration of 0.07% (solid mass) was selected to carry out the zeta potential measurements with varying pH. The zeta potential was measured for a pH range of 2.5 to 12.5. The pH of the diluted microbial suspension was measured to be 7.34, which was adjusted to desired values using acidic (HCl) or alkaline (NaOH) solution.

6.4.5.6 Gas chromatography-mass spectrometry (GC-MS)

Pyrolysis GC/MS (Py-GC/MS) is a technique that has been used widely in the characterization of organic materials, including cow-dung (He et al., 2020). It is useful to determine the chemical composition of unknown samples (Meier & Faix, 1992). Py-GC/MS was conducted to characterise the compounds in the microbial aggregates. The microbial biomass was extracted from cow-dung and heated to 80°C for 24h in an oven prior to analysis. The dried biomass was milled into a fine powder and stored in a sealed bottle until the test. The Py-GC/MS test was performed by ECN-TNO (Petten, Netherlands).

6.4.5.7 Contact angle measurement

Contact angle measurement through the sessile drop method has been used in several studies for characterization of biologically stabilised earthen materials (Aguilar et al., 2016; Guihéneuf et al., 2020; Nakamatsu et al., 2017). In this method, a droplet of water is placed on the sample using a vertical syringe and the contact angle of the droplet is measured using a digital image or video recorder. This method is used here to study the surface energy (hydrophilic and hydrophobic behaviour) of microbial aggregates. The same sample preparation as for Py-GC/MS was used in this test. Contact angles were also measured for kaolinite and bentonite powder. The powdered samples were placed on a sample holder or glass petri dish and tapped on a soft surface multiple times to compact the powder slightly. A sharp knife was used to scrape off excess material and make the surface level. Two techniques were used for the determination of static and dynamic contact angles. The first technique involves dropping 50 μL of a water droplet on the powder while recording a video of the process with a digital camera (Canon 70D). In the second technique, a syringe creating 15μL droplets is used and the contact angle was measured using a vhx-7000 digital microscope (Keyence, Belgium). In addition to powdered samples, the contact angle of water droplets applied on selected earthen blocks was also measured through microscopic analysis.

6.5 Results and Discussion

6.5.1 Water resistance of cow-dung stabilised compressed earth blocks (CD-CEBs)

The results of the immersion test (Test series A) is shown in Figure 6.3. As compared to unstabilised CEBs which disintegrate completely within 20 minutes of immersion, CD-CEBs disintegrate only partially after 24h of immersion, with first cracks appearing after 2h. The qualitative information gathered from the immersion test is congruent with drip test results which provides a quantitative assessment of cow-dung stabilisation efficacy (available in Dataset 6X5 (Kulshreshtha, 2022)). The best performing unstabilised CEBs showed erosion of 14.7% after 10 min of drip test whereas erosion of CD-CEBs after 10 min and 60 min amounted only to 0.03% and 0.28% respectively. Based on the results of the drip test it can therefore be concluded that the addition of cow-dung (2%) results in an improvement in water resistance of over 500 times. While this value is quite high, one should be aware that this value is based on lab results which may not reflect the performance of these materials in outdoor climate. Unstabilised CEBs and CD-CEBs exposed to 134 days of outdoor climate (experiencing rainfall, snow, wind, RH and temperature fluctuations) were found to lose 68% and 8.5% mass respectively (details given in Appendix 6J). While the unstabilised CEBs were found to disintegrate almost completely, the erosion of CD-CEBs was limited to the top surface of the sample, as shown in Figure 6J (Appendix 6J). Therefore, the performance difference between unstabilised and CD-CEBs in real environmental exposure appears rather 8 instead of 500 times lower than as established in the lab tests.

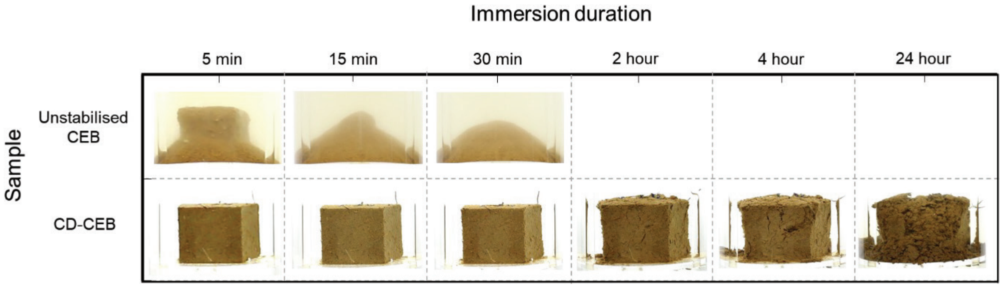

Figure 6.3: Time-lapse of disintegration of unstabilised CEB (prepared at a compaction water content of 12.7%) and CD-CEB (compaction water content of 15.6%). Both the CEBs were compressed with a compaction pressure of 2.5 MPa.

A close observation of Figure 6.3 also reveals that the volume of CD-CEB increases during immersion, possibly due to the presence of hydrophilic fibres that absorbs water and swell, whereas no such swelling was observed in unstabilised CEBs. It is also worth notice that CD-CEBs could be cast with a compaction water content of up to 16%, a value much higher than the highest compaction water content of 14.2% possible with unstabilised CEBs. This could again be due to the presence of fibres in CD-CEBs.

The compressive strength measured for unstabilised CEB samples shown in Figure 6.3 was 4.2 MPa, higher than the compressive strength of 3.8 MPa measured for CD-CEBs. The maximum average compressive strength of CD-CEBs investigated in this research was found to be 4.1 MPa, which was possible by increasing the cow-dung soil mixture ageing duration (discussed in Section 6.5.2). Thus, it can be concluded that the addition of cow-dung does not have a positive impact on the compressive strength of earthen blocks. Although, making a comparison on compressive strength between CD-CEBs and unstabilised CEBs is challenging due to their different dry densities (1.88 g/cm^3 for CD-CEBs as compared to 1.98 g/cm^3 for unstabilised CEBs), caused due to addition of low-density fibre rich cow-dung.

6.5.2 Variables influencing cow-dung stabilised compressed earth blocks (CD-CEB)

6.5.2.1 Influence of ageing of cow-dung on water resistance and strength of CD-CEB

The influence of ageing of cow-dung on compressive strength and water resistance of CD-CEB (Test series B1) is shown in Figure 6.4. The compressive strength values for differently aged CD-CEBs were found to be in a narrow range of 3.5-3.8 MPa, suggesting that the cow-dung ageing does not have a significant influence on the compressive strength of CD-CEBs. The compressive strength for CD-CEBs prepared with cow-dung of 15 day ageing duration was observed to be 3.5 MPa, as compared to other CD-CEBs with about 3.8 MPa compressive strength. These variations (+/- 10%) of compressive strength reduction observed in CD-CEBs prepared with cow-dung of 15 day ageing duration was seen to correlate strongly with the dry density variation, as shown in Figure 6.8. The variation in dry densities was found to be independent of compaction water content (Dataset 6X6), but was possibly due to the variation in soil composition or compaction process.

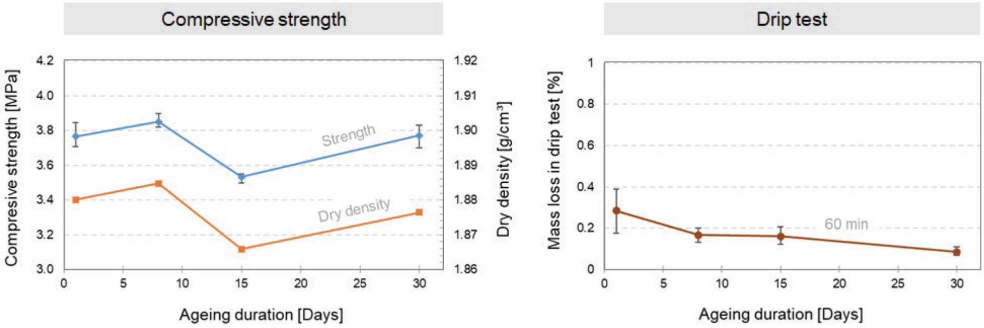

Figure 6.4: Influence of cow-dung ageing on compressive strength (left) and drip erosion during 60 min (right) of CD-CEBs prepared with compaction pressure of 2.5 MPa. The complete dataset used in plotting these results can be found in Dataset 6X6.

Similar to the influence on compressive strength, the water resistance of CD-CEBs is largely unaffected by the cow-dung ageing duration, as shown in Figure 6.4 (right). The mass loss in the drip test (after 60 min) was observed to be within the narrow range of 0.1-0.3%. The results of the drip test are also reflected in the results of the immersion test shown in Figure 6.5, where all samples irrespective of ageing duration survived the immersion test with cracks appearing only in the 2 hours of immersion. The swelling of the blocks and the size of the cracks increased with the immersion duration, leading to a partial collapse of CD-CEBs in 24 hours (the limit of immersion duration).

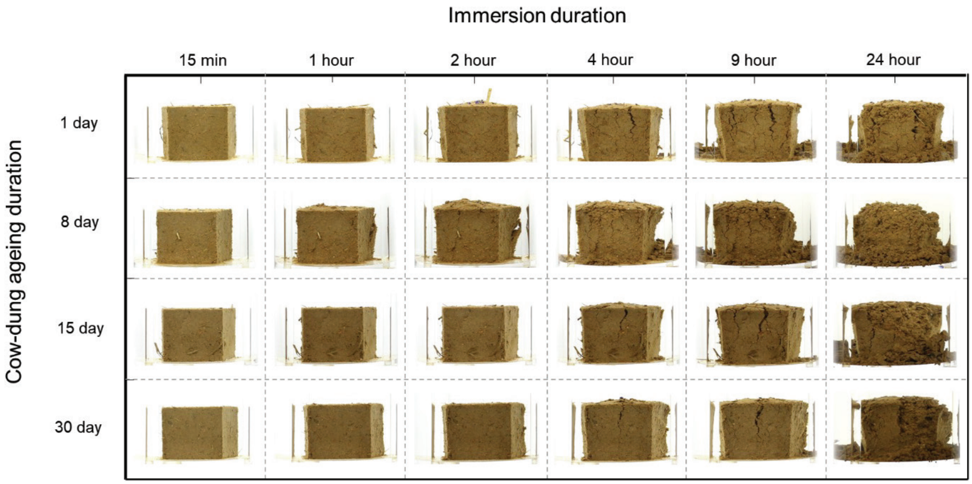

Figure 6.5: Time-lapse of disintegration of CD-CEBs of varying cow-dung ageing duration.

6.5.2.2 *Influence of ageing of soil and cow-dung mixture on water resistance and strength of CD-CEBs*

The influence of ageing of soil and cow-dung mixture on compressive strength and water resistance of CD-CEBs (Test series B2) are shown in Figure 6.6. As compared to the influence of cow-dung ageing, the influence of soil cow-dung mix ageing duration is significant on the compressive strength. Irrespective of similar densities, a significant increase in compressive strength is observed in the mixture stored for 14 days. With increase in mixture ageing duration from 1 day to 14 days, the compressive strength increased with 14% from 3.6 to 4.1 MPa. Based on the information presented in Dataset 6X7, this increase in strength is found to be independent of compaction water content and mineralogical difference in soil.

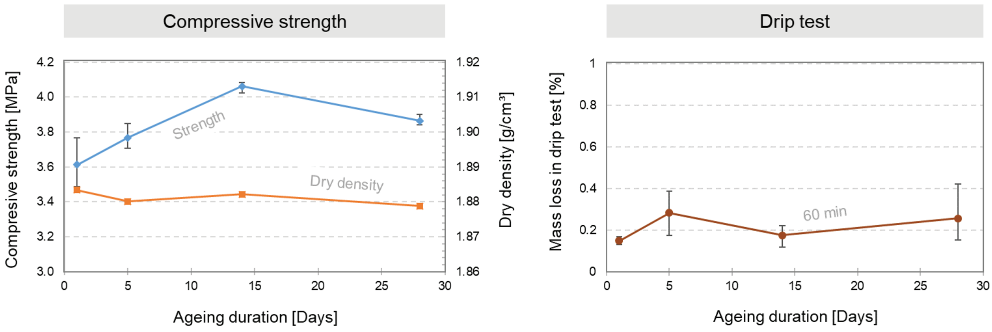

Figure 6.6: Influence of soil and cow-dung mix ageing on compressive strength (left) and drip erosion in 60 min (right) of CD-CEBs prepared with compaction pressure of 2.5 MPa. The complete dataset for plotting these results can be found in Dataset 6X7.

Similar to the improvement in compressive strength, the cow-dung ageing duration of 14 days had an influence on water resistance characteristics. This influence is clearly visible through the immersion test results as shown in Figure 6.7. The CD-CEBs prepared with a mix of 14 day ageing duration had limited disintegration after 24h of immersion as compared to other samples. However, the improved water resistance was not reflected in drip erosion test results (Figure 6.6 (right)). Similar to CD-CEBs in Section 6.4.2.1, the drip erosion of all CD-CEBs was restricted to a narrow range of 0.1-0.3%.

The soil and cow-dung mixture ageing is shown to influence the strength and water resistance characteristics of CD-CEBs, with both properties peaking in 14 days of mix ageing. While it is useful to store the mix for 2 weeks to enhance performance, it may not be feasible in areas where collected cow-dung is known to host insects that can lead to issues in storing. In some cases, such as in this study, the long ageing period for all samples was for practical reasons not possible. Interestingly, the soil cow-dung mixture showed no growth of fungus with increased ageing.

An important aspect of this study was solving the issue of the pungent smell of the cow-dung which is undesirable for some people. By ageing the soil and cow-dung mix for over 3 days, the nuisance of smell could be removed. The smell of aged mix had no distinct smell of cow-dung. While drying of CD-CEB is also known to reduce the pungent smell, wetting results in the reappearance of smell as observed in the study of Ngowi (1997). An extended period of ageing (over 3 days) not only removes the smell from the mixture, but it does not re-occur even after wetting the blocks. The reason behind the removal or reduction of smell is not entirely known and is a subject to be explored in future research. It might be possible that the volatile compound in cow-dung responsible for the smell reacts with soil or escapes the container.

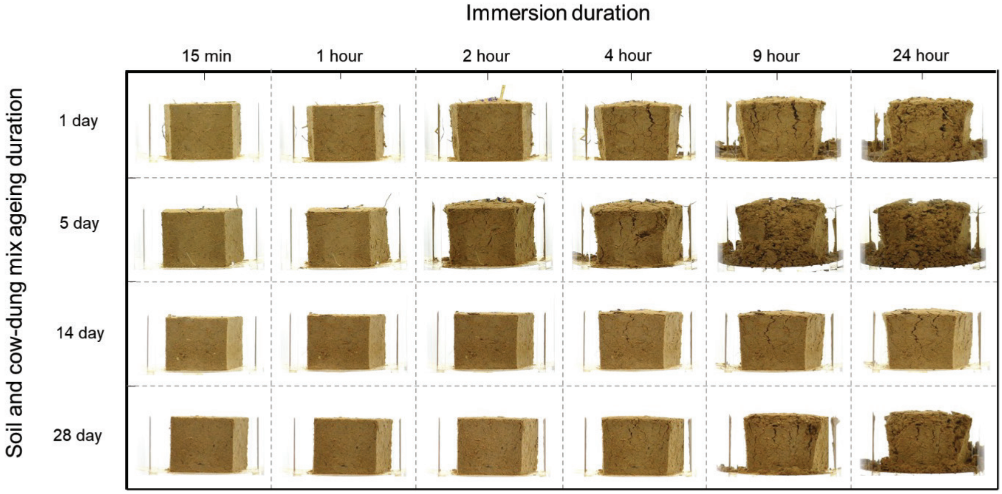

Figure 6.7: Time-lapse of disintegration of CD-CEBs of varying soil and cow-dung mix ageing duration.

The soil and cow-dung mixture ageing is shown to influence the strength and water resistance characteristics of CD-CEBs, with both properties peaking in 14 days of mix ageing. While it is useful to store the mix for 2 weeks to enhance performance, it may not be feasible in areas where collected cow-dung is known to host insects that can lead to issues in storing. In some cases, such as in this study, the long ageing period for all samples was for practical reasons not possible. Interestingly, the soil cow-dung mixture showed no growth of fungus with increased ageing.

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6.5.2.3 Influence of compaction water content on water resistance and strength of CD-CEB

The influence of compaction water content on compressive strength and water resistance characteristics of CD-CEBs (Test series B3) is shown in Figure 6.8. The compressive strength increased from 3.3 MPa to 3.8 MPa with an increase in compaction water content from 12.1 to 13.1%. The maximum strength was achieved around the optimum water content (as calculated by Harvard compaction method as shown in Appendix 6F). The strength decreased with a further rise in compaction water content to 14.2%. As expected, the strength values are directly correlated to dry density values in line with observation in Figure 6.4 and Figure 6.6. A further rise in the compaction water results in a slight decrease in dry density reaching a value of 1.88 g/cm^3, similar to the value observed for the compaction water content of 12.1%. Contrary to the previous observation, the strength values were found to increase irrespective of decreasing dry density. This is an unexpected result that could be caused by an error in manufacturing the blocks. However, by overlaying a region of compression strength (blue) and dry density (orange) values obtained through CD-CEBs in Sections 6.5.2, it is clear that these values are not just mere errors. An increase in water content beyond compaction water content of 14.2%, results in an increase in compressive strength, irrespective of relatively lower dry density values. Due to the lack of explanation behind this unusual trend, it is recommended to study the influence of water content on characteristics of CD-CEBs further in detail.

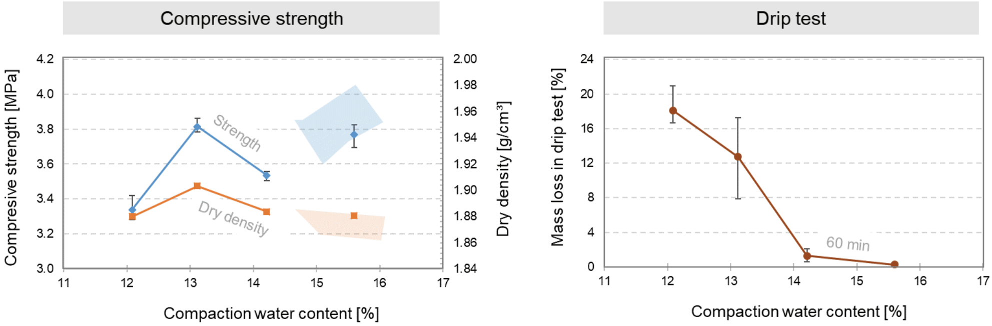


Figure 6.8: Influence of compaction water content on compressive strength (left) and drip erosion in 60 min (right) of CD-CEBs prepared with compaction pressure of 2.5 MPa. The blue and orange regions represent values of compressive strength and dry density respectively, derived from Section 6.5.2. The complete dataset for plotting these results can be found in Dataset 6X8.

The water resistance characteristics of CD-CEBs improved with an increasing compaction water content, as measured through both the drip erosion test (Figure 6.8 (right)) and the immersion test (Figure 6.9). The mass loss in drip test decreased drastically from 18% to 1.3% by increasing the compaction water content from 12.1 to 14.2%. With a further rise in compaction water content to 15.6%, the mass loss decreases again slightly and reaches a value of 0.3%. A similar trend was also found in the immersion test (Figure 6.9) where the CD-CEBs with a compaction water content of 12.1% show a significant level of disintegration beyond 15 mins. With a further rise in compaction water content, the CD-CEBs were more stable in water. The water resistance characteristics, as also observed in the drip test, reaches a plateau at higher water contents and a further increase in compaction water content has a minimal impact on the water resistance characteristics.

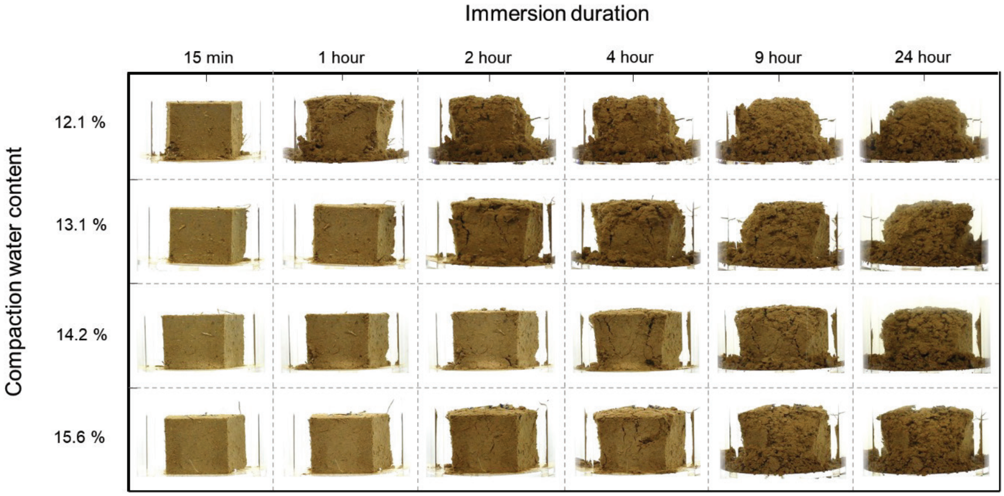


Figure 6.9: Time-lapse of disintegration of CD-CEBs prepared with varying compaction water content.

A comparison of the hardness value of freshly casted cow-dung stabilised CEBs (Dataset 6X8) and unstabilised CEBs (Dataset 4Y3) provides an important distinction between the characteristics of these blocks. The hardness value of 192 was measured on the unstabilised CEB prepared with 8.6% compaction water content. This value reduced to 69 with an increase in compaction water content to 14.2%. The unstabilised CEBs with 14.2% compaction water content were found to be too soft for practical applications. Whereas, in CD-CEBs, the hardness value decreased from 199 for 12.1% compaction water content to 179 for 15.6% compaction water content. The addition of water resulted in a slight reduction in green strength, making CD-CEBs of higher compaction water content much more suitable for practical use than unstabilised CEBs with higher compaction water content.

6.5.2.4 Influence of compaction force on water resistance and strength of CD-CEB

The influence of compaction force on the characteristics of CD-CEBs (test series B4) was studied by comparing the CD-CEBs prepared with compaction pressures of 2.5 MPa and 1.25 MPa. Unlike the CD-CEB used in understanding the influence of compaction water content which were prepared with standard soil cow-dung mixture ageing of 5 days (followed for most series), the CD-CEBs compressed with 1.25 MPa pressure were prepared with the soil-CD mix of 20 days ageing duration. The compaction water content in CD-CEB compressed with 1.25 MPa was 17.1%, much higher than CD-CEB compressed with 2.5 MPa (15.7%).

The compressive strength results presented in Dataset 6X9 reveal that a reduction in compression force also reduces the dry density and compressive strength. The strength and dry density of CD-CEB compressed with the 1.25 MPa force was 3.3 MPa and 1.84 g/cm^3, respectively, as compared to 4.1 MPa and 1.88 g/cm^3 measured for CD-CEB compressed with 2.5 MPa (soil-CD ageing of 14 days). Interestingly, the strength of 3.3 MPa was also observed in CD-CEBs (compaction water content of 12.1% and compaction force 2.5 MPa) of dry density 1.87 g/cm^3. This further reinforces the previous observations that a higher compaction water content of CD-CEB results in higher strength than the CD-CEBs compacted near optimum or drier water content.

While the influence of compaction force on strength is significant, the result of the drip test and the immersion test reveal that the compaction force has a limited impact on the water resistance of CD-CEBs (prepared with high compaction water content). The drip erosion test revealed a mass loss of 0.2% in both the CD-CEBs (Dataset 6X9). Whereas the immersion test results shown in Figure 6.10 show a slightly better performance for CD-CEBs compressed with 2.5 MPa compaction force as compared to CD-CEBs compressed with 1.25 MPa.

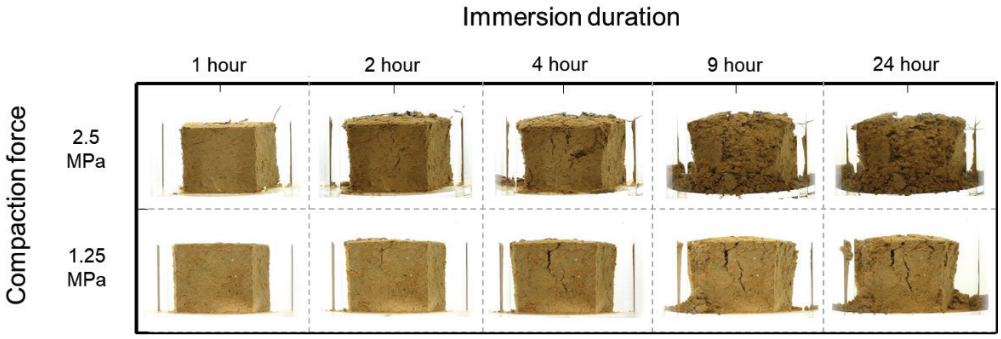


Figure 6.10: Time-lapse of disintegration of CD-CEBs prepared with varying compaction force. Note that the sample prepared with 2.5 MPa represent CD-CEB with soil-CD mix of 14 days ageing duration. The complete dataset on the influence of compaction pressure on characteristics of CD-CEB can be found in Dataset 6X9.

6.5.2.5 *Influence of drying duration on water resistance and strength of CD-CEB*

The influence of the drying duration of CD-CEBs on its compressive strength and water resistance characteristics (Test series B5) is shown in Figure 6.11. The drying of freshly cast CD-CEBs results in the improvement in strength similar to that observed in unstabilised CEBs. The improvement in compressive strength is directly related to the dry density as shown in Figure 6.11 (left). In addition, the compressive strength is also linked to residual or pre-wetting water content, where a higher pre-wetting water content is linked to lower compressive strength (Section 4.5.3, Chapter 4). The pre-wetting water content decreased from 1.9% (7 days) to 1.7% (28 days and beyond), resulting in an increase in compressive strength. The compressive strength values and residual water content were found to be consistent beyond 14 days of drying duration.

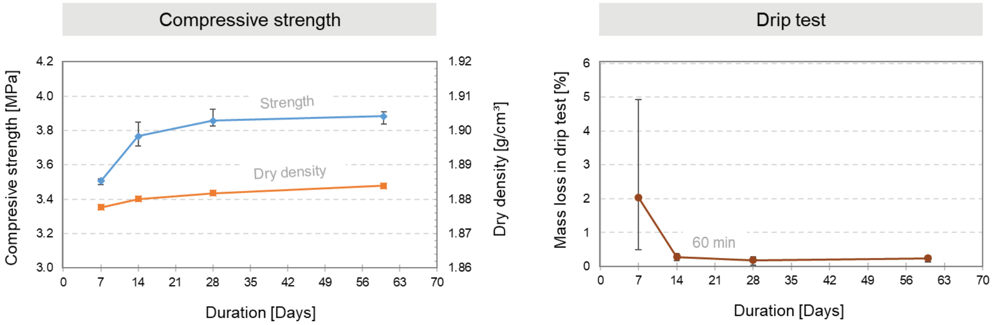


Figure 6.11: Influence of drying duration on compressive strength (left) and drip erosion in 60 min (right) of CD-CEBs prepared with compaction pressure of 2.5 MPa. The complete dataset for plotting these results can be found in Dataset 6X10.

The water resistance of CD-CEBs, as shown in the drip test in Figure 6.11 (right), improved with drying duration and was consistent beyond 14 days. The higher mass loss observed in 7 day dried

CD-CEB was mainly due to a single sample where a portion of the sample was separated from the bulk mass, as can be seen in Appendix 6K. While a longer duration in the drip test could have provided a better comparison between all samples, the immersion test provides a more clear understanding due to the higher severity of the test method. The immersion test results shown in Figure 6.12 indicate that the drying duration has an insignificant influence on the water resistance of CD-CEBs. These results agree with the results of unstabilised CEBs, where the water resistance characteristics of CEBs was consistent beyond 1 day of drying.

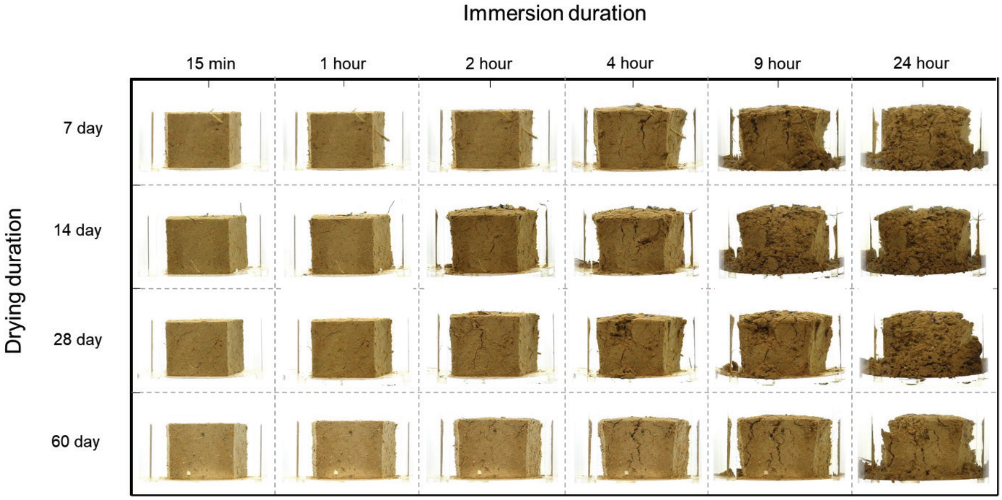


Figure 6.12: Time-lapse of disintegration of CD-CEBs of varying drying duration.

6.5.3 What makes cow-dung stabilised earthen blocks (CD-CEBs) water resistant?

The information presented in Sections 6.5.1 and 6.5.2 shows that the addition of cow-dung improves the water resistance characteristics of CEBs. However, the reason behind this improvement is unknown. Therefore, this section focuses on the question: what makes CD-CEBs water resistant. To answer this question, the separated components of cow-dung were further analysed in order to find evidence of which one contributes most for the water resistance of CD-CEBs.

6.5.3.1 Component of cow-dung responsible for water resistance of CD-CEB

The drip erosion test results of earthen blocks stabilised with the components separated from cow-dung (Test series C) is shown in Figure 6.13. Irrespective of compaction water content, the addition of fibres and MSMA increased the water resistance characteristics substantially in comparison to unstabilised specimens (Figure 6.13). However, it is the CEBs stabilised with small-sized microbial aggregates (SSMA) which shows most significant improvement of water resistance performance, even exceeding that of cow-dung stabilised CEBs. The mass loss recorded in SSMA stabilised CEBs was less than 0.3%.

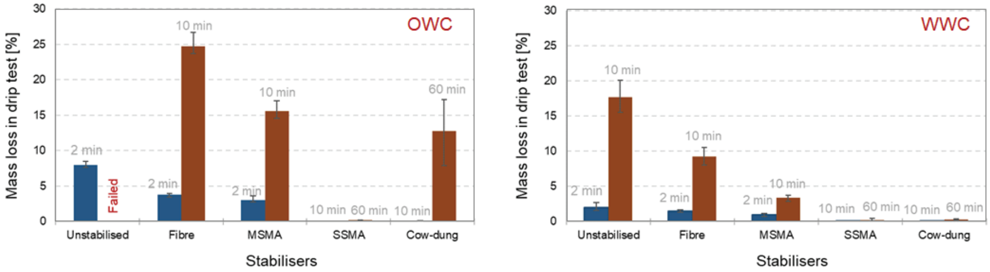


Figure 6.13: Drip erosion test on stabilised CEBs prepared with individual components of cow-dung and compared to cow-dung stabilised CEBs and unstabilised CEBs. The test was performed for short (2/10min – blue bars) and long (10/60min – brown bars) duration on samples prepared at optimum water content (OWC – left graph) and a water content significantly higher than that (WWC – right graph). All samples are prepared with a compaction pressure of 2.5 MPa. The complete dataset for plotting these results can be found in Dataset 6X11 and Dataset 6X12.

The observations in the drip test are also confirmed in the immersion test as shown in Figure 6.14. Unstabilised CEBs and CEBs with MSMA or fibres could not or hardly survive the immersion beyond 15 min. However, SSMA stabilised CEBs could resist 24h immersion with minimal disintegration, also performing significantly better than CD-CEBs. The SSMA stabilised CEBs prepared at OWC were observed to perform slightly better than the ones prepared at WWC. Hence, it can be concluded from the results presented in Figure 6.13 and Figure 6.14 that SSMAs are almost entirely responsible for the water-resistance behaviour of CD-CEBs.

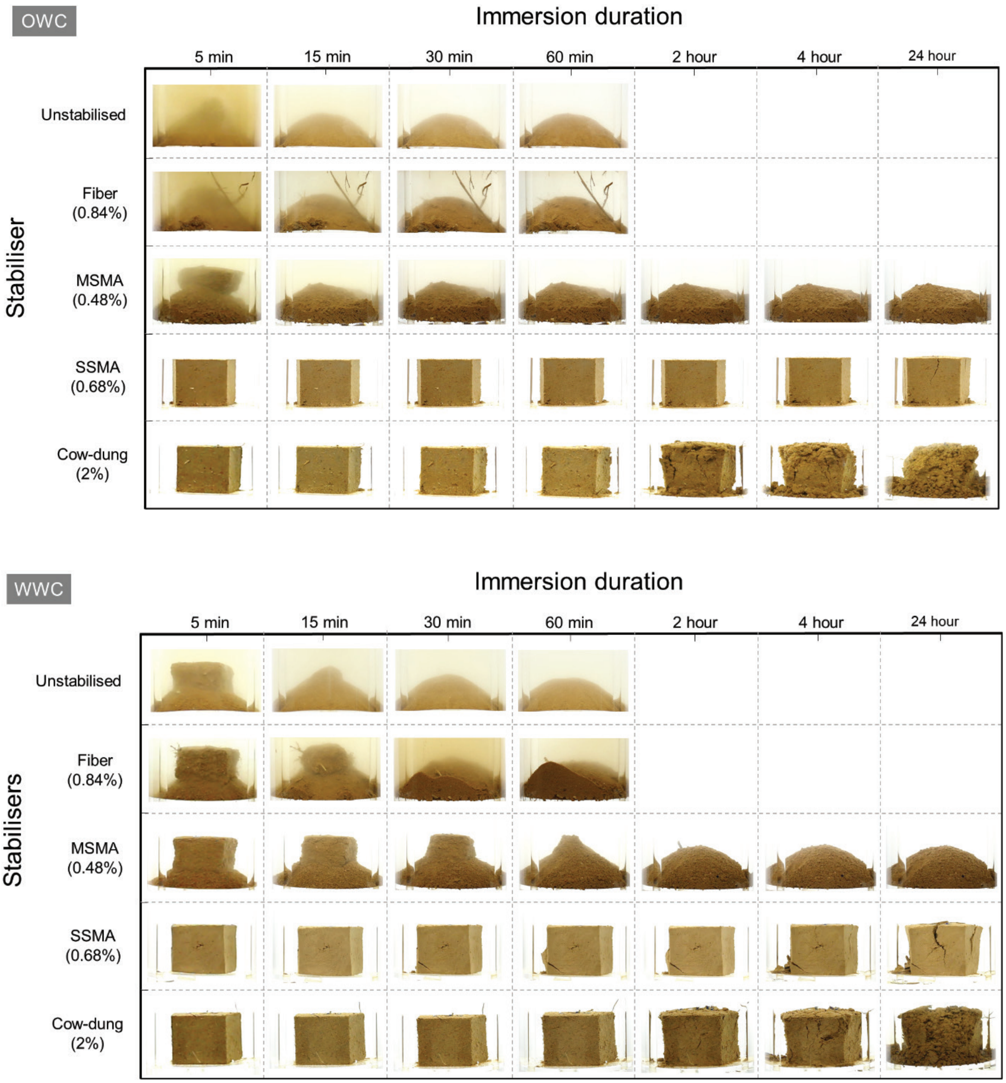


Figure 6.14: Time-lapse of disintegration of stabilised CEBs prepared with individual components of cow-dung and compared to cow-dung stabilised CEBs and unstabilised CEBs. The test has been performed on samples prepared at optimum water content (OWC - top image) and a water content significantly higher than that (WWC - bottom image). The relative percentage of stabiliser added to blocks is also indicated. The role of SSMA in providing water-resistance to cow-dung can be clearly observed.

The result presented in Figure 6.13 and Figure 6.14 proves that the popular notion of fibres being mainly responsible for water resistance is incorrect. In addition to water resistance, the information on strength and other physical characteristics of CEBs can be found in Dataset 6X11 and Dataset 6X12.

The various components of cow-dung were also analysed by ESEM. The microstructure of these components can be seen in Figure 6.15.

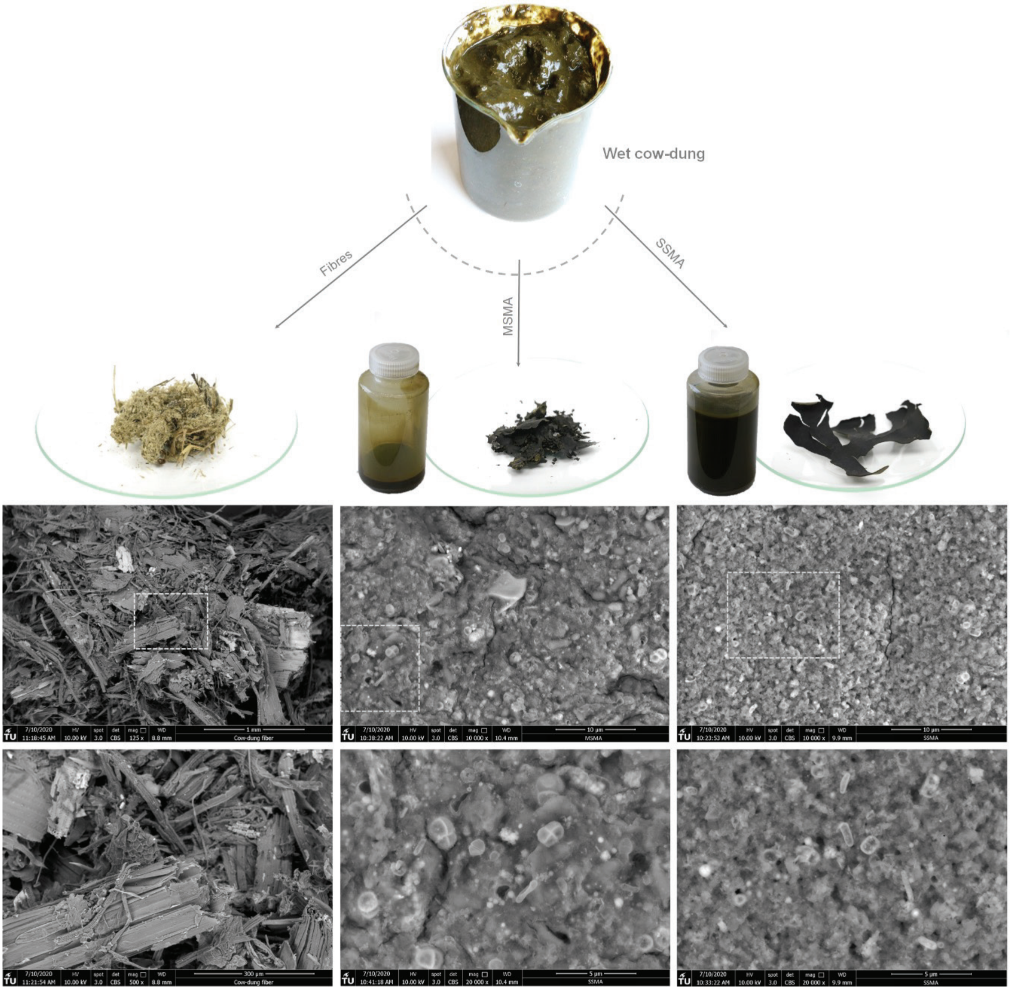


Figure 6.15: ESEM of components of cow dung: Fibres (left pictures), medium-sized microbial aggregates (MSMA – middle pictures) and small-sized microbial aggregates (SSMA – right pictures). Top and bottom ESEM pictures 125x (fibre)/10000x and 500(fibre)/20000x magnification respectively. The information on EDS carried out on these components is available in Appendix 6L.

The undigested fibres present in cow-dung represent 42% of the solid mass in cow-dung. These fibres as seen in Figure 6.15 and Figure 6L2 (Appendix 6L) reveal the porous nature of these elongated fibres, similar to the fibres (from cow-dung) observed in the study of Ormaechea et al. (2018). The EDS analysis (in Appendix 6L) show that the undigested fibres of cow-dung are composed predominately of carbon, oxygen and silica elements, with traces of magnesium, phosphorous, sulphur, chlorine and calcium that could have been due to some microbial aggregates attached to the fibres.

Microbial aggregates represent the remaining 58% of solid mass in cow-dung. Bacteria of different shapes and sizes can be seen in MSMA and SSMA (Figure 6.15). Several spherical or rod-shaped structures of about 1 µm are observed especially in SSMA, similar to bacteria observed in the study of Rao et al. (2021). Both MSMA and SSMA share elemental characteristics with fibres but contain a higher quantity of magnesium, phosphorous, potassium, sulphur, choline and calcium (Appendix 6L). These elements have been also reported widely in studies related to cow-dung (Garg & Mudgal, 2007; Graham, 2004; Gupta et al., 2016; Millogo et al., 2016).

6.5.3.2 Characteristics of small-sized microbial aggregates (SSMA)

As SSMA are responsible for water resistance characteristics of CD-CEBs, they were further investigated (Test series C). The particle size analysis revealed that the SSMAs have a mean diameter of 0.5µm. Moreover, the ESEM and EDS provide information on the morphology and elemental constitution of SSMA (such as the presence of C, O, Mg, P, S, Ca, Cl). The specific surface of SSMA was found in the range of 1.7-2.2 m^2/g, indicating that they have a non-layered structure and low cation exchange capacity. In contrast, the clay minerals used in this study have a specific surface of 52 m^2/g. In conjunction with the observation of the ESEM scan, it can be assumed that SSMAs are spherical or rod-shaped aggregates of relatively low surface area.

Zeta potential measurement conducted on SSMAs, as shown in Figure 6.16, indicate that SSMA are negatively charged aggregates. A decrease in pH results in an increase in coagulation, which may also facilitate interaction with aggregates present in the soil. There might be a possibility to convert negative charge on SSMA into positive charge below a pH value of 2, which could facilitate the interaction between the SSMA and clay surface further. However, achieving a pH of less than 2 is only possible through the addition of chemicals, which is neither economically feasible nor desirable in earthen construction projects.

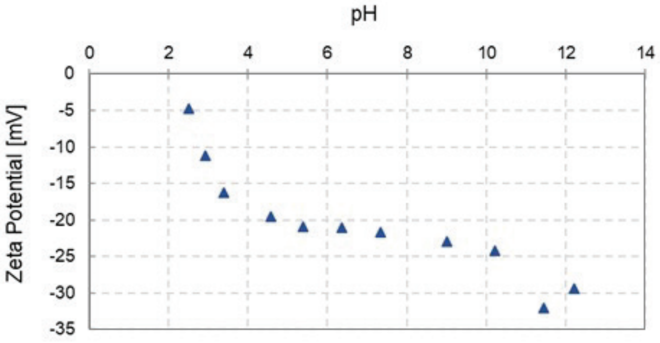


Figure 6.16: Zeta potential measurement on diluted SSMA solution with varying pH values. The complete dataset together with information on the effect of concentration on zeta potential is available in Dataset 6X13.

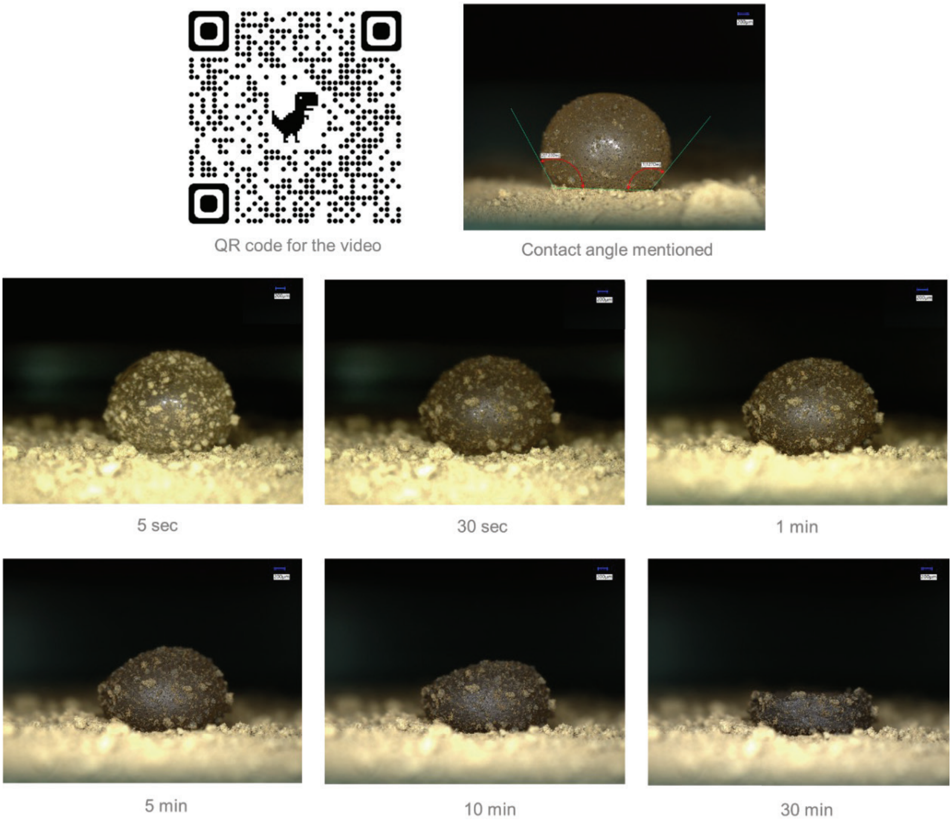
The pyrolysis-gas chromatography mass spectrometry (py-GC/MS) conducted on SSMA shows the presence of over 150 compounds (Dataset 6X14). SSMA is rich in volatile fatty acids of different chain lengths. The relative peak (as determined by py-GC/MS), type of fatty acid, chemical formula and some characteristics of dominant compounds is shown in Table 6.4.

Table 6.4: Dominant compounds identified through pyrolysis-gas chromatography mass spectrometry (py-GC/MS) conducted on SSMA. The complete dataset from the test is available in Dataset 6X14. The information on classification, chemical formula and characteristics are drawn from Pubchem (National Library of Medicine, 2022)

Compound name	Relative Peak area (through py-GC/MS)	Classification (type of fatty acid)	Chemical formula	Characteristics
Acetic acid	18.47	Short chain	CH_3COOH	Antibacterial and antifungal properties, pungent smell
Butanoic acid	9.59	Short chain	$CH_3CH_2CH_2COOH$	Pungent smell
Octadecanoic acid	8.57	Long chain	$CH_3(CH_2)_{16}COOH$	Hydrophobic
n-Tetracosanol-1	8.19	Very long-chain	$C_{24}H_{50}O$	
n-Hexadecanoic acid	5.63	Long chain	$C_{16}H_{32}O_2$	
Propanoic acid	5.12	Short chain	CH_3CH_2COOH	Pungent smell

The dominant compound (55% of the total composition) identified through the py-GC/MS are acetic acid, butanoic acid (butyric acid), octadecanoic acid (stearic acid), n-Tetracosanol-1, n-Hexadecanoic acid (palmitic acid) and propanoic acid. Volatile fatty acids in cow-dung have been widely reported in the literature, with many researchers finding the abundance of acetic, propionic and butyric acids and other compounds that are also detected in this study (Ishler, 2016; Lee et al., 2018; Mao et al., 2015; Page et al., 2014; Sun et al., 2008). The bacteria in cow-dung are responsible for converting grass fibres into volatile fatty acids (Ronald Watson, 2015). For example, short-chain fatty acids are known to be produced through the digestion of dietary fibres by gut bacteria (Brody, 1999; Canfora et al., 2015). Acetic acid, butanoic acid and propanoic acid have a pungent smell (National Library of Medicine, 2022) and are at least partly responsible for the unpleasant smell of cow-dung.

Fatty acids such as butyric acid are commonly available in food products such as butter and oil. One of the dominant fatty acids, octadecanoic acid, has been used with silica nanoparticles to prepare water-resistant superhydrophobic coatings (Heale et al., 2018). These examples indicate that fatty acids are capable of repelling water and therefore, show hydrophobic behaviour. Contact angle test performed on the SSMA powder confirm its hydrophobic behaviour. A contact angle of 120°- 130 ° was measured as shown in Figure 6.17. Once the droplet was placed over the SSMA, images were taken in time. The SSMA powder covers the surface of the droplet and maintains a hydrophobic angle for an extended duration of time. The droplet does not percolate into the material but collapses. Therefore, the SSMA also acts as a barrier to water ingress. The video available through QR code in Figure 6.17 show another contact angle test where water droplets were found to slide down the SSMA until a stable droplet was achieved which had a contact angle of about 120°. Hence, it can be expected that the presence of fatty acid in SSMAs, make the SSMA stabilised CEBs and CD-CEBs water resistant. The presence of fatty acid in soils has been shown to impart water repellence behaviour in soil (Doerr et al., 2000).


QR code for the video

Contact angle mentioned

5 sec

30 sec

1 min

5 min

10 min

30 min

Figure 6.17: Contact angle test showing the hydrophobic behaviour of SSMA. The QR code redirects to a video link showing the contact angle test conducted on SSMA using a different setup consisting of a larger drop size and DSLR camera. The video includes the contact angle test on clay minerals (kaolinite and bentonite) to compare the hydrophobicity of SSMAs with other clay minerals. Video link: https://youtu.be/Jmd_ZPqeDz8

Small-sized microbial aggregates (SSMA) can be considered as organic hydrophobic non-layered clays with a low specific surface area. Their small quantity of 0.68% in the soil is enough to provide the water resistance to the compressed blocks. Studies have also identified bacteria in cow-dung that are capable of producing extracellular polymeric substance (EPS) which could facilitate interaction with each other and the soil (Rao et al., 2020, 2021). The interaction of SSMA and cow-dung with soil will be discussed in Section 6.5.5 in detail using the additional insights gained in the next section.

6.5.4 Practical considerations for the application of CD-CEBs

Cow-dung has been used in earthen construction for several centuries. The practical application of cow-dung in earthen construction could be improved using the insights gained in the previous sections. This section presents various routes to improve the efficiency of cow-dung stabilised CEBs. Additionally, it answers important questions regarding the applicability of results presented in this thesis in different locations and contexts. Moreover, questions important for the valorisation of cow-dung in earthen construction are discussed.

6.5.4.1 Can removing the fibres or increasing microbial aggregate improve water resistance of stabilised earthen blocks?

The CEBs produced with SSMA have shown better water resistance than all CD-CEBs (Figure 6.14 and Figure 6.18). The extraction of SSMA through centrifugation in a lab is a time consuming and expensive process which cannot be reproduced on a site using locally available resources. While extraction of SSMA is extremely challenging, it is still possible to extract microbial aggregates (SSMA+MSMA) from fibres using a sieve of 63μm. Therefore, experiments were also conducted by adding the microbial aggregates solution to the soil, making CD-CEBs but with no fibres (Test series D1). For optimising the water content based on previous results of SSMA, the samples were compacted at a water content slightly higher than optimum water content. Moreover, compacting the mix closer to optimum water content makes them compatible with manual compressed block-making machines used in actual practice (use of CSEB machines for compacting wet soil may cause damage to the machine). It should be noted that the solid content of SSMA+MSMA in the mix was 1.16% (corresponding to 2% cow-dung).

The results of the immersion test on CD-CEBs without fibres (or with SSMA+MSMA) is shown in Figure 6.18. Removal of fibres from cow-dung has a positive influence on the water resistance characteristics. As compared to CD-CEBs, where the first cracks were observed in 2 hours, the crack in CD-CEB without fibres appeared only in 9 hours. It should be noted that the disintegration at the bottom of the block is caused due to non-homogenous compaction of the block making the bottom edges fragile. There are multiple possibilities to avoid this issue, such as adding slightly more water or increasing compaction force or reducing the quantity of mix. The mass loss in the drip test on CD-CEB without fibres was measured to be 0.3% after 60 min of erosion (refer Dataset 6X15). This value is quite similar to the value obtained for CD-CEBs, indicating that the drip test is unable to capture the performance of highly water-resistant samples due to the low severity of the test and limited test duration. The compressive strength was found to be 3.6 MPa, which was lower than CD-CEB, even though the dry density was much higher (1.94g/cm^3 as compared to 1.88 g/cm^3 for CD-CEBs).

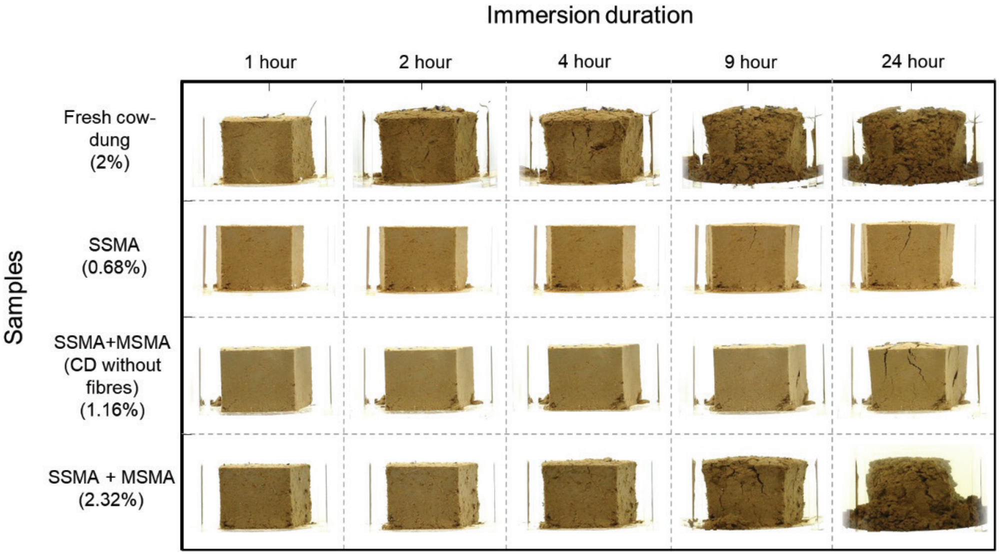


Figure 6.18: Time-lapse of disintegration of stabilised CEBs with SSMA (0.68%), and cow-dung without fibres-SSMA+MSMA (1.16%) and SSMA+MSMA (2.32%).

In addition to removing fibres from cow-dung, experiments were also conducted with cow-dung soil mixture with doubled microbial biomass, MSMA+SSMA (2.32%) (Test series D2). While it was anticipated that doubling of microbial biomass could improve water resistance further, the results of the immersion test on these CEBs, shown in Figure 6.18, proved otherwise. As compared to other CEBs shown in Figure 6.18, the water resistance characteristic of CD-CEBs with extra microbial aggregates was inferior but similar to that of CD-CEB. Therefore, the water resistance characteristics of CEBs stabilised with cow-dung or its component are therefore seen to be significantly dependent on the amount of fibres, rather than the quantity of microbial aggregates (above a certain threshold). More information on the CEBs discussed in this section can be found in Dataset 6X15. In addition to their water resistance performance, the practical use of CD-CEBs with extra microbial aggregate is also restricted by the fungal growth in the sample within 3 days of ageing as visualised in Appendix 6G. Therefore, unlike other mixtures, this mixture is susceptible to microbial growth during storage.

The results above show that irrespective of the quantity of microbial aggregates (tested in a narrow range), the disintegration is facilitated by the presence of fibres. Fibres act as an active water transport network that facilitates water ingress through the sample. The dried fibres also result in volumetric swelling as seen in Figure 6.18 leading to the formation of cracks, providing extra access for water ingress.

Removing the fibres from cow-dung is advantageous for water resistance performance. However, the fibres are known to provide several benefits such as preventing shrinkage cracks and improving flexural strength (Laborel-Préneron et al., 2016). Moreover, the extraction of fibres through sieves can be time-intensive and increase the overall cost of construction. Therefore, a careful assessment should be carried out on the pro and cons of fibre extraction before implementing it. Instead of removing fibres, reducing them might improve the water resistance characteristics. However, further experiments are required to investigate this hypothesis.

6.5.4.2 Is it better to use dry cow-dung or wet cow-dung?

Cow-dung is a stabiliser that has been used for several centuries. However, knowledge on whether fresh/wet or dry cow-dung was used in traditional earthen construction is lost (Graham, 2004). All the previous scientific studies on cow-dung utilised dry cow-dung, with exception of the earliest study by Ngowi (1997) which utilised wet cow-dung.

To understand the difference between fresh and dried cow-dung, CD-CEBs were prepared with dry cow-dung (Test series E). The results of the immersion test of CD-CEB (dry cow-dung) shown in Figure 6.19, which gives clear evidence that dry cow-dung is not as effective as wet/ fresh cow-dung. CD-CEBs with dried cow-dung did not survive 1h of immersion. The mass loss in the drip test after 10 min was measured to be 1%, which was higher than the mass loss measured in CD-CEBs (wet dung) after 60 min (refer Dataset 6X15). The mass loss of CD-CEBs with dry cow-dung after 60 min was measured to be 23.7%. Hence, use of wet cow-dung provides 80 times more water resistance than dried cow-dung (measured through drip test).

Additional mixes were prepared with dried SSMA power and dried microbial aggregate (MSMA+SSMA) powder to study if the drying of microbial aggregates is responsible for poor water resistance performance of CD-CEBs made with dry cow-dung. The results presented in Figure 6.23 provide clear evidence that drying microbial aggregates before mixing them with soil does not facilitate water resistance characteristics. Their water resistance characteristic was slightly better than the CD-CEBs made with dried CD, possibly due to the absence of fibres.

The reason behind the significant difference in properties of dry and wet cow-dung is proposed based on the difference in mean sizes of wet SSMA and SSMA+MSMA (particles in suspension) and powdered SSMA and SSMA+MSMA (produced by grinding dried SSMA through ball milling). When the fresh SSMA were dried and ground, the mean diameter measured was roughly 10 times more than the fresh SSMA (Figure 6.20). Similarly, dried microbial aggregates (SSMA+MSMA) have a mean diameter of roughly 4 times more than that of fresh microbial aggregates. The mean diameter of powdered samples was measured after excessive grinding, followed by stirring the powder in water for 48h. Therefore, once dried it is extremely challenging to produce microbial aggregate with a similar mean diameter as their wet state. It can be hypothesised that when cow-dung dries, the SSMA (and MSMA) coagulate and reduce the effective surface area of aggregates significantly. The reduced surface area and increased size of microbial aggregates could narrow their spatial distribution in the block and reduce their interaction with other particles resulting in lower efficiency.

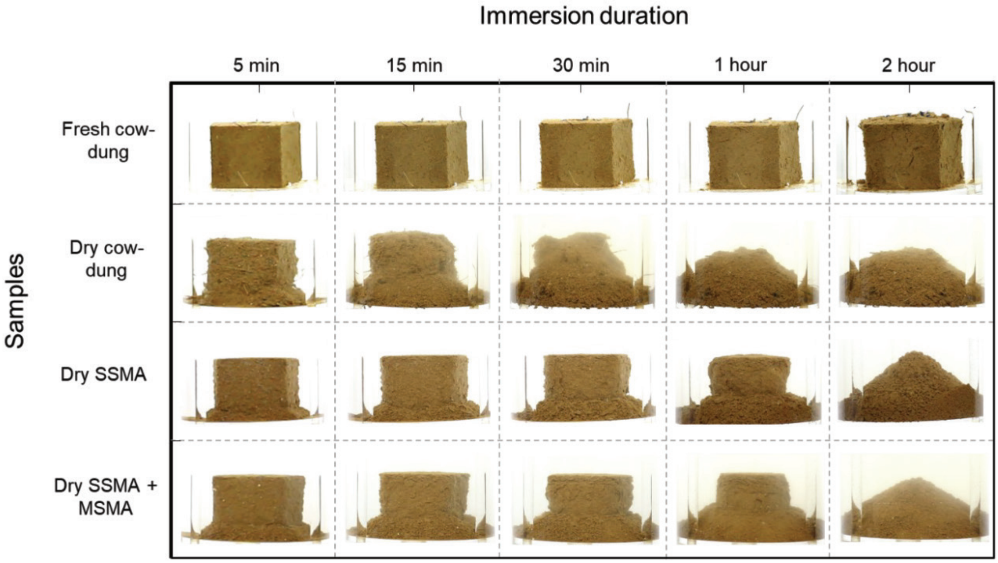


Figure 6.19: Time-lapse of disintegration of stabilised CEBs prepared with fresh/wet cow-dung, dry cow-dung, and various combinations of dried microbial aggregates.

One major difference between wet cow-dung and dry cow-dung is the presence of urine in the fresh cow-dung (at least the one collected for this study had urine mixed with dung). Animal urine has been used in traditional earthen structures for reducing permeability and impact resistance (ITDG, 1999). Thus, urine might play an important role in the property of fresh/wet cow-dung. However, the detailed investigation on the influence of cow-urine on CD-CEBs is beyond the scope of this research.

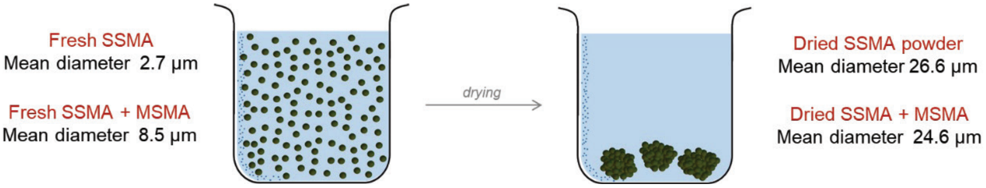


Figure 6.20: The variation in the mean diameter of SSMA and SSMA+MSMA in a wet state (particles in suspension) and powdered state (produced by grinding dried SSMA through ball milling.

6.5.4.3 How to ensure consistent quality of cow-dung? Would cow-dung in every location of the world provide better water resistance?

One of the major challenges in extrapolating the results reported in this study is the non-standardised quality of cow-dung used in the production of stabilised earthen building materials. Standardisation of stabiliser and production process is particularly important for mass housing projects

(Chapter 3). However, the variation in the quality of cow-dung is eminent. The microbial communities and the formation of volatile fatty acid are known to depend on the composition of feed (Hagey et al., 2019; Lee et al., 2018; Mao et al., 2012; Shanks et al., 2011; van Vliet et al., 2007). The influence of feed on the microbial communities in the cow was found to be more significant than the location (Shanks et al., 2011). Thus, unless the composition of the feed is standardised, the volatile fatty acids and characteristics of cow-dung will vary. Moreover, the type of cow (e.g. native, beef, milk) and the presence of some microbial species have an influence on the concentration of fatty acids (Lee et al., 2018; Mao et al., 2012). Irrespective of variation in feed, microbial communities in gut, location and climatic conditions, volatile fatty acids reported in the various study shows the abundance of acetic, propionic, butyric acids and other compounds that are also detected in this study (Ishler, 2016; Lee et al., 2018; Mao et al., 2015; Page et al., 2014; Sun et al., 2008). Thus, irrespective of location, there will still be similarities in the dominant composition of volatile fatty acids found in cow-dung.

The quality of cow-dung collected in different time duration or seasons can also have an impact on the characteristics of CD-CEBs sourced from the same farm. Hence results from different collection batches are compiled in Figure 6.21 to illustrate the slight variation in water resistance characteristics of CD-CEBs (Test series F).

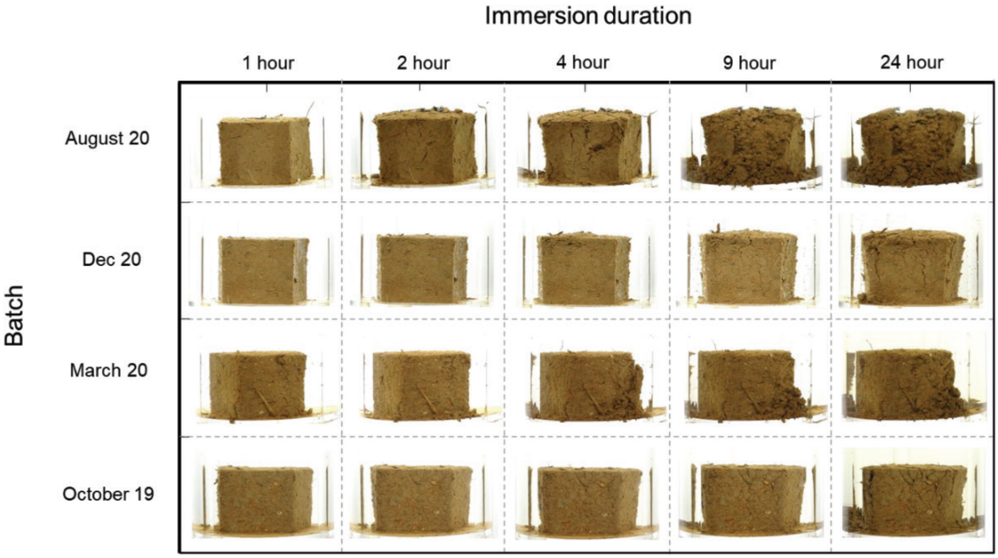


Figure 6.21: Time-lapse of disintegration of CD-CEBs prepared with dung collected in different batches/ season/duration. The CD-CEBs prepared with cow-dung collected in August and December of 2020 are compacted with 2.5 MPa pressure, whereas other March 20 and October 19 CD-CEBs were prepared with 2 and 1.7 MPa compaction force. These details are available in Dataset 6X16.

The batch of cow-dung (month of collection) has an influence on the water resistance characteristics of CD-CEBs. It should be noted that only the CD-CEBs with cow-dung from the August and

December 2020 batch were compressed with 2.5 MPa force. CD-CEBs from cow-dung collected in March 2020 and October 2019 were prepared with 2 MPa and 1.7 MPa force respectively, as the compaction process was not standardized then. However, the compaction process has a limited impact on water characteristics and hence, the variation in compaction pressure is assumed not to affect the water resistance characteristics. Moreover, both these CEBs (March 20 and Oct 19) were tested after a long period of drying. However, drying duration over 7 days does not have much influence on the water resistance characteristics. Figure 6.21 shows that the CD-CEB prepared with cow-dung collected in August 2020 had inferior performance than all other CD-CEBs. The CD-CEB prepared with cow-dung collected in December 2020 shows the best water resistance characteristics. This variation can be due to the difference in concentration of volatile fatty acids but could also be related to fibres that have a significant influence on water resistance characteristics. The temperature during the collection of cow-dung could also have an influence on its characterises and opens up many questions for future research. The season or the batch also has an influence on the strength. A strength of 4.2 MPa was achieved in December 20, higher than 3.8 MPa in August 20 (refer Dataset 6X16).

The feed of cow-dung has a major impact on the gut microbial communities and the formation of volatile fatty acids. The water resistance in the cow-dung is dependent on the volatile fatty acids which will be formed in all cows (irrespective of location) as they are produced during the metabolism of feed cows eat. Hence, improvement in water resistance characteristics by the addition of cow-dung is expected globally. However, the degree of improvement is expected to depend on the feed, concentration of fatty acids, microbial communities in gut and quantity of fibres. The type of soil would also play a significant role in the water resistance characteristics of CD-CEBs.

6.5.4.4 Can the results of this study generalised for soils globally?

In addition to the variation in cow-dung with location, the variation in soil may have even a greater influence on the water resistance characteristics. While a study on natural soils sourced from different locations would have been ideal, it was not within the scope of this study. A limited test series was conducted on artificially created soils with varying soil components (Test series G). The results of water resistance and strength performance are discussed in the following sub section.

(a) Influence of soil type on water resistance of CD-CEBs

The result of immersion tests conducted on various artificially prepared soils is shown in Figure 6.22. It is seen that the presence and type of clay minerals have a major influence on the water resistance characteristics of CD-CEBs. The CD-CEBs prepared with bentonite/sand mixture start disintegrating faster than the CD-CEB made with natural soil. These results were contrary to the performance of bentonite/sand mixture without cow-dung which performed extremely well in immersed conditions (discussed in Section 4.5.5, Chapter 4). An additional test series was conducted to understand the poor performance of cow-dung stabilised bentonite and CEBs. These results are presented in Appendix 6M. CEBs prepared with bentonite soil and fibres proved that the fibres are responsible for the poor performance of bentonite rich soil when stabilised with cow dung. This again reinforces the negative role of fibres in water resistance characteristics. It should be noted that with increasing immersion duration, the colour of the surrounding fluid changed to yellowish. The yellowish water is probably a result of leached microbial aggregates which have shown the same colouration when diluted with water.

The CD-CEBs prepared with kaolinite soil performed extremely well with the first cracks appearing in 5 days. The test was not continued beyond 5 days as large cracks were already formed in the CEBs. Based on the performance of kaolinite and bentonite clay-rich soil, it can be inferred that the activity of clay (which is determined by its surface area and cation exchange capacity) plays an important role in determining its interaction with cow-dung and overall water resistance. The lower cation exchange and low surface area, thus low-activity of clay (such as in kaolinite clay) is favourable to cow-dung stabilisation. However, clays with higher activity such as bentonite (and the clay in the natural soil used in this study) are susceptible to disintegration upon immersion. Hence, cow-dung stabilisation is favourable to soils with low activity and low swelling potential. With an increase in the swelling potential of soil minerals, the efficacy of stabilisation decreases. It should be noted that the quantity of these components in soil could also have a significant impact on the water resistance characteristics and future studies should explore these variables.

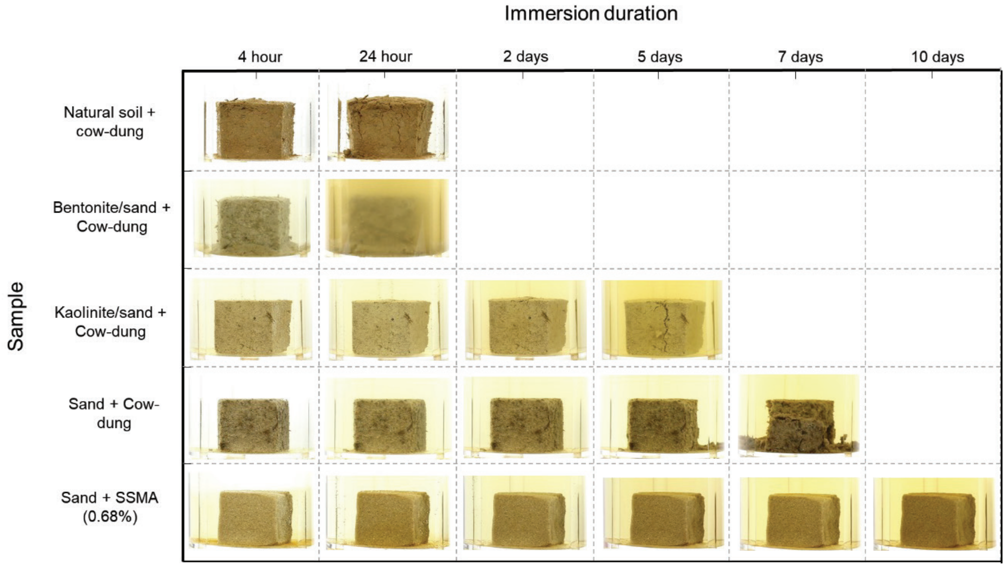


Figure 6.22: Time-lapse of disintegration of CEBs prepared with different types of soil minerals. The cow-dung used in bentonite and kaolinite rich soil was collected in December 2020. Therefore, the comparison is drawn with CD-CEBs from Dec 2020 batch. The CD-CEBs with sand and SSMA were prepared with cow-dung from August 2020 batch.

Low activity clay as a component of CEBs is favourable for water resistance behaviour. However, its absence has even a greater impact. The cow-dung stabilised sand block resisted immersion for over 2 days without any disintegration (Figure 6.22). The disintegration started on the 4th day and a significant mass disintegrated after 7 days. As known from the previous discussion, fibres aid to disintegration. Therefore, a block was also prepared with SSMA (0.68%) and sand. These blocks could survive disintegration for 10 days with no erosion (Figure 6.22). The only variation observed in the immersion setup was the colouration of water caused due to leached microbial aggregates.

(b) Influence of soil type on strength of CD-CEBs, and its interplay with water resistance

The strength of CD-CEBs prepared with natural Dutch soil was measured to be 4.2 MPa, higher than CD-CEBs prepared with kaolinite (1.7 MPa) and bentonite (1.2 MPa) (refer Dataset 6X17). The lower strength of artificially created soil could be due to poor grading and lower cohesion (especially for kaolinite) than clays present in natural soil but need further investigation. Although it may seem that cow-dung stabilised sand blocks and SSMA stabilised sand blocks would prove to be excellent in earthen construction (due to their water resistance performance), they are in fact not due to the extremely low strength and fragile nature of blocks (could be broken by crushing with mild force from hand). No compression test could be performed on both these blocks, due to this very low strength. The drip test conducted on these samples shows the appearance of a groove due to the impact of falling rain on weakly bonded sand particles (Appendix 6N). Figure 6.23 shows the relationship between compressive strength and water resistance of all types of soil minerals. It can be observed that with an increase in water resistance performance, the compressive strength generally reduces. This indicates that while the absence of clay may favour water resistance, clays are required for the strength of earthen materials.

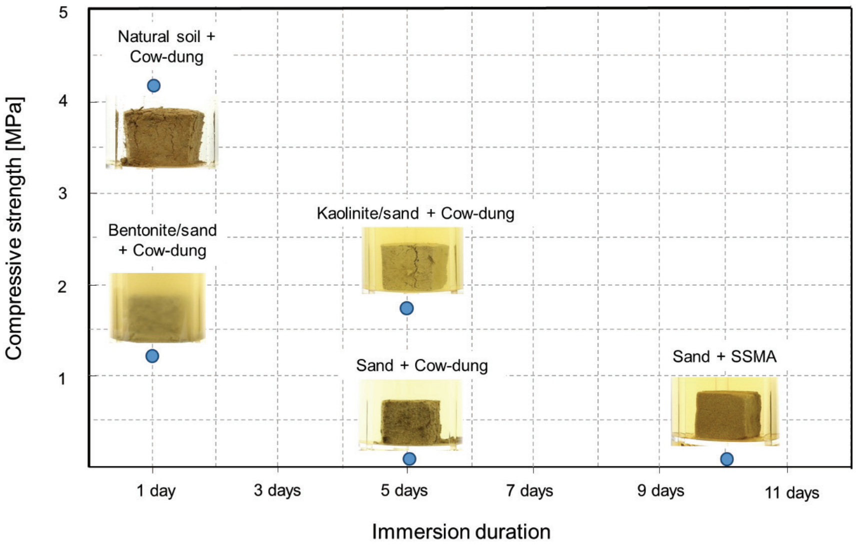


Figure 6.23: Relationship between compressive strength and water resistance test (results from immersion test). The compressive strength values of sand+ cow-dung and sand+SSMA could not be measured due to their fragile nature.

Unlike the influence of cow-dung on strength of CEBs made with natural Dutch soil and bentonite rich soil, the strength of CD-CEBs prepared with kaolinite rich soil improved drastically with the addition of cow-dung. The compressive strength was found to increase by 17 times (from 0.1 MPa for unstabilised CEBs to 1.7 MPa with cow-dung stabilisation). A similar observation of the positive impact of cow-dung on strength of kaolinite rich soil was observed Rao et al. (2021), Hence, the interaction of cow-dung and its component varies significantly with the type of soil mineral.

In order to understand the interaction of cow-dung and its components with various soil minerals, ESEM was conducted. To get clear images without the interference of other unwanted particles (such as fibres and bigger fragments of MSMA), samples were also prepared with SSMA added to kaolinite, bentonite and sand ESEM was also conducted on cow-dung stabilised sand. The images from ESEM are shown in Figure 6.24. The SSMA particles attached to bentonite clay can be seen in the form of agglomerated aggregates (Figure 6.24 (a)), whereas in kaolinite, agglomeration is not observed and SSMA is shown to coat clay particles more homogeneously (Figure 6.24 (b)). In the cow-dung stabilised sand blocks, the fibres are clearly visible (Figure 6.24(c)). The sand particles are bonded together with microbial aggregates, which can be seen more clearly in Figure 6.24(d). The microbial aggregate appears to form bridges between the sand particles. These observations are explored further in Section 6.5.5.

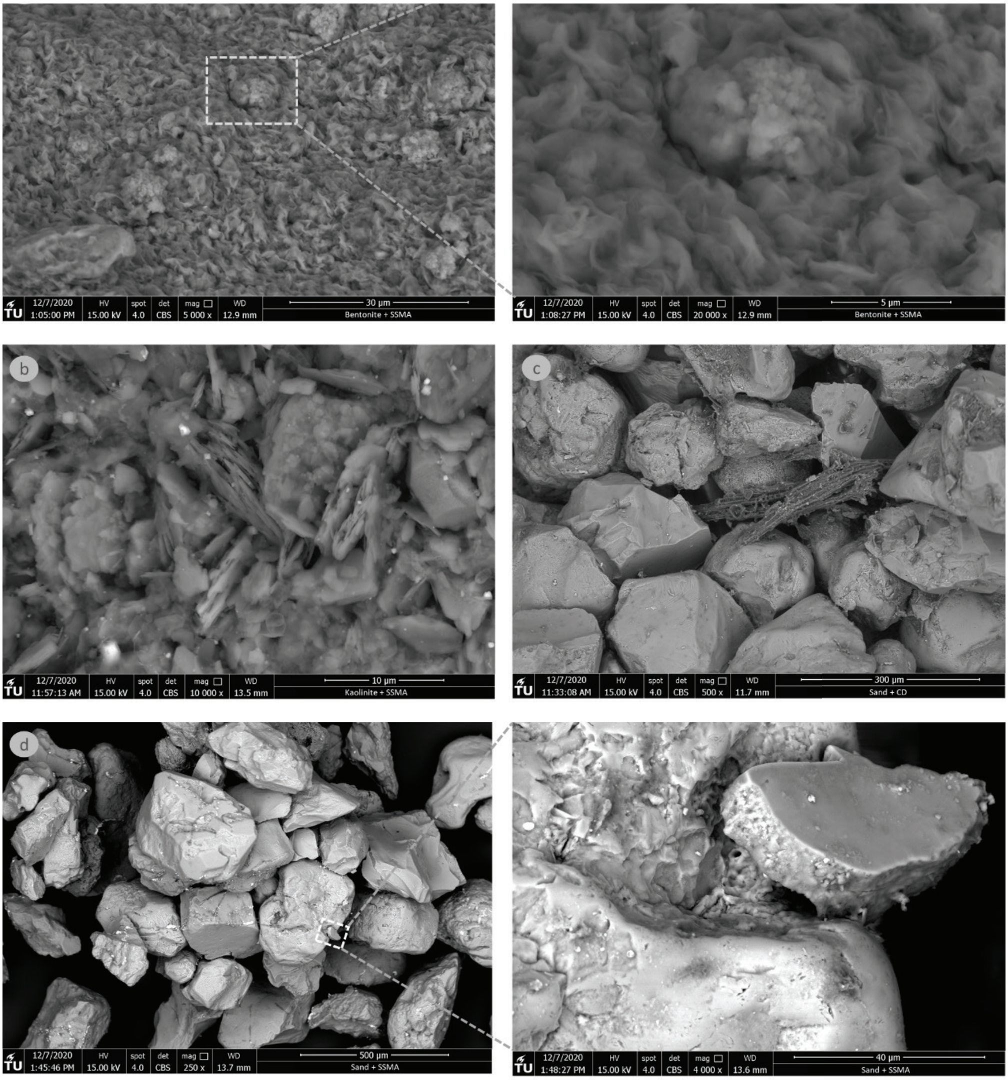


Figure 6.24: ESEM images of (a) Bentonite + SSMA, (b) Kaolinite +SSMA, (c) Sand + Cow-dung and (d) Sand + SSMA.

6.5.4.5 What is the impact of recycling of CD-CEBs on its water resistance characteristics?

The disintegrated CD-CEBs were collected after the immersion test and dried with an air dryer to reach a desirable consistency and compaction water content (Test series H). The water resistance of these recycled CD-CEBs was tested through immersion, as shown in Figure 6.25. The recycled CD-CEB does not resist immersion as much as the original CD-CEBs and disintegrates after 2 hours. However, its performance is slightly better than the CD-CEBs prepared with dry cow-dung and significantly better than the unstabilised samples which disintegrate within 15 min. Therefore, recycling of CD-CEB is still advantageous but results in decreased water resistance characteristics. However, it is still a better alternative than using unstabilised blocks. The reason behind the reduction in water resistance of recycled CD-CEB is not explored in detail in this study and could be a topic for future studies.

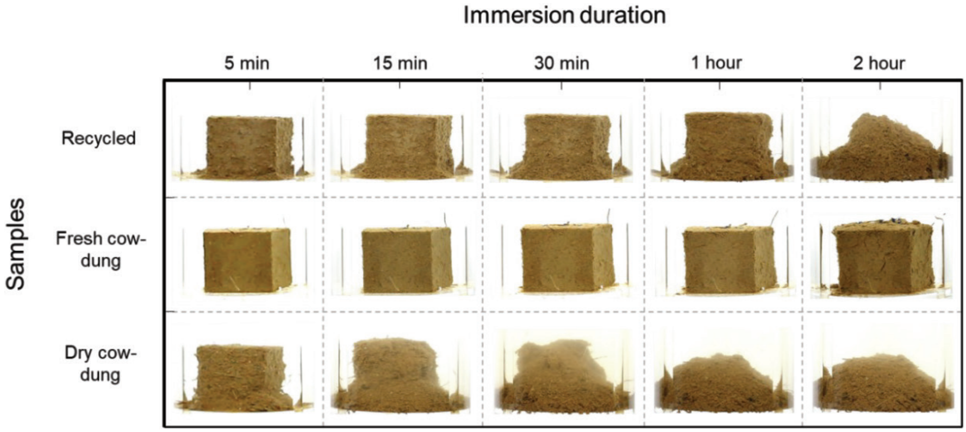


Figure 6.25: Time-lapse of disintegration of recycled CD-CEB and its comparison to CD-CEBs prepared with either wet or dry dung.

6.5.4.6 *How does CD-CEB compare to conventional stabilisation with Portland cement and hydraulic lime?*

Biological stabilisers such as cow-dung are suggested as an alternative to conventional binders used in earthen construction. Therefore, it is important to evaluate the performance of CD-CEBs in comparison to conventional stabilisers such as Portland cement and hydraulic lime (Test series I). The water resistance of CD-CEBs was compared to stabilised CEBs prepared at the same stabiliser content of 2%. The results of the immersion test, as shown in Figure 6.26, reveal that CD-CEBs have better water resistance characteristics than chemically stabilised CEBs. The results of drip erosion available in Dataset 6X18 also supported these observations. The compressive strength was also found to be lower when using low stabiliser content (Dataset 6X18).

In practical applications, the stabilisers are often in the range of 5-12% (Chapter 2). Therefore, a 2% dosage is quite low for chemical stabilisers. When CEBs were prepared with higher cement dosage (5%), the results improved drastically, and the sample did not disintegrate even after 10 days (Appendix 6O). Moreover, the addition of 5% cement increased the compressive strength from 2.2 MPa (for 2% cement stabilisation) to 4.5 MPa (6X18).

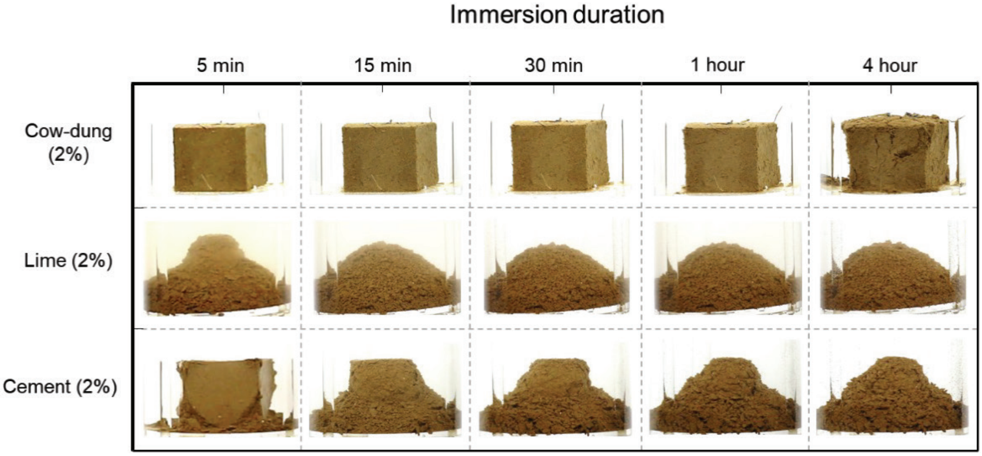


Figure 6.26: Time-lapse of disintegration of CD-CEB, and lime and cement stabilised CEBs (2%).

6.5.5 Performance of cow-dung stabilised earthen materials

6.5.5.1 Understanding the water resistance characteristics of CD-CEBs

The addition of a cow-dung modifies the material composition of the stabilised soil mixture and therefore, affects the water resistance of cow-dung stabilised earthen material through transforming cohesion, capillary suction and/or water permeability (Figure 6.27).

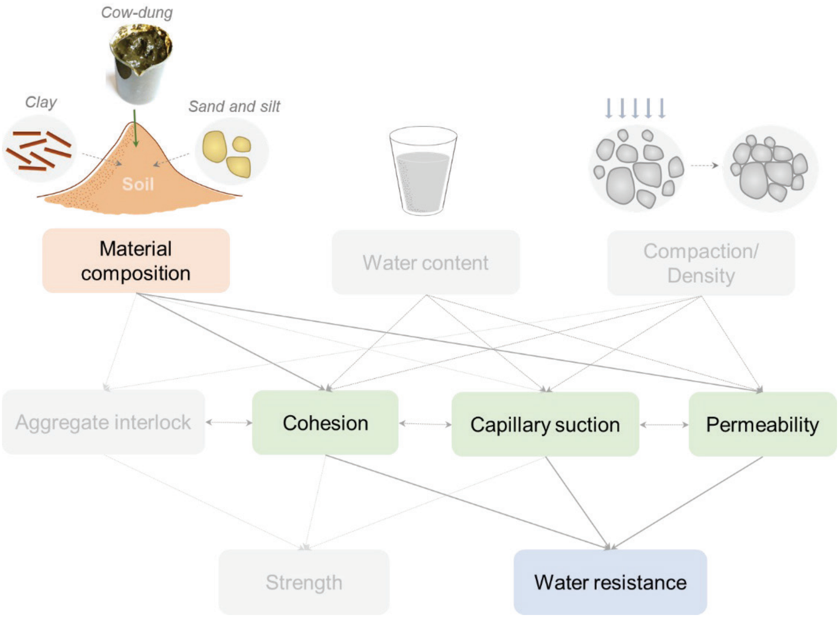


Figure 6.27: Parameters affecting the water resistance of cow-dung stabilised earthen materials.

The addition of cow-dung in soil introduces various components of distinct physico-chemical characteristics in the mixture. The results from Section 6.5.3 show that small-sized microbial aggregates (SSMA) present in cow-dung are responsible for enhanced water resistance performance of CD-CEBs. SSMA are hydrophobic and this characteristic could aid in improved water resistance. However, it should be remembered that the hydrophobic property of SSMA was associated with testing on SSMA powder (100%), whereas the amount of SSMA in the stabilised block is merely 0.68%. This impact can be observed in Figure 6.28 where the water droplet immediately ingresses into the cow-dung stabilised block. Therefore, while SSMA provides a barrier to water ingress, the stabilised earthen block does not prevent water ingress.

Figure 6.28: Contact angle measured on SSMA powder and CD-CEB after 2 sec upon droplet placement on the samples.

The addition of biological stabiliser often results in pore-filling leading to the reduction in the size of pores, therefore reducing the water permeability (Chapter 5). MIP tests were conducted on CEBs stabilised with SSMA to understand the role of SSMA on microstructural transformation. The results of MIP test conducted on SSMA stabilised CEBs is shown in Figure 6.29. The CEB with SSMA compacted at optimum water content (sample that performed the best) had a slightly lower volume of pores. On contrary, when CEB with SSMA are compacted at a higher water content, the volume of pores increases. In both the SSMA stabilised CEBs, size and relative contribution of macro and meso-pores does not change. Based on these results it can be concluded that pore-filling is not responsible for better water resistance of SSMA stabilised CEBs and cow-dung stabilised CEBs

The results from Section 6.5.4 reveal that the water resistance of stabilised blocks is dependent on the presence of SSMAs, fibres and clay minerals. Therefore, to understand the water resistance characteristics of CD-CEBs it is essential to understand the role and interaction of all these components..

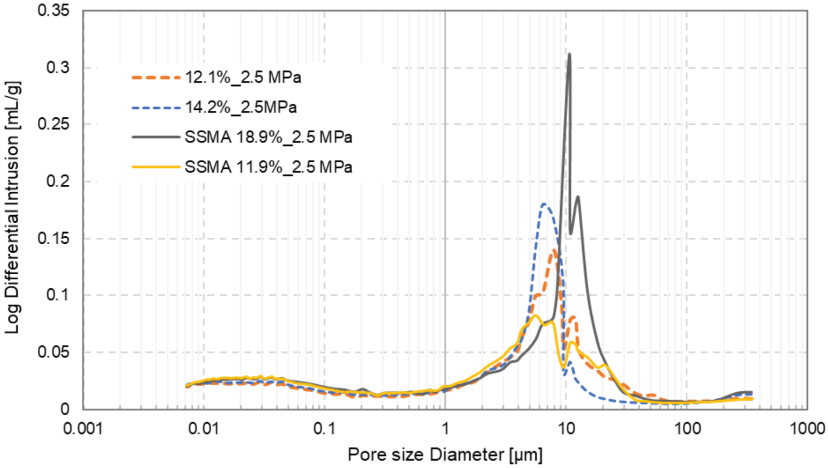


Figure 6.29: Results from MIP test conducted on SSMA stabilised CEBs and compared to unstabilised CEBs. The raw data of MIP test is available in Dataset 6X19 (Kulshreshtha, 2022).

The blocks prepared with sand and SSMA provides a simple experimental model to understand the role of SSMA in binding the sand grains. The microscopic images shown in Figure 6.24 (Section 6.5.4.4) provide evidence that SSMA acts as 'glue' and binds the sand particles. To visualise the interaction better, specimens were prepared by adding excess SSMA (~1.5%) to sand and studied under ESEM. The ESEM images shown in Figure 6.30 clearly provide evidence that these SSMA particles form bridges between the sand grains apparently binding them together. Moreover, when the quantity of SSMA is limited, it forms thinner bridges between the sand grains (Figure 6.30 (b-c)). Clay particles also play a similar role of bridging the sand particles, however their response to water ingress is significantly different to that of SSMA. Cohesion and capillary suction are two inter-related parameters that governs the stability of earthen material upon water ingress (Figure 6.27). In case of a block prepared with clay and sand grains, the water ingress subsequently decreases the capillary suction holding the clay and sand grains together, leading to disintegration. The reduction in capillary suction between clay particles and sand, is due to water absorbing (hydrophilic) nature of clays. Whereas SSMA are hydrophobic, and the water ingress is expected not to substantially reduce the capillary suction holding SSMA and sand grains together. Thus, SSMA stabilised sand show no disintegration whatsoever (Figure 6.22), indicating that the cohesive bond between SSMAs, and SSMA and sand is stable upon immersion or wetting. This bond between SSMAs and, SSMA and sand could be due to extracellular polymeric substances (EPS). Studies have revealed that cow-dung contains EPS producing bacteria (Rao et al., 2020). In a study by Rao et al. (2021), these EPS were found on the surface of microbes and were suggested to be responsible for bonding between clay particles.

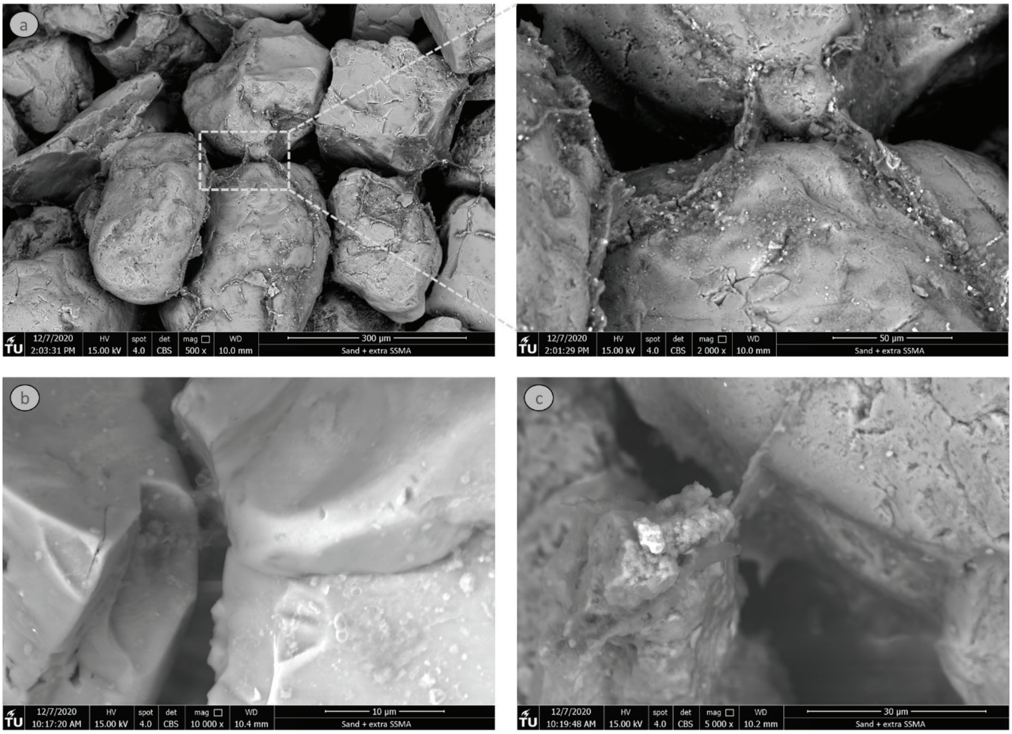


Figure 6.30: ESEM images illustrating bonding of sand particles through small-sized microbial aggregate bridges: (a) Sand+SSMA(1.5%), (b) Sand + Cow-dung and (c) Sand + SSMA.

Clays are responsible for the strength of earthen materials, as also evident by the strength results of unstabilised CEBs prepared with kaolinite and bentonite rich soil (Section 4.5.5, Chapter 4). While it could be interesting to compare the cohesive characteristics of clays and SSMA, it is challenging due to low quantity of SSMA (0.68 wt.%) used in stabilising sand as compared to 14.8 wt.% of clays. Separating a comparable quantity of SSMA (14.8%) is currently challenging due to extensive extraction process. Irrespective of their comparative performance, the low quantity of SSMA lead to extremely weak cohesive bonds as suggested by the fragile nature of SSMA stabilised sand blocks (Figure 6.22, Section 6.5.4.4). Thus, in scenarios such as the drip test, the force of eroding water was sufficient to erode the top surface locally (as seen in Appendix 6N). Upon wetting, there is no volumetric swelling in sand or SSMAs and only with increasing duration of immersion SSMAs disassociate from the sand surface and leach into the liquid (indicated by the colour change of water to yellow). The conceptual process of SSMA stabilisation of sand upon wetting is visualised in Figure 6.31.

The addition of fibre increases the susceptibility of stabilised sand block upon immersion (Figure 6.18, Section 6.5.4.1). Fibres are expected to act as water transportation channels in the stabilised blocks and facilitate water ingress to the inner core of the sample. Upon wetting, the fibres not only swell but could re-align themselves to their original orientation. Thereby, swelling and re-alignment of fibres could create sufficient pressure to break the bonding between sand grains and SSMAs. The swelling of fibres is expected to occur instantaneously, whereas the realignment could be much slower and occurs after a sufficient duration of immersion. It is expected that the effectiveness of cohesive bond reduces over the duration of immersion, leading to the de-bonding of sand grain and SSMA (observed through leaching of SSMAs in the surrounding fluid). The reduction in the effectiveness of cohesive bond in time (upon immersion) coupled with the realignment of fibres could be responsible for the disintegration of blocks. A simple illustration of the impact of fibre addition in SSMA stabilised sand is illustrated in Figure 6.31.

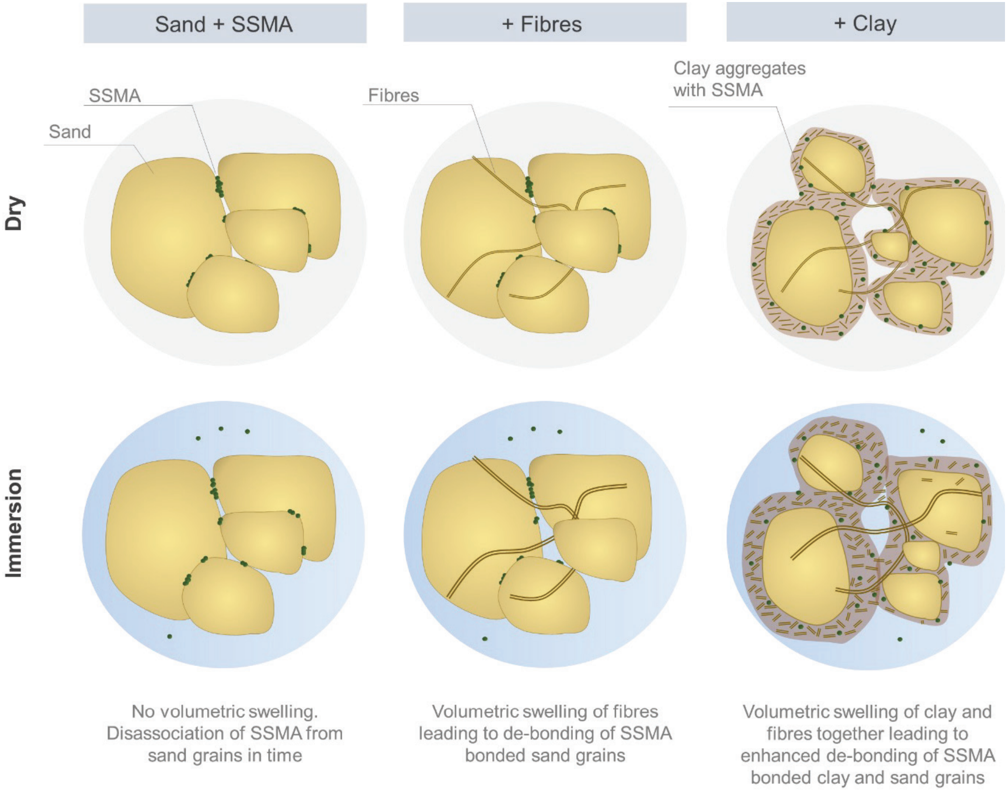


Figure 6.31: Conceptual explanation of failure of cow-dung stabilised CEB upon water ingress. Impact of immersion on (a) Sand + SSMA, (b) Sand + SSMA + Fibres, (c) Sand + SSMA + Fibres + Clays.

The impact of fibre on water resistance is much more pronounced when clay particles are present in the soil (Figure 6.31). The type, activity and swelling potential of clay minerals play a major role in the water resistance characteristics (as shown in Figure 6.22, Section 6.5.4.4). However, it's the combination of clays with fibres and SSMA, that determine the overall water resistance characteristics of CD-CEBs. A low swelling clay such as kaolinite has limited swelling that is insufficient to disrupt the bonding between SSMAs and clay/ sand instantaneously. However, with an increase in immersion duration, the effectiveness of EPS is expected to reduce facilitating re-alignment of fibres. The softening of the bond between clay minerals coupled with the re-alignment of fibres disrupting the bond between aggregates results in the disintegration of the sample. In a high swelling clay mineral such as bentonite, the swelling has been shown to prevent water ingress and improve stability (as seen in unstabilised bentonite clay sand mixture in Chapter 4). However, the presence of fibres provides water ingress routes to the core of the material, leading to faster disintegration. The presence of fibres in CD-CEBs (prepared with natural soil) also increased the rate of disintegration. Therefore, the swelling of clay minerals together with swelling and re-orientation of fibres leads to de-bonding of SSMA and soil minerals, causing disintegration upon wetting.

6.5.5.2 Compilation of water resistance and strength results

While the water resistance of CD-CEBs is discussed throughout Section 6.5, the strength characteristics are also important for practical applications. Hence, the water resistance and strength results obtained in experiments are compiled and the results of selected stabilised CEBs is presented in Figure 6.32.

Figure 6.32 shows the relationship between strength and mass loss in the drip test of several stabilised CEBs. Although water resistance tests have been discussed in earlier sections, Figure 6.32 compiles all the results together and provides information on the relative impact of different variables. It can be observed from the figure that most CEBs have sufficient compressive strength for construction (>1 MPa, refer to Chapter 2), with the exception of stabilised sand blocks that were fragile (see blue markers in the plot). The mass loss in most cow-dung stabilised blocks was measured in the range of 0.1-1% (60min test duration). The addition of cow-dung in CEBs improves water resistance by over 500 times (calculated based on 10 min drip erosion values). However, the addition of cow-dung results in the reduction of strength by about 10% (compare dark and bright red markers). This difference was insignificant when cow-dung from a different batch (December) was utilised (see light grey marker in Figure 6.32 (top). Figure 6.32 (bottom) provides a visual of the dominant influence of a few selected variables. Increasing the compaction water content by 3%, resulting in an improvement of over 40 times in water resistance of CD-CEBs (see route 1, compare orange and red markers in Figure 6.32 (bottom)). Use of wet cow-dung over dry cow-dung results in over 80 times better water resistance and 17% higher compressive strength (see route 2, compare grey and red markers). The water resistance of CD-CEBs were improved 30 times, by using a low-swelling clay mineral such as kaolinite rich soil (see route 3, compare red and blue markers). Although, use of kaolinite rich soil decreases the strength by more than half. The significance of this increased water resistance and decrease in strength will be depending on the architectural design and climatic conditions.

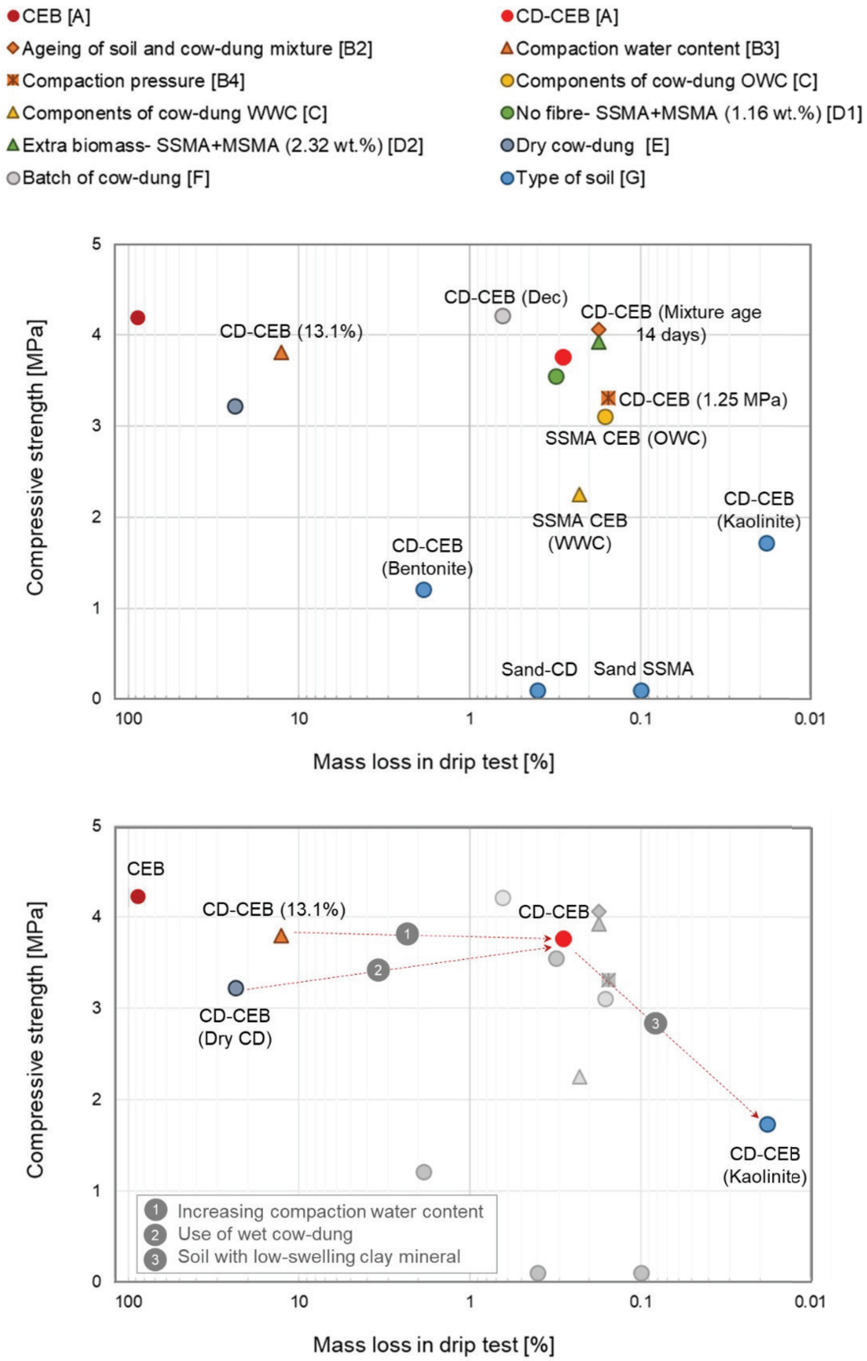


Figure 6.32: Relationship between compressive strength and mass loss in drip test (60 min) for selected samples. The legends on top provide information about the sample and the corresponding test series code. The bottom plot presents key findings that leads to better water resistance. For samples that were tested only for 10 min, a correction factor is applied to estimate the mass loss in 60 min. Refer Dataset 6X20 for a complied list of results.

The results from the drip test provide a quantitative assessment of the relative influence of several variables however, it makes the comparison between CEBs with closer erosion values challenging, and in some cases, contradicts the immersion test results. Due to the longer duration of the immersion test, it provides more nuanced information on the relative performance of stabilised CEBs. Hence, in addition to drip test results, immersion test results are compiled and presented in Figure 6.33.

The visuals shown in Figure 6.33 are in line with the results observed in Figure 3.32. In comparison to the drip test, the results of the immersion test provide a clearer information on the influence of some variables such as ageing of soil and cow-dung mixture (Test series B2) and components of cow-dung (Test series C and D), where the difference in their relative performance is smaller than variables discussed in Figure 6.32. Figure 6.33 (bottom) shows the positive impact of the ageing of soil and cow-dung mixture on both strength and water resistance of CD-CEBs (see route 4). Similarly, the positive influence of reducing the fibres (as in CD-CEBs with no fibres and SSMA stabilised CEBs) is presented (route 5). While the addition of extra biomass improves the strength, the improvement in water resistance is negligible. Based on the information presented in Figure 6.33, reduction in fibres has a similar impact on the water resistance as ageing of cow-dung soil mixture. Although, ageing of the mixture also improves the compressive strength by 8%.

Both Figure 6.32 and Figure 6.33 provide quantitative and qualitative information on the influence of several variables on the strength and water resistance performance of stabilised CEBs. These results provide an insight into various processes or choices that could lead to the optimisation of CD-CEBs for practical application.

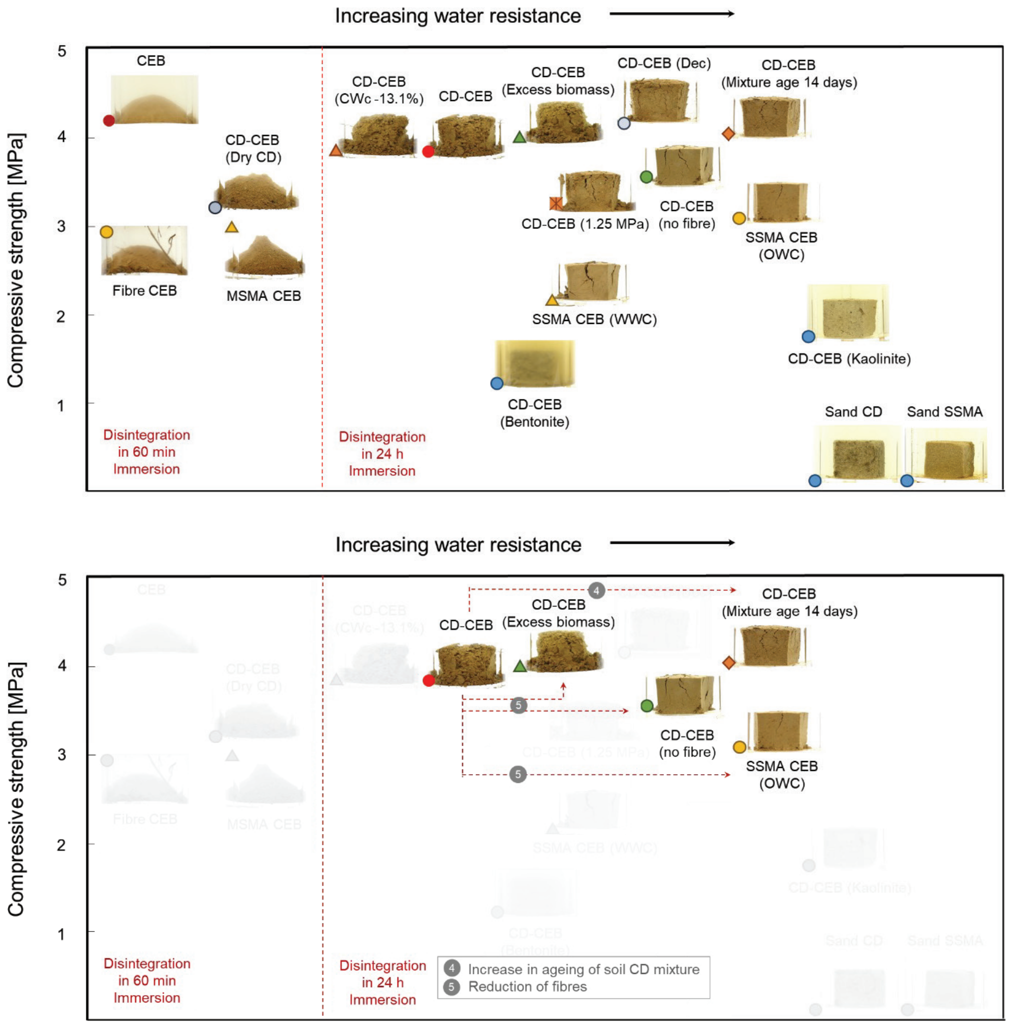


Figure 6.33: The relationship between compressive strength and water resistance measured through immersion test. The region left to the red line show images of CEBs captured after 60 min of immersion whereas, the region on the right shows images captured after 24h of immersion. The horizontal axis provides information on the relative performance of CEBs and is not to scale. In CEBs with a similar disintegration profile after 24 h of immersion, the drip test values were used in positioning the samples on the relative scale of water resistance performance. The markers (legend) used in the figure are defined in Figure 3.32.

6.5.6 Valorisation of cow-dung for development of improved CEBs

Cow-dung is an important resource that is used as a fertiliser in farmlands. It is also used for the production of Biogas and as a cooking fuel in India (Kaur et al., 2017; Rao et al., 2021). When not treated properly, its usage as a fertiliser can cause environmental problems such as acidification and eutrophication (Hanifzadeh et al., 2017; Torrent et al., 2007). Moreover, Cow-dung is responsible for emitting ammonia which is considered a threat to air quality (Ishler, 2016). Methane (a powerful greenhouse gas) emission during the storage of cow-dung is also an environmental concern (De Vries et al., 2012).

The management of cow-dung on a farm is an important task that requires significant financing. This management is important for countries such as the Netherlands, where excess cow-dung is sometimes dumped illegally (Levitt, 2018). Valorisation of waste cow-dung adds value to the cow-dung while reducing its environmental impact. Valorisation of cow-dung in the production of compressed earth blocks could provide farmers with the opportunity to get rid of waste with no extra cost and prevent leaching of cow-dung components into the groundwater.

The production of CD-CEBs requires only two ingredients, the soil and the cow-dung. The cow-dung can be collected in large containers and transported to a factory that contains soil and compaction equipment. In cases where the soil is available near the farm, the equipment can be transported to the farm itself and a small production unit can be installed to generate extra revenue for the farmer.

The quantity of cow-dung required in the production of CD-CEB prepared with natural soil used in this study is recommended to be 2% solid cow-dung, which corresponds to around 16-20% wet cow-dung (depending on the amount of liquid in cow-dung). In order to determine the exact amount of cow-dung to be added to a particular soil, some testing and trials would be required. Cow-dung is a biological material that is biodegradable and facilitates the growth of microbes. Although, results presented in this study (Figure 6.4 and Figure 6.5) show that the cow-dung ageing duration has an insignificant influence on the strength and water resistance of CD-CEBs, it is still advisable to use the fresh cow-dung soon after collection to avoid growth of fungus on top of it during storage. If present, the surface layer with fungus should be removed before using the stored cow-dung. It is recommended to mix freshly collected cow-dung with soil to form a mixture that can be stored for a longer duration. The storage process not only removes the pungent smell but also improves the strength and water resistance characteristics. For example, in this study 14 days of storage was optimum for producing strong and durable CD-CEBs. While it is ideal to produce CD-CEBs after storing the mixture for optimal duration, it is not always feasible. Test on 230 days old soil cow-dung mixture revealed that a longer storage period does not have a major influence on the water resistance characteristics of CD-CEBs (Appendix 6P). Moreover, there was no growth of fungus even after such a long storage duration.

This study also reveals that the removal of fibres from the cow-dung can improve the water resistance characteristics of CD-CEBs. Fibres are known to provide other benefits to CEBs as briefly discussed in Section 6.5.4.1. Therefore, a careful assessment should be undertaken before making the decision to remove fibres. One of the additional benefits of using cow-dung soil mixture to produce CD-CEB is the possibility to use a wet mixture in the compaction machine. Preliminary trials on a semi-automated compaction equipment showed that the machine was able to compact the cow-dung mixture with higher water content, which was otherwise impossible for unstabilised blocks.

To understand the opportunities and challenges in scaling up this research, 1000 kg of cow-dung was collected from the cow farm and mixed with 6000kgs of soil to produce CD-CEBs which were used in the construction of a demonstration structure as shown in Figure 6.34. The details of the demonstration project are excluded from this thesis as it is a part of separate research project for the application of CD-CEBs in the Netherlands. However, the upscaling process was a success, and it reinforces the potential of using cow-dung in earthen construction. To compare the performance of cow-dung stabilised blocks, walls were also constructed with unstabilised compressed earth blocks. The degradation of these walls will be assessed for at least a few years to evaluate their performance.

The valorisation of cow-dung for earthen construction in India is expected to be more challenging than in the Dutch context, as most cow farms are not automated to facilitate quick collection of cow-dung. Nevertheless, many rural areas in India have an efficient collection system for cow-dung. As a part of the traditional lifestyle in India, cow-dung is collected from individual houses and stored in a large heap near the village (Kaur et al., 2017). Such heaps were also seen in the survey shown in Chapter 3. The production of cow-dung is estimated to be 1.92 million tons per day (Rao et al., 2021). The availability of cow-dung and soil in rural areas, together with possibilities of getting CSEB equipment under the government employment scheme (discussed in Chapter 3), provide opportunities to build houses with cow-dung stabilised earthen material. It is also possible to use cow-dung as a stabiliser for cob, adobe or any other low resource intensive techniques. It is important to provide design elements that avoid the pooling of water near the walls as otherwise the durability of CD-CEB walls will be jeopardised. The possibilities for long term storage of cow-dung soil mix provide opportunities to use it as a stabiliser for mass housing in rural areas. Due to the hot and humid climate in some parts of India, it is important to assess if soil cow-dung mix storage is possible at such a large scale. Moreover, a reliable source of cow-dung is important, but cow-dung is often reported to contain pathogens such as E.coli (Sinton et al., 2007), causing potential health risk to people and possible difficulties in obtaining a reliable source.

The CD-CEBs can also be produced commercially and sold in the market as an alternative to fired bricks. An efficient collection system could provide ample opportunities to set up multiple factories in rural areas that can provide employment to local people. However, building codes supporting the use of cow-dung is also required for the large-scale adoption of CD-CEBs. One of the most important aspects that facilitate valorisation of cow-dung in India is its wide acceptance due to cultural and religious beliefs.

Figure 6.34: Upscaling of CD-CEBs for construction of demonstration walls at the Green village, TU Delft. (a) Mixing of cow-dung and soil, (b) Production of CD-CEBs with a hydraulic press, (c) Masonry with CD-CEBs. The mortar used has the same composition as the CD-CEB but with more water, (d) the fully constructed front wall of CD-CEBs (without the metal roofing) and (e) The finished demonstration structure with an unstabilised wall on left and cow-dung stabilised walls on the right. The demonstration structure is a full-scale test on the performance of the CD-CEB wall as compared to the unstabilised wall. (Image c and d are credited to Justyna Botor).

Cow-dung is a high value product in India!

Cows are considered holy and sacred in India and hold a deep routed value amongst many people (especially those following the Hindu religion). Any product from a cow is regarded as valuable. Therefore, cow-dung is a product with extremely high value in India. Irrespective of the high value, waste cow-dung can be found throughout the country. In fact, cow dung or other waste product from cows has after been touted as the cure to many diseases including Covid-19. From drinking cow urine to taking a bath with cow-dung, all have been claimed to be ways to prevent Covid infection (Caulfield, 2020; DW News, 2020; Scroll.in, 2020). Keeping cow-dung in homes is also claimed to reduce radiation (Express news services, 2020). The cow dung in India is constantly surrounded by pseudoscientific claims. Therefore, the valorisation of cow-dung in earthen construction is also fuelled by the prevailing attitude towards it. Moreover, the products from cow-dung such as cow-dung based paint are also getting immense popularity and support from the ruling government. Hence, the valorisation of cow-dung to produce low-cost products has the potential to be endorsed by the government. With growing support for cow-dung based products, it can be estimated that the CD-CEBs would be accepted amongst a wide audience. Therefore, cow-dung can improve the low acceptance of traditional earthen houses in India. Moreover, several people in India are recognising the benefits of indigenous materials and moving towards an ecological lifestyle. This also contributes to the growing opportunities to valorise cow-dung.

6.6 Conclusions

Cow-dung is one of the most used yet one of the least studied stabilisers in the field of earthen construction. The use of cow-dung is anecdotally attributed to its water resistance characteristics, which is also confirmed by this study where the addition of cow-dung improves the water resistance of earthen blocks by (up to) over 500 times (as measured through drip test) and has no significant impact on compressive strength. However, there were no comprehensive studies that provide insight into the water resistance characteristics of cow-dung stabilised earthen materials. This study explores these insights through an extensive experimental investigation. Wet cow-dung collected from a local farm was separated into fibres, medium-sized microbial aggregates (MSMAs) and small-sized microbial aggregates (SSMAs). It was found out that SSMAs, which constitute approximately one-third of the solid mass of cow-dung, are entirely responsible for water-resistance of cow-dung and cow-dung stabilised compressed earth blocks (CD-CEBs). SSMAs are negatively charged clay-sized particles of low specific surfaces that are hydrophobic and rich in fatty acids. SSMAs are stable upon wetting and are expected to be weakly bonded through extra-polymeric substances (EPS). Swelling of clays, in conjunction with swelling and re-alignment of fibres, can disrupt this bond leading to faster disintegration of cow-dung stabilised earthen blocks.

Contrary to the anecdotal belief in the role of fibres in water resistance, this study provides evidence that removing fibres can, in fact, improve the water-resistance of stabilised earthen blocks. It is interesting to note that the pH measurement on fresh and dried cow-dung, and multiple cow-dung-soil mixes was in the range of 6-9. This signifies that an alkaline medium and thereof, the formation of an insoluble compound, is not a pre-condition for the enhanced water-resistance behaviour of cow-dung stabilised earthen blocks, as suggested in previous studies.

The insights gained through the experimental study could facilitate the valorisation of cow-dung in practical earthen construction applications. These insights are compiled in form of recommendations to enhance the water resistance and strength characteristics of cow-dung stabilised earthen materials:

- Use of fresh or wet cow-dung is advised over dry cow-dung. The drip erosion test conducted on CD-CEBs in this study revealed that the stabilised block made with wet cow-dung perform 80 times better than dried cow-dung. Moreover, the ageing or storage of wet cow-dung does not influence the characteristics of CD-CEBs.
- It is useful to adopt a higher compaction water content for casting the cow-dung stabilised earthen materials. A high compaction water content enhances both the water resistance and strength characteristics. A soil cow-dung mix with higher water content can also be compacted with higher pressures (such as the one used in CEBs), which is otherwise not possible for unstabilised mixes. In absence of high compression equipment, a lower compression force can be used. The influence of compaction force on the water resistance characteristics is minimal.
- The low activity, swelling or cation exchange capacity of clay minerals is favourable for the water resistance behaviour of CD-CEBs. Therefore, for the selection of appropriate soil for the earthen construction project, it is advised to select soil with low swelling clay minerals, such as kaolinite minerals. Although the water resistance could be improved by selecting a low-swelling mineral rich soil, it is important to evaluate if the selected soil provide sufficient strength for the construction.
- Once the fresh cow-dung is collected, it is recommended to mix it with soil soon and store this mix until casting blocks. The storage or ageing of soil cow-dung mix has a positive influence on strength and water resistance characteristics. In this study, the optimal ageing duration was found to be 14 days. Moreover, by ageing the soil and cow-dung mix for over 3 days, the pungent smell of cow-dung can be removed. An extended period of ageing not only removes the smell from the mix but does not re-appear even after wetting the blocks. In addition, the soil cow-dung mix can be stored for a long duration (6-12 months), without the growth of fungus.

- Fibres act as an active water transport network that facilitates water ingress in the earthen materials. Removal of fibres from cow-dung has shown a positive influence on the water resistance characteristics of CD-CEBs. Therefore, removal or reduction of fibres is advised only if it is economically feasible and appropriate for the construction project.

With a growing interest in ecological building materials, research and application of earthen materials are expected to grow. In this regard, cow-dung stabilised compressed earth blocks can offer a significant improvement over unstabilised blocks by using locally available resources. The recommendations proposed in this article can facilitate architects, practitioners, self-builders and natural-building enthusiasts to build earthen houses that are affordable, durable and desirable.

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7

Making an Impact on Earthen Construction Practice: A Science Communication Perspective

"oh truly fascinating, that one for the journal"

– Professor Zei, Avatar the Last Airbender (S2 E10)

This chapter draws on the observation of the field survey (Chapter 3) and extends it through additional interviews to understand the sources and dissemination of scientific knowledge within the earthen construction community in India. The results reveal that social media platforms such as blogs and online videos (e.g., via YouTube) are often used by practitioners to aid in their research and practical earthen construction. Therefore, communication through online videos is recognised as an effective and impactful medium to disseminate scientific knowledge practitioners. To understand the characteristics of an effective video, 124 YouTube videos were assessed regarding 'viewer engagement', 'quality of content' and 'potential impact', followed by a discussion if each video was relevant, holistic, and actionable. It was found that the overall assessed quality of earthen construction videos was inferior to 'popular science' videos. The majority of high-quality videos (throughout all categories) were found to be relevant (how relatable the message is to contemporary issues), holistic (touches upon the topic from multiple perspectives) and actionable (motivate the viewer to take action in line with the message of the video). The learning from the video analysis was utilised in the production of two videos, one to create wider awareness of building with earth as an eco-friendly alternative building material and another to provide recommendations or instructional on the efficient use of cow-dung in earthen construction for earthen construction professionals.

Data accompanying Chapter 7 is available in Kulshreshtha (2022).

7.1 Introduction

The acceptance of earthen houses in India could be improved through measures such as improved material performance, good aesthetics of buildings to enhance desirability and through education, knowledge dissemination and demonstration of successful earthen building (Chapter 3). From these suggestions, education, dissemination, and demonstration has the potential to create a widespread positive awareness of earthen materials and construction in India. Demonstration of successful earthen house projects at diverse locations is expected to have the greatest impact on the perception of people and government. However, demonstration of earthen houses is often restricted due to available finance, slow and challenging approval process, and lack of local expertise. Therefore, education and dissemination offer a relatively lower resource-intensive approach that has the potential to create awareness towards earthen construction, especially with the growing use of social media. Education and dissemination are here considered to be the process of transferring information to others and are used interchangeably in this chapter. This is opposed to the definition sometimes used where education is only used in a formal environment, i.e. at schools, colleges and universities.

Education plays an important role at two different levels; 1. Educating the public on various aspects of earthen construction (such as benefits, misconceptions etc.) to improve awareness and, 2. Educating people involved in earthen construction on various practices and techniques to aid in the enhancement of material performance and desirability of the structure. While it is undeniable that educating people on building with earth is necessary to promote it, educating earthen construction practitioners is equally essential. This is because the field of earthen construction is still dominated by self-learners who do not have any formal education in this field of earthen construction and often rely on anecdotal knowledge, and therefore examples are not always positive. In the past decade, there is an insurgence in scientific work on earthen construction due to the growing interest in ecological materials. However, it is unclear how scientific knowledge disseminates within the earthen construction community in India and if scientific publications have an impact on earthen construction practice. Therefore, it is essential to understand the source and dissemination of knowledge to prepare an educational strategy that has an impact on earthen construction practice.

The survey carried out in Chapter 3 provided some information on the sources and dissemination of knowledge within the earthen construction community. However, the survey was restricted to low-income families living in earthen houses with limited access to resources. Therefore, the survey in Chapter 3 was extended in this chapter to include practitioners that also cater to middle and high-income families. The insights from the survey are then used in choosing a communication platform appropriate to reach the target audience (earthen construction practitioners and general audience). The chosen medium is analysed for insights on impactful communication which are then applied to communicate the selected outcomes of this study.

7.2 Survey to understand the sources and dissemination of scientific knowledge on earthen construction

7.2.1 Survey methodology

In addition to forty informal and semi-structured field interviews conducted in various bioclimatic regions of India (presented in Chapter 3), ten interviews (nine through call and one face to face) were conducted to understand the sources and dissemination of scientific knowledge within the earthen construction community. The additional interviews were conducted on earthen construction practitioners who were at various stages in their career of earthen construction (1-6 years of experience). The majority of them had a background in architecture or civil engineering. Information on the region, educational background and experience level of the survey group is available in Appendix 7A. Almost all interviews were conducted remotely in April-May 2021, three years later than the field interviews. As compared to the broad scope of information provided by the interviewees in the field survey, the scope in the additional interviews was mostly restricted to the sources and dissemination of knowledge on earthen construction. Several questions were asked to understand the sources of learning the practical aspects of earthen construction and the medium used in disseminating the knowledge gained through the field experience. A non-exhaustive list of the questions asked were:

- What is the first source of knowledge they refer to when searching for a query related to earthen construction?
- Where did they obtain the working knowledge of building with earth?
- Have they attended training programs and workshops offered by experienced professionals?
- If and how often do they refer to scientific literature published in journals or conferences?
- What is the primary medium of documentation and dissemination of their work, and why do they prefer this approach?
- The survey questions were kept open-ended and wider discussion around the education and dissemination approaches used by other professionals were included in the interview.

7.2.2 Results

The results of interviews are summarised in Table 7.1. These results in combination with the field survey (Chapter 3) are used to gain insights on sources and dissemination of knowledge within the earthen construction community of India.

Table 7.1: Summary of response by earthen construction practitioners on their sources and dissemination of knowledge on earthen construction.

Identification of interviewee	Source of information	Refer to scientific article	Training as earth builder	Medium of documentation (and motivation for the choice)
I1	Videos, blogs	No	Volunteering	Video (used same approach for learning)
I2	Google search, books	No	Workshop, volunteering	Video (useful for promoting the work)
I3	Google search, videos	No	Workshops, training under expert	None
I4	Blogs, books	No	Workshop, volunteering	Video (easy to share with wider community)
I5	Personal communication with expert, Video	No	Workshop	None
I6	Personal communication with expert	No	Workshops, volunteering	Video (other professionals use it too)
I7	Research articles, video	Yes	Workshop, volunteering	PDF instruction files (preference of collaborators)
I8	Personal communication with expert	No	Training under expert	None
I9	Google search, personal communication with expert	Yes	Workshop, volunteering	Workshop (hands-on)
I10	Google search, video	No	Volunteering	None

The source of knowledge used in practical earthen construction was found to relate to the economic situation (low, middle and high income background) of the practitioner or builder. In low-income families, the knowledge for building with earth is transferred through their ancestors, whereas middle-income families construct earthen houses with help of practitioners who derived their knowledge from previous experience of earthen construction projects, workshops, and social media platforms. High-income families were seen to often rely on the expertise of experienced architects and engineers who train and collaborate actively with earthen construction organisations in India. The results from the survey and the insights into the knowledge sources are compiled in Figure 7.1 and discussed in the sections below.

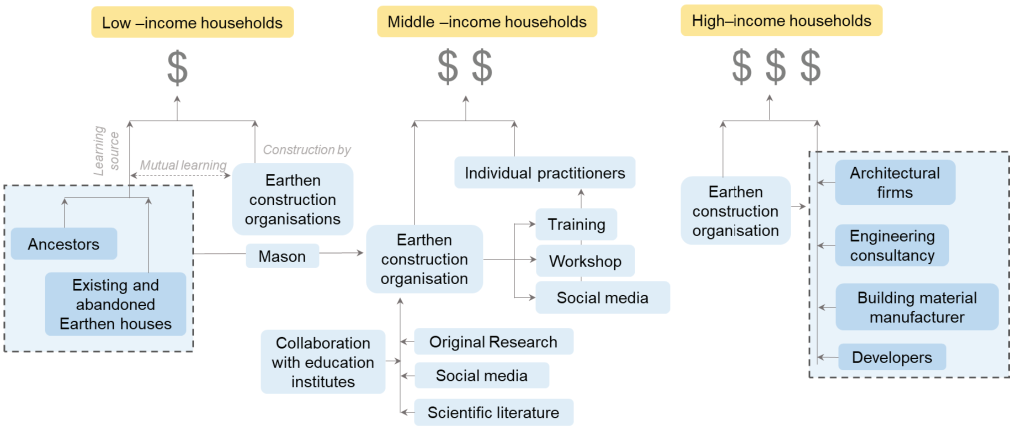

Figure 7.1. A flow chart compiling the insights from the survey on source and dissemination of knowledge within the earthen construction community of India (based on household income levels).

Most of the traditional earthen houses visited during the field survey were constructed by low-income dwellers with the help of neighbours and relatives. The knowledge of building with earth was transferred to them by their parents. This transfer of knowledge was verbal, and most dwellers acquired the required knowledge through assisting their families in the construction of other earthen houses. A few low-income earthen dwellers, including a mason, mentioned that they acquired a significant part of their knowledge through observing and analysing the existing, abandoned and deteriorated earthen construction in their region.

In addition to low-income households, several middle-income households also build their own earthen houses with the assistance and knowledge of earthen construction practitioners and volunteers. Most of those practitioners interviewed started as volunteers in earthen constructed organisations and learned through hands-on experience. Several practitioners reported that they followed multiple workshops on building with earth. A practitioner from the north of India mentioned that their primary source of information for the construction of an earthen house was YouTube videos. The instructional and time-lapse videos on their chosen construction technique were mentioned to be useful in understanding the construction process. Most practitioners mentioned the use of such videos before and during the construction. In addition to a source of information, multiple practitioners mentioned that they use video as a source of documentation. Most interviewees mentioned that a simple google search was often the first thing to resolve a query, followed by contacting an experienced person. Blogs and books by experienced earthen construction practitioners were also referred to by some interviewees. Upon questioning the earthen construction practitioner on the use of scientific articles, it was found that scientific articles were rarely used as a source of knowledge due to their inaccessibility, both in terms of complex writing and open availability. Only 2 practitioners mentioned their interest in an in-depth understanding of earthen materials and reported using scientific literature to satisfy their curiosity.

While only a few members of high-income families could be interviewed during the field survey, it was found that they often contacted experienced architectural firms to construct their earthen houses. These architects and associated consultants and engineers have the knowledge and experience of building with earth. They often collaborated actively with earthen construction organisations which provided them with the required knowledge. Several developers are also emerging in India which caters to the demands of environmental conscious families and built earthen communities. There is also a rise in compressed earth blocks manufacturers in India who often collaborate with the earthen construction organisation or educational institutes to develop their products.

Earthen construction organisations in India were stated to be leading the way in training the new generation of earthen construction practitioners. Some of the leading organisations visited during the survey were Hunnershala (Bhuj), Auroville Earth Institute (Auroville), Mrinmayee (Bangalore), Thannal (in Tiruvannamalai) and Dharmalaya (Bir). These organisations conduct original research and disseminate it through workshops, artisan training, handbooks, and social media (see Appendix 7C). An earthen construction practitioner with half a decade of experience in a leading organisation mentioned that prior to 2003 most of the knowledge used in construction was acquired through the advice of academic experts. With the growth of their organisation, they were also involved in conducting some original research to support the existing and future projects. The literature supporting the preliminary research was reported to be gathered through blogs and videos, followed by in-depth research by referring to scientific journals. It was also mentioned that the educational background and research experience played a key role in the choice of a source of knowledge.

Some organisations reported collaborating actively with universities to create knowledge. In fact, Mrinmayee is an organisation that is a direct outcome of scientific work conducted at Indian Institute of Science, Bangalore. Based on the purpose and values of each organisation, these organisations cater to all income groups. Some of these organisations are involved in the construction of affordable houses for low-income households, which is often supported by governmental or non-governmental funding. Earthen construction organisations also play a key role in developing several non-housing infrastructural projects.

7.2.3 Discussion

The knowledge generated and disseminated by earthen construction organisations in India is responsible for the growth in the construction of modern earthen houses in India. These organisations are not only involved directly in the construction of earthen structures, but they provide training and workshops to the new generation of earth builders. While training and workshops introduce enthusiastic individuals to earthen construction, they often rely on the internet and their human network to guide them during the construction of earthen houses. Similarly, the research work in the organisation is also supported through information drawn from social media (videos, blogs) and scientific articles. Some organisations, such as Thannal, also use videos and blogs to disseminate their knowledge of building with earth. After the success of their videos, they have also produced courses on earthen construction which have a wide outreach.

Unlike the development of cementitious building material, the earthen materials are not yet commercialized at a large scale and the development of knowledge still rely on organisations that have limited resource to carry out advanced research. Although research institutes such as the Indian Institute of Science are involved in research, the dissemination of knowledge is mostly through scientific publication and collaborations, which have a limited reach and are often restricted to a few earthen construction professionals. Dissemination of scientific insights of academic research through a social media platform such as YouTube has the potential to reach practitioners who are already using this platform as both source of knowledge and documentation. Moreover, YouTube has a user base of 2 billion people, with the highest user base from India (GMI Blogger, 2022). Therefore, effective communication of scientific research through YouTube could not only impact earthen construction practitioners but have a wider outreach.

While online videos are an excellent tool for communication, there is a lack of information and insights on the characteristics or requirements of engaging video content. Therefore, a YouTube video analysis was conducted on videos from the field of earthen construction and the built environment, and the insights are used in the production of videos related to this thesis.

7.3 Video analysis

7.3.1 Methodology

The main objective of the video analysis was to understand the requirements for an 'effective video'. In the context of this chapter, an 'effective video' is defined as a video that is (a) engaging, (b) has a good quality of content and (c) is impactful. Hence, as a part of the video analysis, several YouTube videos were reviewed on three key parameters, 1. 'Viewer engagement': how easy is it to follow the content of the video? 2. 'Quality of content': How is the quality of the information presented in the video, and 3. 'Potential impact': Does the video have the potential to impact the behaviour of target audience?

A total of 124 YouTube videos (from 50 YouTube channels) were selected predominately from the domain of earthen construction and building materials, and analysed on their 'viewer engagement', 'quality of content' and 'potential impact'. The selection of videos and channels was performed using the following criteria: 1. All the videos were educational, 2. The length of video selected was restricted to between 1-15 minutes, 3. Video channels with less than 1500 subscribers were excluded, and 4. Only channels running for over 2 years were included in the analysis. Apart from 15 YouTube channels (and 36 videos) on earthen construction, 'popular science videos' published by established science channels, scientific journals, universities, and news channels were included as a benchmark to access the overall quality of earthen construction videos. Nineteen popular science channels were shortlisted based on recommendations of a few blogs (Feedspot, 2022; Hayward, 2018; Nikishaev, 2018), and 5 channels on scientific journals, 6 channels from leading universities and 5 news and media channels were selected based on prior knowledge and keyword search. 'Earth', 'mud', 'concrete', 'material', 'building' was some of the keywords used in finding channels and videos. The complete list of selected channels is available in Dataset 7X1 (Kulshreshtha, 2022). For each channel, no more than 4 videos were included in the analysis. Due to a limited number of videos on building materials (excluding earthen construction channels), videos from broader themes of 'material', 'sustainability', 'environment' were included. The video analysis was carried out from June to October 2020.

The video analysis consisted of 2 steps. The first step involved assessing the videos on 'viewer engagement' and 'quality of content' and rating them out of 10 points by making a qualitative judgement. The assessment was carried out immediately after watching a video by filling out an assessment sheet (available in Dataset 7X2). This assessment was carried out by 2 people, including the author. The assessors were related, and both had an educational background in the field of civil engineering and architecture. For assessing the 'viewer engagement', videos were evaluated on various sub-parameters such as video style (cinematic, animation, hybrid), video/animation quality (low-high), video length feel (short-long), text use (none - significant), audio (yes/no), narration speed (slow-fast) and layout of content. Whereas the assessment of 'quality of content' was dependent on knowledge depth (superficial- in-depth) and the scientific correctness of the information. The 'potential impact' of the videos was assessed through parameters such as the number of views, likes and dislikes. The video from the 'popular science' category acted as a benchmark for assessing and rating the videos of 'earthen construction' hence, the adopted rating was relative.

After rating a video on 'viewer engagement', 'quality of content' and 'potential impact', the second step of video analysis included a discussion (between two assessors) on additional interlinked parameters namely, 'relevant' (linked to 'viewer engagement'), 'holistic' (linked to 'quality of content') and 'actionable' (linked to 'potential impact'). After the discussion, it was noted (in 'yes' or 'no') if the video appeared relevant from the perspective of various stakeholder groups (how relatable the message is to contemporary issues), holistic (touches upon the topic from multiple perspectives) and actionable (does it motivate the viewer to take action in line with the message of the video). These parameters were found to be important based on the experience of developing a previous video (Kulshreshtha, 2020).

7.3.2 Limitations of video analysis

Although the detailed video analysis provided insights on the viewer engagement and quality of content, the overall analysis needs a scientific framework for quantitative results assessment. While scientific studies from the field of information science have investigated the impact of online videos through webometric analysis software, it has been so far restricted to qualitative (subjective) parameters related to viewers engagement to video (Kousha et al., 2012; Thelwall et al., 2012a; Thelwall et al., 2012b). This present research can therefore be considered as one of the pioneering attempts to analyses the content of videos quantitatively. While methods are available to assess qualitative information (such as the Harris profile method), it is useful when multiple people (of different backgrounds) are part of the assessment. This video analysis was restricted to assessment by 2 people only who moreover shared a rather similar background, hence limits its generality.

The rating used in this study could therefore be regarded as subjective or qualitative rather than quantitative.

7.3.3 Insights from video analysis

The assessment of YouTube videos gave insights on the characteristics of 'effective video', which could especially be useful for disseminating scientific knowledge on earthen construction. The highlights from the analysis are discussed briefly in this section. The complete database of the video analysis is available in Dataset 7X2 and Dataset 7X3.

Some of the key insights gained through the analysis were:

- The overall assessed quality of videos from the field of earthen construction was inferior to videos from the 'popular science' category. The average rating for earthen construction video was 6.3, as compared to 7.6 for the popular science category (see Figure 7.2). This could be due to a small audience or target group and a lack of resources to produce higher quality videos. Most channels from the 'popular science' category are already established and have multiple and more experienced/professional people working towards content creation. Whereas the channels entirely dedicated to earthen construction are relatively young, less experienced/ professional and have not yet established themselves.

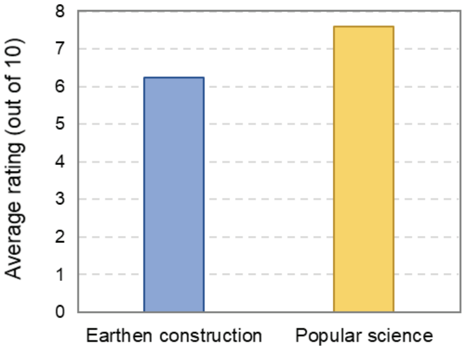

Figure 7.2: Relative performance of 'earthen construction' videos in comparison to 'popular science' videos. The complete database is available in Dataset 7X2 and Dataset 7X3

- The 'viewer engagement' was found to correlate with the cinematic or animation quality. The average rating of videos that were assessed 'high' in cinematic/animation quality was higher than videos that were assessed 'low' (figure 7.3(a)). However, a 'high' cinematic/animation quality is not necessarily linked to highly rated videos, as 5% of videos with 'high' cinematic/ animation quality scored lower than 6 (out of 10) in the assessment. Similarly, 8% of videos that were assessed low in cinematic/ animation scored higher than 7 (see Figure 7.3 (a)). The various aspects of storytelling (e.g., layout of content, narration style) also play an important role in the 'viewer engagement'. The use of entertainment in disseminating information through videos is effective, as also recommended by Thelwall et al. (2012a). In most high-rated animated videos, the viewer engagement was facilitated by developing humorous and enchanting animation characters. Moreover, it was found that minimal use of text and audio narration enhances 'user engagement' (see Figure 7.3 (a,b)). Whereas the long subjective length of video makes the content uninteresting. (See Figure 7.3 (c)). Other aspects of 'viewer engagement' such as narration speed were found to have no significant impact on the assessed rating (refer Appendix 7D).

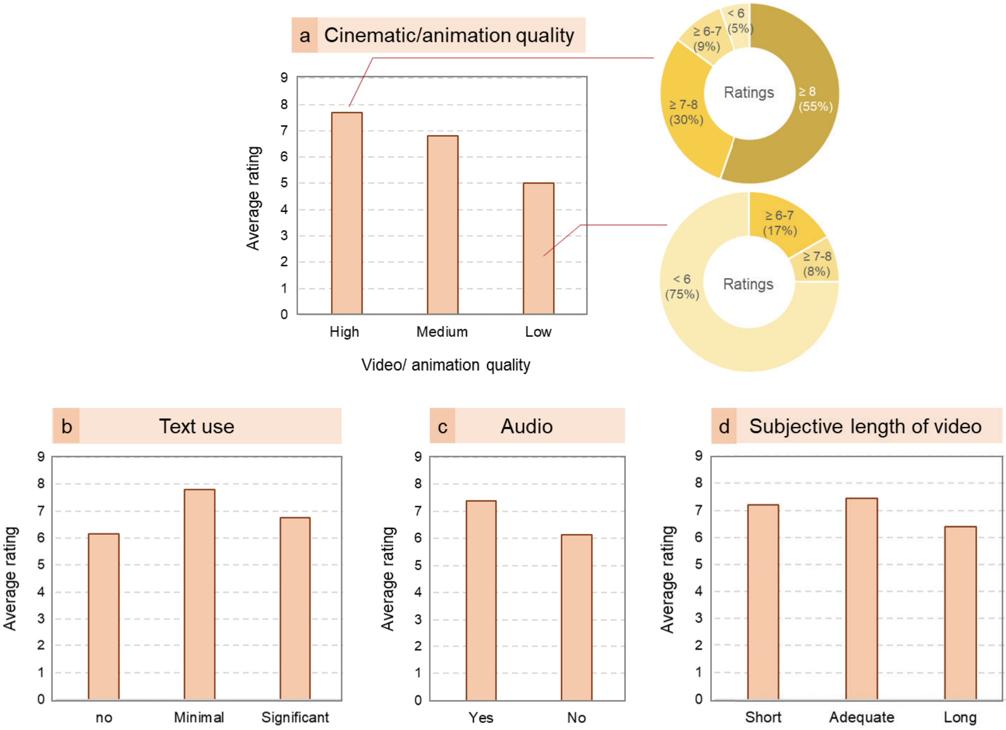

Figure 7.3: Various sub-parameters evaluated to assess the 'viewers engagement'. (a) Video/animation quality (the pie chart next to the plot represents the percentage share of videos based on rating levels), (b) text use, (c) audio, (d) video length feel. The complete database is available in Dataset 7X2 and Dataset 7X3

- The 'quality of content' of earthen construction videos was found to be inferior to the 'popular science' category. About 17% of videos on earthen construction were opinionated (biased) and lacked a scientific basis and therefore, assessed lower than rest of the videos (Figure 7.4). In addition, references supporting claims were missing from the majority of videos and their descriptions. Whereas these biases and lack of reference were not found in channels from 'popular science' category. Although in-depth videos scored higher than superficial videos, this was not necessarily an indication of higher quality of content. The depth of knowledge communicated through video depends on the purpose and targeted audience of the video.

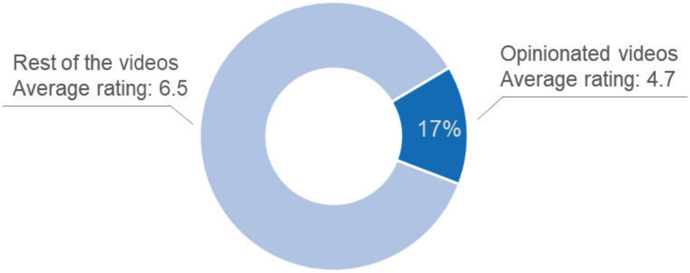

Figure 7.4: Opinionated earthen construction videos scored lower rating than rest of the videos.

- A positive trend between the assessed overall quality of videos and the number of views/ likes was found in earthen construction videos (Figure 7.5). Although a similar trend was observed for 'popular science' videos (refer Appendix 7E), this relation was more prominent in the earthen construction category (when comparing a same range of number of 'likes'). Analysis of all channels reveals that views and likes are not necessarily a useful indicator of impact, but rather useful for comparing the popularity of the channels. A channel gains popularity by publishing consistent quality videos over many years.

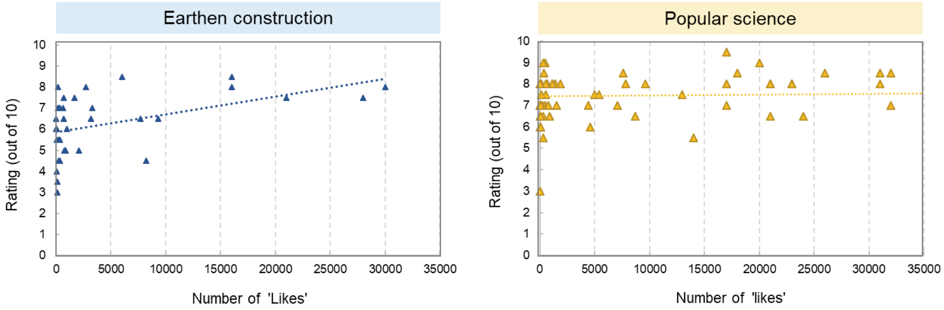

Figure 7.5: Relationship between rating and number of 'likes' in both 'earthen construction' and 'popular science' videos (within a limited range as determined by the maximum liked earthen construction video. The complete database is available in Dataset 7X2 and Dataset 7X3

- The majority of high-quality videos (throughout all categories) were found to be relevant, holistic and actionable (Figure 7.6). A video on a topic that is relevant to its target audience increases user engagement. About 52% of all videos were found to be relevant, whereas this proportion increased to 64% in videos of high quality (rating ≥ 8) (see Figure 7.6). A holistic approach to a video improves the quality of content and connects the topic to a diverse audience. While just 30% of the videos were found to be holistic, over 50% of high-quality videos (rating ≥ 8) were holistic. An actionable video promotes viewers to take action in line with the message of the video, and therefore, increases its potential impact. All the videos that were found to be actionable (6%) were of high quality. The videos with a moderate score (≥6-8) were assessed to be relatively less relevant and holistic, and none of them were actionable (see Figure 7.6). Videos with a rating of less than 6 were found to be neither actionable nor holistic.

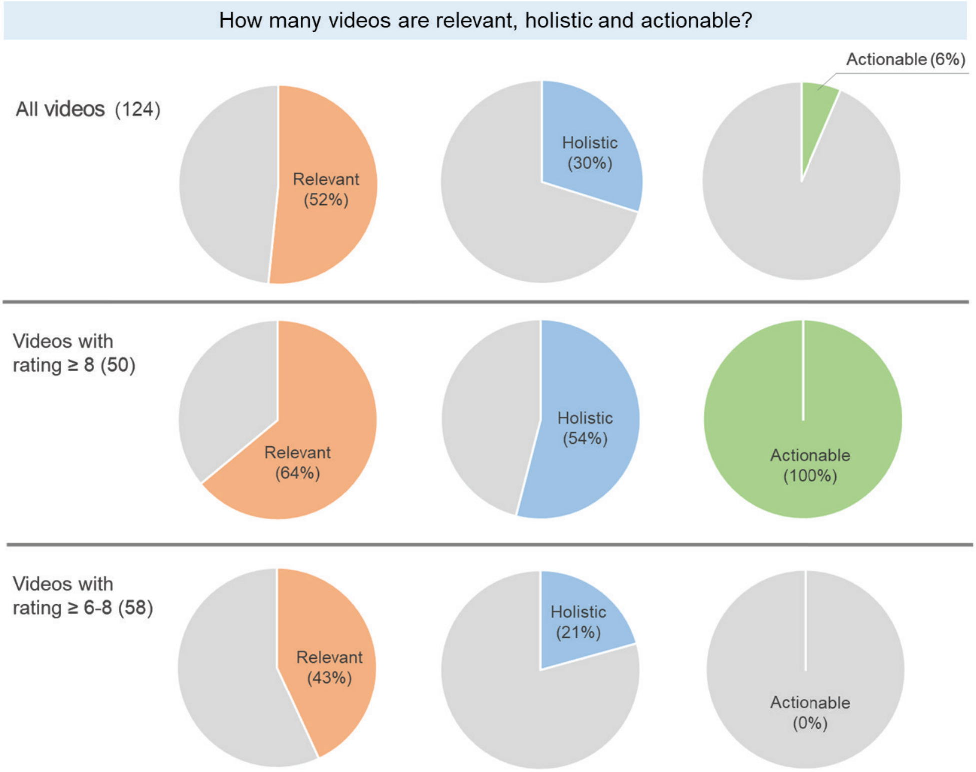

Figure 7.6: Proportion of relevant, holistic and actionable videos (based on their ratings). Note that the total number of videos in each category is different. The complete database is available in Dataset 7X2 and Dataset 7X3.

In general, videos from channels such as Kurzgesagt, TED-Ed, Veritasium and Vox were high in quality. The Nito Project and Storyhive were shown to have produced good quality content for people interested in earthen construction. The insights gained in video analysis are used as an input for the production of 2 videos related to content developed in this thesis.

7.4 Videos produced to disseminate the content of this research

The insights gained through video analysis provide essential guidelines for transforming the selected content of this thesis into two videos that 1. lead to wider awareness of building with earth and 2. could impact the practice of earthen construction. Both videos use the term ‘mud’ instead of ‘earth’, as mud is a more common word for people in India.

Details of the two videos are discussed below:

Video 1: Video to introduce various aspects of earthen construction to people unfamiliar with it and introduce it as an alternative material for construction

There is a lack of video that introduces various aspects of earthen construction to a general audience. Hence, a video is produced to create wider awareness of the potential of building with earth as an environmental friendly alternative to building with concrete and fired bricks. The target audience for this video are adults that are not yet aware of building with earth or the people who are slightly aware but lack the necessary information to evaluate it as an option for housing.

To improve the viewer engagement, the video uses digitally animated character and showcase a conversation between characters called earth (mud), fired brick and concrete to make the overall content engaging (Figure 7.7). To make the content relevant to people, the video starts with an introduction to the growing awareness of the polluting impact of building materials and the need for environmental friendly alternatives.

The quality of the content of the video is ensured by using scientifically accurate content from Chapter 2 to convey information on the history, strength, durability and techniques of earthen construction, in addition to uncovering a few myths. References are also included in the video and the link to the supporting detailed scientific document will also be added to the description, whenever the video is published online.

The video is meant to make people aware of several benefits of building with earth and prompt them to take an active part in reducing the environmental impacts of building material by choosing ecological building materials such as 'earth'. The video concludes with information on a working document that includes information on earthen construction organisations throughout the world. The documents will be updated based on the feedback of viewers and interested people could contact one of the nearest organisations to initiate discussion on earthen houses. Hence, it is expected that this video could have a positive impact on the choice of people in favour of earthen buildings.

The video can be accessed through this link: https://youtu.be/8cpu_2ghJaE

Figure 7.7: Screenshots and QR code of the video to introduce various aspects of earthen construction to people unfamiliar with it and introduce it as an alternative material for construction.

Video 2: Video communicating insights and recommendations for use of cow-dung in earthen construction

One of the useful scientific outputs of this thesis is the insight into how and why cow-dung leads to improved stabilised earthen blocks (discussed in Chapter 6). As discussed in Section 7.2, earthen construction practitioners and organisations use social media platforms such as YouTube as a source of information for research and practical projects. Hence, an instructional video is prepared with an aim of communicating insights on cow-dung stabilisation of earth to practitioners and organisations, especially those located in India.

As compared to Video 1, the requirements for this video are distinct due to the narrow focus of the content and specific target audience. As several earthen construction practitioners are already using online video to search for content related to earthen construction, the content of the video itself makes the video relevant. The video is meant to be useful for practitioners who are interested in biologically stabilised earthen materials. To make the video engaging, it includes stop motion animation in conjunction with original clips and shots from the experiments and upscaling. While the animation is used to explain complex ideas through simple visuals, the video shots provide the viewer with a proof of concept that could increase their trust in the message communicated through the video.

The quality of content is ensured through the use of experimentally validated results that were generated in Chapter 6. The video provides information on what makes cow-dung stabilised earthen material water resistant and lists recommendations that facilitate the valorisation of cow-dung stabilised earthen material. Although the content of the video has a narrow focus (and therefore, not holistic per definition), it addresses multiple concerns that a practitioner may face. The video will also be released with a scientific document linked to its description.

The video provides useful recommendations on building with cow-dung stabilised earthen materials and therefore, it has the potential to impact the practice of earthen construction. The video also encourages practitioners to test and validate the recommendations for their local context. The reach and potential impact of the video will be improved further through forwarding the video to earthen construction organisations and practitioners through email and social media.

The video can be accessed through this link: https://youtu.be/y-C3CtY1idA

Figure 7.8: Screenshots and QR code of video communicating insights and recommendations for use of cow-dung in earthen construction

7.5 The potential of YouTube videos in scientific communication: a way forward

The dissemination of scientific research is predominantly carried out through the publication of articles in journals. However, these are often inaccessible to a wider (non-scientific) community due to lack of financial resources or scientific understanding. However at the same time the use of social media for the dissemination of research by the scientific community is growing (Sugimoto et al., 2017). Dissemination of research through videos can lead to a wider impact on public understanding of science (Thelwall et al., 2012a). In addition, it could be valuable for fields such as earthen construction, which are dominated by independent practitioners who often use videos as a source of knowledge (refer Table 7.1). YouTube has a large user base and its various features such as ‘comment’, ‘like’, ‘dislike’ can support public engagement and discussion more effectively than scientific publications do. Although communication through YouTube videos has several advantages, limitations such as the need for a significant time in making effective and good quality videos, risk of bias due to no peer review, and the possibility of inaccuracy or factual misinformation reduces its widespread use by the scientific community (Kousha et al., 2012). While it is undeniable that YouTube videos cannot replace traditional academic publishing (yet), it can be used as a complementary tool to disseminate peer-reviewed information to a wider audience in engaging ways. Much like the wider use of impact factors to access the usefulness of scientific journal articles, a multi criteria evaluation system (as proposed and exemplified in this study) for valuing the quality of videos can perhaps motivate researchers to use video as an additional tool for scientific communication.

The availability of software to extract all the information related to YouTube video responses (comments, views, likes, dislikes), together with progress in content/comment analysis have led researchers to understand users engagement with the content of the video (Thelwall et al., 2012b). These advances in information science, in parallel with progress in machine learning and artificial intelligence, could enable assessment of complex information linked to audience response and provide quantitative information on its impact using algorithm. Thus, similar to journal articles, quantitative information on the impact of videos could motivate researchers to use YouTube as a scientific communication platform. The departmental or university YouTube channels could also play an emerging role for dissemination of scientific knowledge actively.

Investing financial resources in academic videos could promote valorisation of scientific research

'The growing inaccessibility of science', is a commentary by Hayes (1992) whose screenshot (webpage of 'Nature' with this title and asking a payment to access the article) is widely shared on social media platforms to reflect the dichotomy in the scientific publication. While the debate around this screenshot is primarily focused on scientific research that still sits behind a paywall, the discussion regarding the original content of the article is scarce. The article reveals that scientific articles are getting increasingly complex for non-specialists, thus restricting dissemination of its results. In addition to open availability, the dissemination of science is an aspect that can be bridged if resources are invested in transforming results of research into simple understandable videos.

The current academic infrastructure provides financial assistance for the open availability of scientific literature, including payment of article processing charge (APC) which often ranges from a few thousand euros to €9500, charged by Nature and

32 other journals (Else, 2020). The profit margins of private publishers and increasing open access fees has led to wide criticism. With a variety of options available to make research openly available without any cost (such as publishing pre-final versions of articles in institute repository or uploading it to Research Gate), it could be better to invest a part of the money on effective dissemination e.g., thorough independent artists and designers who can transform research into engaging videos. For example, instead of choosing a private journal with a higher APC, choosing a journal published by a non-profit organisation can save money that could be invested in scientific communication through social media. This will not only have a wider impact on the research but will also promote the growth of artists and the local economy. A major bottleneck in the realisation of such an approach is the perceived link between academic success and publication in high impact journals, which needs to be decoupled to promote the accessibility and dissemination of scientific knowledge globally.with cow dung used due to its perceived water-resistant characteristics. Several food-based stabilisers such as Terminalia Chebula (also known as Kadukkai or Haritaki),

7.6 Summary and conclusion

This chapter investigates the method of obtaining and disseminating knowledge in earthen construction practice. The dissemination of scientific knowledge is often carried through journal publications, which is then picked up by industries to develop and scale up the technology (independently or in collaboration with researchers). In comparison to other disciplines of sciences, earthen construction in India is still dominated by independent practitioners and organisations who lack resources to develop materials and technology themselves. Hence, an alternative science communication approach is proposed and investigated briefly in this thesis.

This chapter draws on the observation of the field survey (Chapter 3) and extends it through additional interviews to understand the sources and dissemination of scientific knowledge within the earthen construction community in India. The results reveal that the source of knowledge depends on the economic situation of the builders and practitioners. While low-income people get the knowledge to build from their ancestors and family members, middle-income practitioners learn from hands-on experience and use various social media platforms such as blogs and online videos (e.g., via YouTube). Along with social media, scientific articles are also referred sometimes to aid in research and earthen building construction. Communication through online videos is recognised as an effective and impactful medium to disseminate scientific knowledge to practitioners.

To understand the characteristics of an effective video, 124 YouTube videos were assessed on 'viewer engagement', 'quality of content' and 'potential impact', followed by a discussion if each video was relevant, holistic and actionable. It was found that the overall assessed quality of earthen construction videos was inferior to 'popular science' videos. Moreover, 17% of earthen construction videos were opinionated and lacked scientific background. The video analysis revealed that viewer engagement can be improved through good storytelling and entertainment. The majority of high-quality videos (throughout all categories) were found to be relevant (how relatable the message is to contemporary issues), holistic (touches upon the topic from multiple perspectives) and actionable (motivate the viewer to take action in line with the message of the video). The learning from the video analysis was utilised in the production of two videos. The first video is produced to create wider awareness of the potential of building with earth as an environmental friendly alternative building material. The video introduces various aspects of earthen construction (such as history, strength, durability, techniques of earthen construction, myths etc.) to a general audience. The second video (instructional) provides useful recommendations on building with cow-dung stabilised earthen materials and is therefore relevant for earthen construction practitioners and organisations.

The lack of effective scientific dissemination through the traditional publication system and increase in the use of social media by the scientific community is paving way for alternative science communication and dissemination. The large user base of online video platforms, e.g., YouTube provides opportunities to engage with a wider audience and make a bigger impact. Online videos could be used in conjunction with scientific articles to reach a diverse audience. The progress in the field of information science could enable qualitative assessment of the impact of a video, thus motivating more researchers to use online videos for the dissemination of their research.

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8

Conclusions, Reflection, and Recommendations

“Sometimes life is like this dark tunnel. You can’t always see the light at the end of the tunnel, but if you just keep moving… you will come to a better place”

– Iroh, Avatar the Last Airbender (S2 E20)

8.1 Conclusions

This research focused on developing a low-cost, water resistant and desirable earthen building material for rural housing in India. The development of the material was initiated with a field survey in different bioclimatic regions of India to understand the factors favouring and limiting the everyday use of earthen houses in India. The low image of earthen materials was found to be a key barrier towards its widespread acceptance. The low acceptability was identified to be mainly due to its poor water resistance characteristics leading to the need for frequent maintenance. Based on the survey results, the improvement in water resistance characteristics through enhancing material characteristics was determined as a prime focus of the thesis. Due to the lack of fundamental studies on water resistance characteristics of unstabilised earthen material, an investigation was carried out to understand factors influencing water resistance of unstabilised earthen blocks. The investigation provided insights on improving water resistance of unstabilised earthen blocks slightly. To enhance the water resistance of earthen materials significantly through natural additives, biological stabilisers were investigated as an alternative to chemical additives. A literature review on biological stabilisers was conducted to understand their effect on the water resistance of stabilised earthen materials. A technical, economic and environmental assessment indicated the potential of cow-dung, a widely available and accepted material in India, for rural housing. A thorough investigation into cow-dung stabilised earthen material led to multiple insights for improving their water resistance characteristics and their applicability in practice. To widen the impact of scientific research work, YouTube as a communication medium was analysed and insights were used in transforming the selected parts of this thesis into engaging videos.

The conclusions of this thesis are presented as answers to the research questions that were formulated in Chapter 1.

Can earthen materials be a solution to the contemporary rural housing shortage in India?
What are the factors favouring or limiting the construction and everyday use of earthen houses in rural India? What are the requirements and demands for the re-invention of earthen houses as a necessary step towards its wide-scale adoption?

Building houses with earthen materials is a practical choice for low-income households living in rural areas due to the unaffordable cost of conventional building materials such as cement and fired bricks, availability of abundant earth locally and knowledge and understanding of building with earth. However, the number of earthen houses are consistently declining in India and hence, it was important to understand the factors favouring and limiting the construction and everyday use of earthen houses.

A survey was carried out in several bioclimatic regions of India and revealed that while factors such as low-cost, ecology and thermal performance favour construction of earthen houses, factors such as low social image, low durability and requirement of frequent maintenance limit the construction and everyday use of traditional earthen houses in rural India. Amongst all factors, the low image of earth was identified as the key barrier towards the acceptance of earth as a building material for low-income households.

The image is strongly linked to poverty, and it is significantly influenced by the poor performance of traditional earth houses (in terms of poor water and weather resistance and termite infestation), frequent maintenance and governmental policies that give a negative reputation to earth. To improve the acceptance and wider adoption of earthen materials for affordable rural housing, some of the identified requirements and demands for the re-invention of earthen materials were: 1. Good durability performance (water resistance, termite resistance etc.), 2. Limited required maintenance, 3. Good aesthetics of both the material and structure, and 4. Affordable for low-income households. The adoption of earthen construction for rural housing is expected when these requirements are met, and several high-quality earthen structures are built in diverse locations. In this regard, modern earthen construction techniques such as compressed stabilised earth blocks (CSEB) are viable due to the good quality of the finished product and the wide availability of low-cost CSEB making presses/machines. The cost of CSEB can be reduced by minimising the use of cement and hydraulic lime in favour of bio-based alternatives.

Earthen materials may not be immediately applied to the contemporary construction of mass housing due to lack of successful demonstrations and trust of government and people. However, the growth and progress in earthen construction in India especially led by ecologically conscious people, in parallel to increasing interest in traditional and indigenous practices, is expected to make earthen construction a practical solution for rural housing soon. Therefore, the research on affordable, durable, and desirable earthen materials should be carried forward to support the adoption of earthen material for rural housing.

How can the characteristics of unstabilised compressed earthen blocks be optimised for enhanced water resistance? *What are the factors that influence water resistance and compressive strength of unstabilised earthen blocks? How does the microstructure of earthen block impact water resistance?*

Unstabilised compressed earthen blocks are economic and ecological alternatives to stabilised earthen blocks. However, their use in construction is often restricted by their durability, especially water resistance performance. Hence, enhancing the water resistance of unstabilised earthen blocks can contribute to its wider acceptance.

Experiments were conducted to test the influence of variables such as clay mineralogy, compaction pressure, compaction technique, compaction water content (water content in the earthen block immediately after compaction), and pre-wetting/residual water content (water content in earthen block just prior to the water resistance test or during strength test) on water resistance and compressive strength of unstabilised CEBs. It was found that, unlike compressive strength that is linked to soil composition and the dry density, the water resistance of unstabilised CEBs depends on soil composition, dry density and also on the compaction water content. In CEBs of similar dry density and strength (and soil composition), a higher compaction water content resulted in better water resistance. A microstructural investigation on CEBs revealed that compaction water content impacts the distribution of pores within the materials. With the addition of water, the pore size and the volume of the largest pores (macro-pores) decrease significantly. As the water ingress is known to depend on the size of the largest pores, the reduction in macro-pore size and volume improves the water stability of earthen blocks. In CEBs of similar dry density and porosity, the increase in compaction water content from 8.6% to 16.2% reduced the macro-pores volume by 13 times, resulting in 6.5 times better water resistance performance (measured through drip test).

The volume of macro-pores volume can also be reduced by increasing the compaction pressure, thus resulting in improved water resistance. The influence of compaction pressure on water resistance is significant in drier mixes (dryer than optimum water content) but decreases with increasing compaction water content. The compaction method (compressed or rammed block) was found to have a minor influence on the water resistance characteristics of earthen material.

The clay mineralogy was found to have the most significant influence on water resistance behaviour. Blocks prepared with bentonite clay could survive immersion for 5 days whereas blocks made with kaolinite clay disintegrated in 2 minutes. While the positive result motivates the use of bentonite clay in earthen construction, the swelling and shrinking of clays due to cyclic wetting and drying could lead to the formation of cracks, increasing the susceptibility of earthen materials to water ingress and structural failure.

The pre-wetting water content (water content in earthen block just prior to the water resistance test) had a major influence on the water-resistance behaviour of unstabilised CEBs. CEBs with higher pre-wetting water content (12.6%) performed 6 times better in the drip test than CEBs with low pre-wetting water content (<6%). A higher pre-wetting water content (or a high degree of saturation) reduces the hydraulic gradient and therefore, reduces the rate of water ingress.

Based on the investigation, an affordable option to enhance the water resistance of unstabilised blocks is to prepare blocks with a higher compaction water content and if feasible, a high compaction force. Moreover, the clay mineralogy, hence soil selection plays a crucial role in determining water resistance characteristics. Hence, the selection of appropriate soil is an essential step towards improved water resistance of earthen houses.

Which biological stabilisers are feasible to be used for affordable rural housing in India? *How do various biological stabilisers resist water ingress? How do biological stabilisers compare on technical, environmental and economic performance?*

The widespread debate around the use of chemical stabilisers has led to growing interest in biological stabilisers which are perceived eco-friendly and have proven their effectiveness in traditional earthen construction. In addition, the use of biological stabilisers in earthen construction can be an affordable alternative to conventional stabilisers such as Portland cement and hydraulic lime. Hence, a wide range of biological stabilisers derived from animals (cow-dung, casein, chitosan), plants (starch, guar gum, cactus mucilage, lignin, tannin, linseed oil), seaweeds (alginate, agar, carrageen) and microbes (xanthan gum, gellan gum) were reviewed and assessed for their feasibility in construction of affordable houses in rural India.

While significant information on strength related characteristics of biologically stabilised earthen materials is available in scientific literature, the information on water resistance characteristics is limited. Therefore, a thorough theoretical investigation was conducted to understand how various biological stabilisers resist water ingress. This investigation was then used to propose interaction mechanisms that facilitates water-resistance of biologically stabilised earthen material. The water ingress and the subsequent effect in biologically stabilised earthen material is a coupled process, where more than one mechanism affects the flow of water through the earthen material. A stabiliser can modify the pore structure by pore-filling, or by altering the physico-chemical properties of soil surface, or by transforming stabiliser into a water-stable form by heating or addition of cation, or by a combination of these mechanisms. The addition of a stabiliser modifies the pore structure (such as in cactus, lignin) by filling the voids of earthen material, thereby reducing the size of the largest pore, and enhancing the water resistance. The physico-chemical properties of stabilisers such as hydrophobicity (observed in chitosan, linseed oil, carrageenan) modify the surface characteristics of clays/sand, thereby affecting water ingress. Processes such as heat treatment (as shown to be effective in casein, starch, agar gum and gellan gum) and cation addition (effective in casein, alginate and gellan gum) also enhance the water resistance of stabilisers and their interaction with soil under wet condition. Stabilisers also form ionic (as reported in chitosan, casein, lignin) and hydrogen bond (as reported in starch, xanthan gum, guar gum, Gellan gum) with clay and could limit their swelling.

A technical assessment of biological stabilisers reveals that while some of them can improve compressive strength characteristics, they do not perform comparatively well to chemical stabilisers in water resistance tests. Moreover, the costs of industrially produced biological stabilisers are significantly higher than cement and hydraulic lime, even though lower quantities of the material are required for stabilisation. In this regard, traditional stabilisers such as cow-dung, cactus juice and tannins could be cost-effective if sourced and processed locally. While biological stabilisers are perceived as environmental friendly, a clear assessment through life cycle analysis is missing to reveal their actual ecological impact. Extraction of industrial biological stabilisers involves significant energy, chemical and water usage, which can increase their ecological footprint. Stabilisers that can be extracted from waste (such as cow-dung, casein, starch) could be explored as an eco-friendly alternative.

Based on the assessment of biological stabilisers, cow-dung was found to be an economic and ecological stabiliser that is relevant for rural housing in India due to its known water resistance characteristics, wide availability, and wide acceptability.

How to enhance the water resistance characteristics of cow-dung stabilised earthen blocks for practical applications? *What makes cow-dung stabilised earthen material water resistant? How do the various components of cow-dung and soil impact the water resistance characteristics of stabilised earthen blocks?*

The use of cow-dung is anecdotally attributed to its water resistance characteristics. However, there are no comprehensive studies that provide insight into the water resistance characteristics of cow-dung stabilised earthen materials Therefore, an experimental investigation was carried out to gain insights and re-invent cow-dung stabilised earthen blocks for contemporary earthen housing construction.

The addition of cow-dung improves the water resistance of stabilised compressed earth by (up to) over 500 times (as measured through drip test). However, the addition of cow-dung had no impact on compressive strength. Several variables related to composition (soil and cow-dung) and casting were tested to investigate their influence on water resistance characteristics of cow-dung stabilised compressed earth blocks (CD-CEBs). The ageing of cow-dung (duration of storage after collection of fresh cow-dung) and compaction force were found to have a minimal impact on the performance of CD-CEBs. However, the ageing of cow-dung soil mixture up to 14 days (duration of storage after mixing soil and dung) and a higher compaction water content improved both strength and water resistance.

The components of cow-dung and soil play an influential role in determining the water resistance of cow-dung stabilised blocks. When a cow-dung stabilised block is immersed in water or subjected to rain, the water ingress results in swelling and re-alignment of fibres, in conjunction with swelling of clays. These processes results in disruption of the bond between soil aggregates, leading to disintegration of stabilised earthen blocks. To further investigate the impact of different components of cow dung, wet cow-dung was collected and separated into 3 components: Fibres, Medium-sized microbial aggregates (MSMAs) and Small-sized microbial aggregates (SSMAs). Amongst these components, SSMAs, which constitute approximately one-third of the solid mass of cow-dung, were shown to be responsible for water-resistance characteristics of cow-dung and cow-dung stabilised compressed earth blocks (CD-CEBs). SSMAs extracted from cow-dung are negatively charged particles (0.5-7µm) of low specific surfaces. They are extremely water repellent and rich in fatty acids.

The disintegration of a cow-dung stabilised block is sensitive to the presence and type of clay minerals. In absence of clays and fibres, a stabilised block (sand + SSMA) was able to survive immersion without disintegration for a substantial time, whereas the presence of fibres or swelling clays resulted in faster disintegration. Moreover, the water resistance of CD-CEBs were improved over 30 times by using a low-swelling clay mineral such as kaolinite rich soil. Although the water resistance could be improved by selecting a low-swelling mineral rich soil, it is important to evaluate if the selected soil provide sufficient strength for the construction.

The insights gained through the experimental study are compiled in form of recommendations to enhance the water resistance characteristics of cow-dung stabilised earthen materials. The full list of recommendations is available in Section 6.6 (Chapter 6), whereas a shorter version is enlisted here:

- Use fresh or wet cow-dung over dry cow-dung for enhanced water resistance. The use of wet cow-dung in CD-CEBs provided over 80 times better water resistance than CD-CEBs prepared with dry cow-dung. The ageing or storage of wet cow-dung does not influence the characteristics of cow-dung stabilised earthen materials.

- Adopt a higher compaction water content for casting the cow-dung stabilised earthen materials. A higher water content enhances both the water resistance and strength characteristics. Adopting a higher compaction water content (by 3%) improved the water resistance by over 40 times.
- After collecting the fresh cow-dung, mix it with soil soon and store this mix until the casting. The storage or ageing of soil cow-dung mix for over 3 days removes the pungent smell of cow-dung permanently. Interestingly, the soil cow-dung mix can be stored for a long duration (6-12 months) without the growth of fungus.
- While selecting a soil for mixing with cow-dung, it is recommended to select soil with low or no swelling clay minerals such as kaolinite minerals.

These recommendations are expected to facilitate architects, practitioners, self-builders and natural-building enthusiasts to build earthen houses that are affordable, durable and desirable.

How to maximise the impact of scientific research through alternative science communication approach? *What are the sources of scientific knowledge that enables practitioners to build with earth? What are the characteristics of an effective communication medium to convey the outputs of the thesis to a target audience?*

Earthen construction in India is still dominated by independent practitioners and organisations who often lack the necessary resources to access the growing scientific literature on earthen construction. Hence, in conjunction with scientific articles, an alternative science communication medium could disseminate scientific knowledge to wide users and maximise the impact of the research project. A survey to understand the sources and dissemination of scientific knowledge within the earthen construction community in India revealed that the source of knowledge depends on the economic situation of the builders and practitioners. While low-income builders get the knowledge from their ancestors and family members, middle-income practitioners and organisations learn from hands-on experience and various social media platforms such as blogs and YouTube videos.

Communication through online videos (eg. YouTube) was recognised as the effective communication medium to disseminate scientific knowledge to practitioners. To understand the characteristics of an effective video, 124 YouTube videos were assessed on 'viewer engagement', 'quality of content' and 'potential impact', followed by a discussion if each video was relevant, holistic, and actionable. The video from the 'popular science' category (by stabilised channels) acted as a benchmark for assessing and rating the videos of 'earthen construction'. (Some of insights gained from video analysis were: 1. The overall assessed quality of earthen construction videos was inferior to 'popular science' videos. 2. 17% of earthen construction videos were opinionated. 3. The majority of high-quality videos (throughout all categories) were found to be relevant (how relatable the message is to contemporary issues), holistic (touches upon the topic from multiple perspectives) and actionable (motivate the viewer to take action in line with the message of the video). 4. Viewer engagement can be improved through good storytelling and entertainment, for example using humorous and enchanting animation characters.

The learning from the video analysis was utilised in the production of two videos, one to create wider awareness of building with earth as an eco-friendly alternative building material and another to provide recommendations or instructional on the efficient use of cow-dung in earthen construction for earthen construction professionals. It is expected that these videos will create widespread awareness of earthen construction and influence the earthen construction practice in India.

8.2 Reflection and recommendations for future research

This thesis is anticipated to contribute to the field of earthen construction and other fields within the broader theme of science and technology. The research work is expected not only to provide scientific insights that facilitate understanding of earthen materials but the knowledge that can be directly applied for the construction of earthen houses. This thesis contributes towards a better understanding of water ingress and water resistance in unstabilised and biologically stabilised earthen materials, especially cow-dung stabilised earthen materials.

A reflection on shortcomings of this research and gaps identified in existing literature and present study provides interesting research topics to explore in future research. The gaps in scientific understanding of unstabilised and biological stabilised earthen material are addressed throughout the thesis, especially in Section 5.5 and therefore, not repeated here. Although, the major limitations and gaps in the current study are compiled to guide future research in earthen materials and construction:

- The experimental research in this thesis was carried out on a single type of soil and a single source of cow-dung. Hence, replication studies involving a variety of natural or artificial soils and various sources of cow-dung are required to reinforce and generalise the validity and conclusion of this research. Most methods used in this research are designed to be replicated. Hence, it is expected that this study would facilitate future research on cow-dung stabilised earthen material. Studies are also required on scaled-up blocks or walls to test the validity of results across all scales.
- Although the demonstration structure (briefly presented in Chapter 6 and Chapter 7) is not an integral part of this thesis, it provides insights revealing major gaps in the understanding of water resistance of unstabilised earthen material at different scales. While the thesis provides a microstructural understanding of water ingress, the understanding of water ingress and water resistance of unstabilised earthen material is required at an architectural scale. A thorough scientific understanding of the water resistance of unstabilised earthen

materials is urgently required to increase trust in unstabilised earthen materials, especially in India.

- The experiments conducted to evaluate water resistance of earthen blocks were custom made and not entirely indicative of the real-life performance of unstabilised and stabilised earthen materials. The choice of the tests was also governed by the pandemic. Therefore, it is suggested to use suitable water resistance tests that provide representative results and can also be replicated easily in modestly resourced labs. There is also a need for standardised tests to measure water resistance of earthen material. Standardisation of tests, in addition to availability and supply of standard soil, can facilitate a fair comparison between studies conducted in different labs.

- Attention is required on the research of biological stabilisers, in particular understanding their water resistance performance. The gaps in the knowledge of environmental performance, biodegradability, moisture buffering capacity and scalability of biologically stabilised earthen materials need to be addressed to evaluate their feasibility in practical applications.

- The informal and semi-structured surveys were restricted to a small number of interviewees (40), majorly from low-income households. A formal and structured survey on a large number of people from diverse regions and economic backgrounds can provide further insights into the aspirations of people and future trajectory of earthen construction in India. The survey should include people from middle- and upper-income households, policymakers, earthen construction entrepreneurs, building material industry etc. to capture a wide range of viewpoints on building with earth.

- The original planning of the thesis included research on starch extracted from waste rice water. However, this study was abandoned due to the closure of the restaurant (due to Covid-19 restrictions) that supplied the raw material. The preliminary results were encouraging, and the starch stabilised blocks performed as good as cow-dung stabilised earthen blocks. Hence, research into stabilisation with starch extracted from wastewater should be continued in future, provided if it is economically and logistically feasible to extract large quantities of starch and use it in a housing project.

Appendix

Appendix Chapter 2: Supplemental information to Chapter 2 "Earthen construction: as simple as A, B, C, D?"

Appendix 2A: National standards for earthen construction

The information regarding national standards (and some other normative documents) for earthen construction is based on Jiménez Delgado and Guerrero (2007); Schroeder (2012); Marsh and Kulshreshtha (2021)

Country	Standard
India	IS: 4332 (1967), 2110 (1998), 13827 (1998), 1725 (2013), 17165 (2020)
United States of America	ASTM E2392/E2392M (2010)
Brazil	NBR 8491-2, 10832-6, 12023-5, 13554-5 (1984-96), 13553 (1996)
Nigeria	NIS 369 (1997), ARS 670-683 (1996)
Ethiopia	ARS 670-683 (1996)
Egypt	HBRC (2016), ARS 670-683 (1996)
Democratic Republic of the Congo	ARS 670-683 (1996)
Turkey	TS 537 (1985)
Germany	Lehmbau Regeln (2009), DIN 18945 (2018), DIN 18946 (2018)
France	AFNOR XP.P13-901 (2001)
United Republic of Tanzania	ARS 670-683 (1996)
Columbia	NTC 5324 (2004)
New Zealand	NZS 4297 (1998), NZS 4298 (1998), NZS 4299 (1998)
Peru	NTE E 080 (2000)
Zimbabwe	SAZS 724 (2001)
Australia	HB 195 (2002), Bulletin 5 (1992), EBAA (2004)
USA	NMAC 14.7.4 (2000), ASTM E2392/E2392M (2010)
Spain	MOPT (1992), UNE 41410 (2008)
Kyrgyzstan	PCH-2-87 (1988)
Kenya	KS02-1070 (1999)
Nigeria	NBC 10.23 (2006), NIS 369 (1997)
Switzerland	Regeln zum Bauen mit Lehm (1994)
Tunisia	NT 21.33, 21.35 (1998)

Appendix Chapter 3: Supplemental information to Chapter 3 "The potential and current status of earthen material for low-cost housing in rural India"

Appendix 3A: Information on survey locations

Information on bioclimatic, geographical and meteorological classification of the interview location is presented in Table 3A.1.

Table 3A.1: Bioclimatic, geographical and meteorological classification of the surveyed location. The number of census houses made up with mud/unburnt bricks as the predominant material of wall [based on Census 2011 (Chandramouli, 2011)] is also listed.

Location	**Indian state**	**Geographical Location**	**Elevation (m)**	**Bioclimatic-zone: BIS classification (Köppen-Geiger)**	**Ambient temperature**	**Relative humidity**	**Rainfall (mm)**	**No. of rural houses with mud wall (% of total houses)**
Bir, Kangra district	Himachal Pradesh	North	1410-1620	Cold and Cloudy (Humid subtropical climate)	Summer: 17–29 °C (Jun 24.2),winter: 3–19 °C (Jan 7.6), Average temp: 16.6°C	70–80%	2135 mm	518,775 (22%)
Rakkar village: Dharmshala, Kangra district	Himachal Pradesh	North	1260-1280	Cold and cloudy (Humid subtropical climate)	Summer: 21–32 °C (Jun 27.1),winter: 3–19 °C (Jan 8.6), Average temp: 19.1°C	70–80%	2883 mm	518,775 (22%)
Delhi	Delhi (union territory)	North	209	Composite (Semi-arid)	Summer: 25–41 °C (Jun 34.3),winter: 6–25 °C (Jan 14.2), Average temp: 25.2°C	20–25% (dry), 55–95% (wet)	693 mm	82,507 (urban,2%)
Kripara-mpura, Jaipur district	Rajasthan	North-west	295	Hot and dry/ Composite , (Semi-arid)	Summer: 25–41 °C (Jun 33.1),winter: 8–26 °C (Jan 15.5), Average temp: 25.1°C	25–40%	601 mm	3,089,906 (26%)
Namchi	Sikkim	North-east	1325-1340	Cold and cloudy, (Oceanic climate)	Summer: 16-22 °C (Aug 21.4),winter: 7–18 °C (Jan 11.1), Average temp: 17.5°C	70–80%	2699 mm	13,159 (13%)
Khunti	Jharkhand	East	610-620	Composite/ Warm and humid (Humid subtropical climate)	Summer: 21-39 °C (May 31.3), winter: 10–29 °C (Dec 16.8), Average temp: 23.9°C	20–25% (dry), 55–95% (wet)	1350 mm	3,684,954 (67%)

Sundargarh district	Odisha	East	210-220	Composite/ Warm and humid (Tropical wet and dry climate)	Summer: 23-42 °C (May 34.2), winter: 11–30 °C (Dec 19.3), Average temp: 26.5°C	20–25% (dry), 55–95% (wet)	1448 mm	4,883,041 (49%)
Bhuj	Gujarat	West	125-130	Hot and dry, (Desert climate)	Summer: 22-39 °C (May 32), winter: 10–29 °C (Jan 17.9), Average temp: 26.3°C	25–40%	358 mm	2,109,301 (26%)
Khavda	Gujarat	West	15-20	Hot and dry, (Desert climate)	Summer: 25-42 °C (June 33.8), winter: 7–30 °C (Jan 17), Average temp: 26.9°C	25–40%	300 mm	2,109,301 (26%)
Auroville	Tamil Nadu	South	30-60	Warm and Humid (Tropical wet and dry climate)	Summer: 25-37 °C (June 31.8), winter: 20–30 °C (Jan 24.3), Average temp: 28.1°C	70–90%	1141 mm	3,020,940 (28%)
Sittling	Tamil Nadu	South	380-400	Warm and Humid (Tropical wet and dry climate)	Summer: 23-36 °C (May 30.1), winter: 17–33 °C (Dec 23.3), Average temp: 26.8°C	70–90%	877 mm	3,020,940 (28%)
Tiruvannamalai	Tamil Nadu	South	160-170	Warm and Humid (Tropical wet and dry climate)	Summer: 25-38 °C (May 32.1), winter: 19–31 °C (Dec 24.2), Average temp: 28.2°C	70–90%	1033 mm	3,020,940 (28%)
Bangalore	Karnataka	South	880-940	Moderate (Tropical wet and dry climate)	Summer: 19-34 °C (April 27.1), winter: 14–30 °C (Dec 20.7), Average temp: 23.6°C	20–55% (dry), 55–90% (wet)	831 mm	649,849 (Urban, 10%)
Pondicherry	Pondicherry	South	30-35	Warm and Humid (Tropical wet and dry climate)	Summer: 25-38 °C (June 32.1), winter: 22–30 °C (Jan 24.5), Average temp: 28.3°C	70–90%	1171 mm	15,385 (14%)

Appendix 3B: Information on survey group

Table 3B.1: Information on the region, profession, and the relation of each interview with earthen construction.

Identification	Region	Profession	User/ Expert
P1	Eastern	Farmer	User
P2	Eastern	Homemaker	User

P3	Eastern	Farmer	User
P4	Eastern	Head of village	User
P5	South	Architect	Expert
P6	South	Architect	Expert and User
P7	South	Farmer	User
P8	South	Volunteer	None
P9	South	Mason	Expert
P10	South	Consultant/ Engineer	Expert and User
P11	Western	Head of village	User
P12	North	Homemaker	User
P13	North	Mason	Both
P14	North	Volunteer	None
P15	North	Architect	Expert and User
P16	North	Psychiatrist	User
P17	North	Government	None
P18	North	Volunteer (student)	Student
P19	Northeast	Architect	Expert
P20	Northeast	Architect	Expert
P21	Northeast	Farmer	User
P22	Northeast	Homemaker	User
P23	Northeast	Writer	User
P24	Northeast	Engineer (Government)	Expert and User
P25	South	Architect	Expert
P26	South	Consultant/ Engineer	Expert
P27	South	Architect	Expert and User
P28	South	Architect	Expert
P29	South	Architect	Expert
P30	South	Potter	Expert
P31	South	Architect	Expert and User
P32	South	Mason	Expert
P33	South	Architect	Expert and User
P34	North	Policy maker (Government)	None
P35	North	Head of village	User
P36	North	Shopkeeper	User
P37	West	Mason	Expert and user
P38	West	Farmer	User
P39	West	Homemaker	User
P40	West	Priest	User

Appendix Chapter 4: Supplemental information to Chapter 4 "Water Resistance of Unstabilised Compressed Earth Blocks: An Experimental Investigation"

Appendix 4A. Mercury Intrusion Porosimetry (MIP)

4A1. MIP procedure

A dried sample was placed in the penetrometer and closed tightly. The penetrometer was inserted in the low-pressure chamber of the device and the test was started. The penetrometer (and the sample) was evacuated to remove air and residual moisture before reaching a gas pressure of 60 μm of mercury when the mercury intrusion starts. The intrusion of mercury in the penetrometer (in low-pressure chamber) is caused by the air pressure that increases from 0 to 0.14MPa gradually and fills up all the large pores (0.5 to 400 μm). After completion of mercury intrusion in the low-pressure chamber, the penetrometer was transferred to a high-pressure chamber where mercury is pressurised into the sample by surrounding hydraulic fluid. The pressure was increased from 0.14 MPa to 210 MPa filling up the pores as small as 7 nm. After the intrusion cycle, the pressure was reduced from 210 MPa to 0.14 MPa, resulting in the extrusion of highly pressurised mercury. After reaching the pressure of 0.14 MPa, the test finishes. Thereafter, the penetrometer can be removed and both sample and mercury could be discarded and stored in a safe manner.

4A2. MIP Error in Mercury Intrusion Porosimetry (MIP) measurement caused due to inappropriate closing of high pressure chamber.

Initial tests conducted on CEB samples gave an error in measurement making the test result unreliable and non-usable (Figure 4A.1). In these tests, no mercury intrusion was recorded between 0.14 and 1 MPa. It was found that the error was caused due to inappropriate closing of the high-pressure chamber resulting in some intrusion of mercury in the sample before the measurement in high-pressure chamber started. However, by reducing the speed of closing the chamber by about 25% (taking 2-3 minutes to close the chamber), the error was prevented in all the follow-up tests.

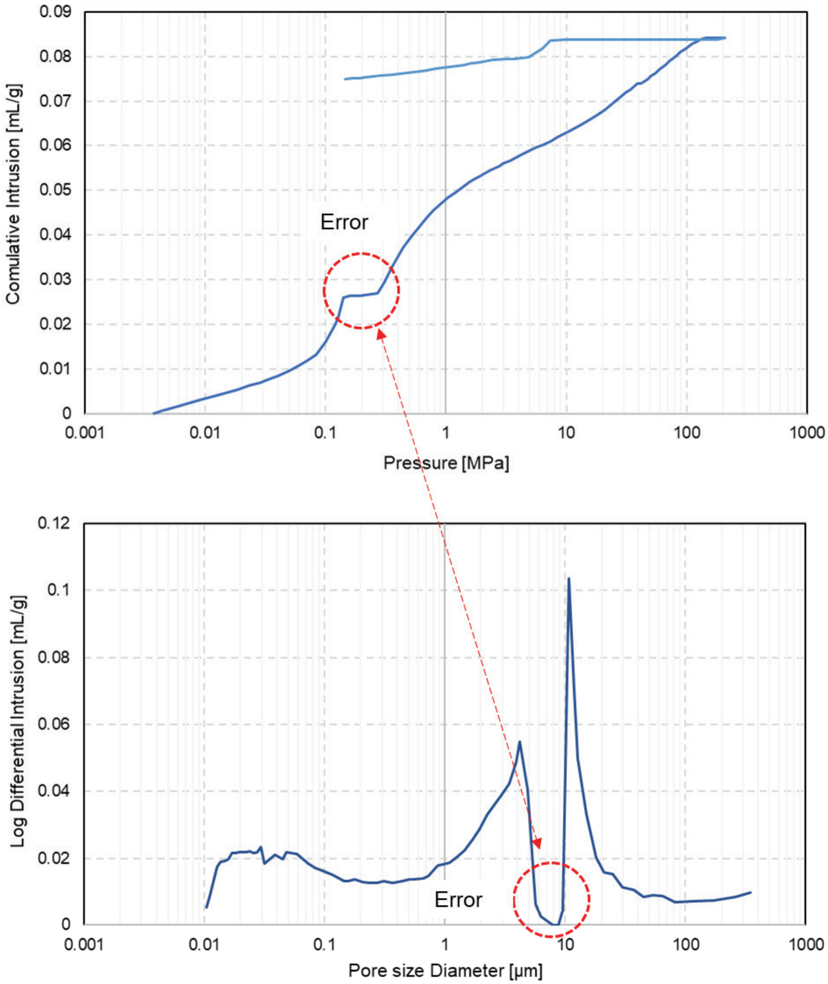


Figure 4A.1: Error in MIP causing no change in intrusion with increasing pressure, resulting in missing data points in the graph of log differential intrusion and pore size curve.

Appendix 4B. Loss of water during compaction process

A loss of water was observed in all the samples compacted beyond water content of 12%. The CEBs with the highest compressive strength was prepared with soil of 15.1% water content, but the compaction process resulted in a significant loss of water (2.6%) bringing the compaction water content to 12.6%. Similarly, the water content in CEBs prepared with soil of 17.1% water content reduced to 14.2% after the compaction process.

Due to the difference in sample preparation method, the compaction curve obtained through Proctor test is different than and curve obtained through CEB production process (Figure 4B 1). In both the compaction processes, similar maximum dry density was achieved. However, the optimum moisture content (corresponding to maximum dry density) obtained in CEB production process is higher.

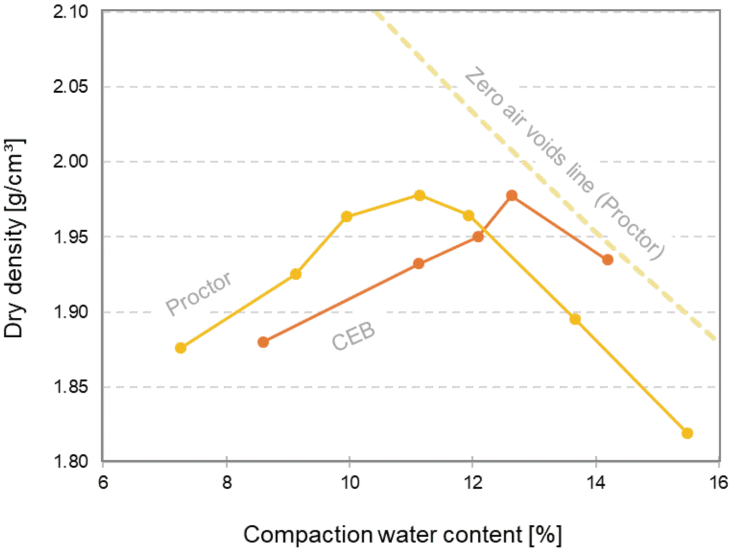


Figure 4B.1: The relationship between dry density and water content, i.e compaction curve, obtained through Proctor test and CEB production process.

Appendix 4C. Image of samples from the drip test (compaction water content and its effect on water resistance)

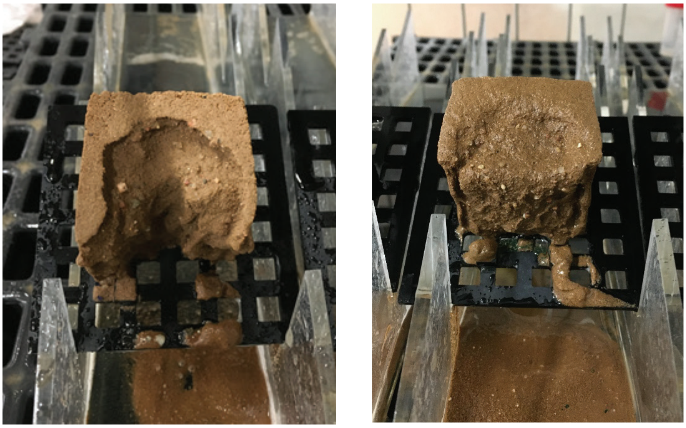

Compaction water content:11.1%   Compaction water content:14.2%

Figure 4C.1: Results from drip test: CEB with 11.1% compaction water content after 7.30 min (complete failure) and CEB with 14.2% compaction water content after 10 min. Both samples have a dry density of 1.93 g/cm^3

Appendix 4D. Shrinkage and hardness test

The dataset on shrinkage and hardness test is available in Dataset 4Y3 (Kulshreshtha, 2022). Shrinkage in CEBs increased from 0.15% to 3.4%, as expected with the increasing compaction water content of 8.6-14.2% . The hardness of freshly casted CEBs decreased (from 192 to 69) with a rise in compaction water content (8.6-14.2%). This was expected as the green (fresh) strength or hardness of earthen material is dependent on the water content in the sample. The samples with hardness less than 90 were found to deform slightly due to the pressure exerted during holding them. Therefore, the wet CEBs (of 14.2% compaction water content) are not easy to handle and transport. The hardness of freshly compacted CEBs and shrinkage upon drying are quite consistent with the water content of CEBs.

Appendix 4E. Influence of compaction pressure on mass loss in drip erosion

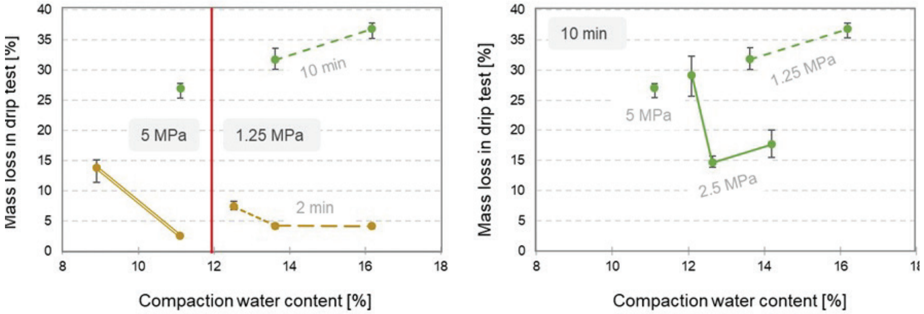


Figure 4E.1: Influence of compaction pressure on mass loss in drip erosion. Results of compaction pressure 5MPa and 1.25 MPa are shown for 2- and 10-min test duration (left). The drip test result for the duration of 10 min for 5 MPa, 2.5 MPa and 1.25 MPa compaction pressure (right).

Appendix 4F. Effect of compaction pressure on water resitance of CEBs

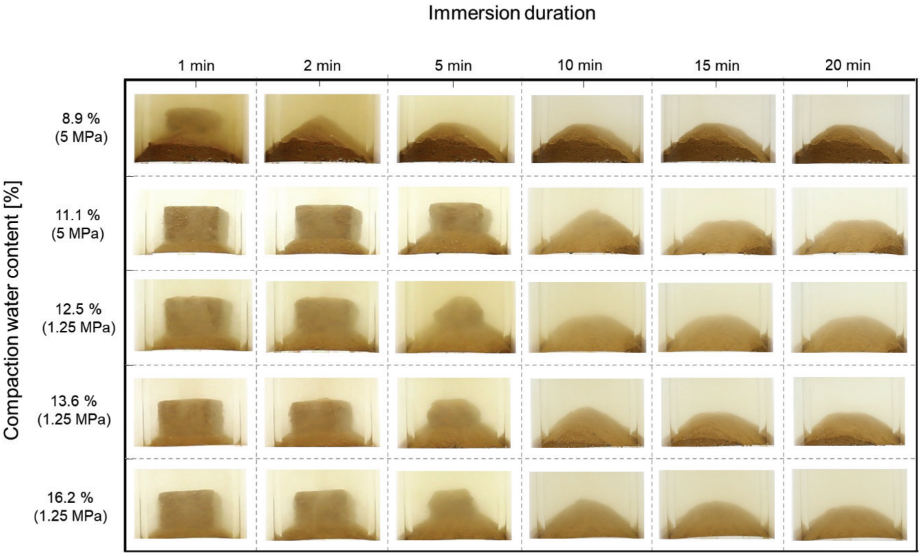


Figure 4F.1: Results from immersion test: Effect of compaction force (and compaction water content) on water resistance

Appendix 4G. Effect of pre-wetting water content (drying period) of CEBs on water resistance

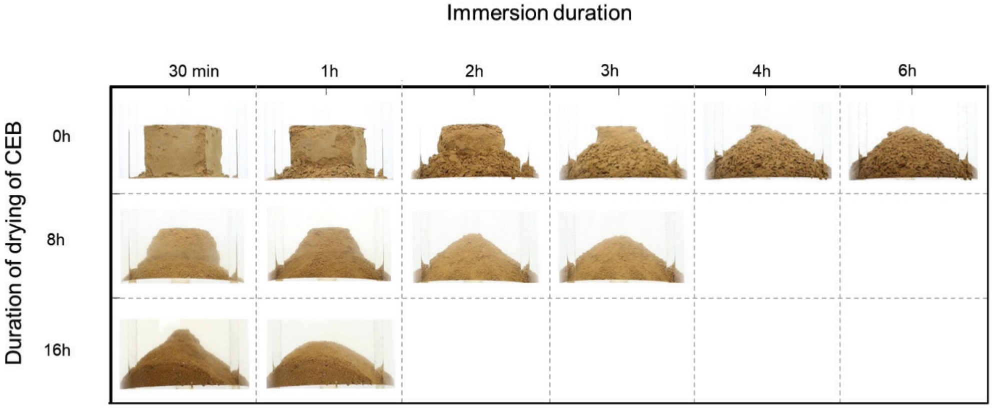
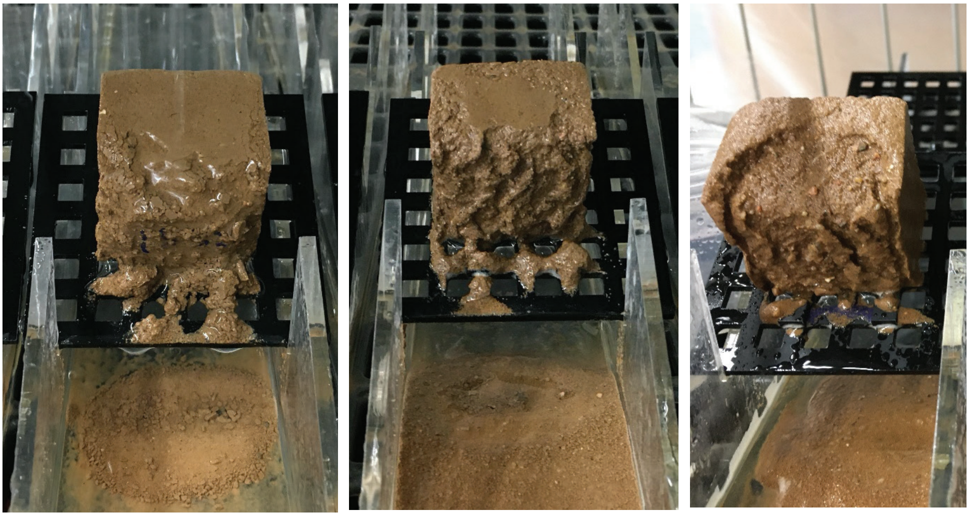


Figure 4G.1: Results from immersion test: Time-lapse of various CEB of varying duration of drying. The CEBs were prepared with 2.5 MPa compression force at 12.6% compaction water content.



0 h- 12.6% (60 min) 8h -10.3% (60min) 1 day-5.3% (10 min)

Figure 5G.2: Image of eroded CEBs after drip test. The CEB on left was tested freshly after casting (with pre-wetting water content of 12.6). The CEB in middle was tested after 8h of drying (with pre-wetting water content of 10.3%). The CEB on right was tested after 1 day of drying (with pre-wetting water content of 5.3%). The samples with lower drying duration than 1 day were tested for 60 minutes.

Appendix 4H. Unreliable results on 3rd day in the test series: Influence of residual or pre-wetting water content on strength and water resistance of unstabilised CEBs

Similar to consistent disintegration observed beyond 1 day of drying in immersion test, Figure 4F1 reveals that the variation in mass loss in drip test (measured after 2 and 10 min of rain) is insignificant after 1 days of drying. However, an exception to the trend is observed on 3 days of drying (or pre-wetting water content of 2.3%) (Figure 4F1). There is no strong reasoning behind the increase in mass loss for CEBs dried for 3 days when lower mass loss values are obtained for 1- and 7-day samples. The variation in pre-wetting water content between 1- and 7-day CEBs sample is significant (5.3% and 1.9%), while the variation in water resistance is not (Figure 4H1). Therefore, the pre-wetting water content of 1.9% observed in 3-day sample was expected to have a similar water resistance behaviour as other samples. This error could be due to a measurement error in the drip test. However, the results of the immersion test (Figure 4.13) also indicate the same phenomena with the 3-day sample. Hence, the parameters of sample preparation presented in Dataset 4Y6 (Kulshreshtha, 2022) are evaluated for detection of error. A first glance into the dataset reveals that the compaction water content calculated for these CEBs was 12.3%, lower than other CEBs prepared with 12.5-12.6% compaction water content (with the exception of 16h and 1 day drying where non-homogeneity of water content in samples could have resulted in an error in the calculated values). The difference between 12.6 and 12.3% seems minor, but Figure 5.7 reveals a sharp decrease in mass loss during the drip test (in 10min) from 12.1% to 12.6% compaction water content. Therefore, a slight change in compaction water content (especially around 12%) can have a significant influence on the water resistance characteristics of the CEBs. Hence, the process of compacting CEBs resulting in lower compaction water content could be the reason behind the inconsistency in values of CEBs dried for 3 days. Although it should be noted that the compaction water content is re-calculated based on 3 samples which were used in determination of compressive strength. As observed in CEBs of 1 day drying duration (Dataset 4Y6 (Kulshreshtha, 2022)), the variation of pre-wetting water content between the 9 casted CEBs can be different and hence, the average compaction water content is not merely reflected by the 3 samples used in its determination. This reliability issues are valid for CEBs that have been dried for a shorter duration and not all the samples have attained a constant mass (which is observed for CEBs with >7 day of drying duration).

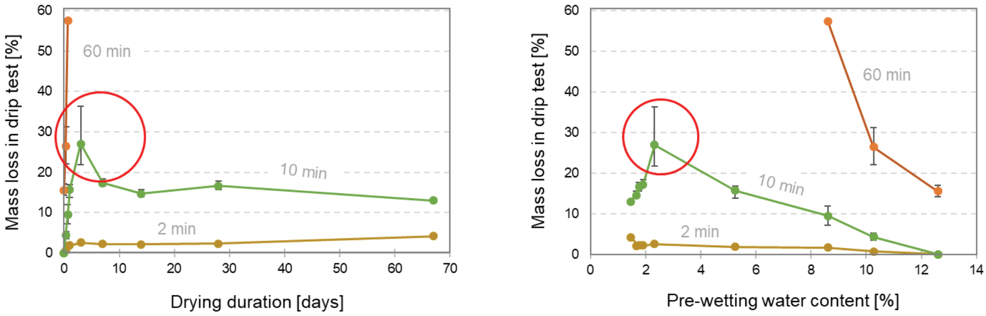


Figure 4H1: Inconsistent value in the plot of influence of drying duration (left) and pre-wetting water content (right) on the mass loss of CEBs in drip test.

It should also be noted that other factors related to composition of soil (the variation between batches of soil) and the complex interplay of suction, strength and water ingress could also be responsible for high erosion measured for CEBs of 3 day drying duration. These speculations should be tested by repeating the experiments. Irrespective of the inconsistent values, the conclusion from the Figure 4H.1 are straightforward showing that higher pre-wetting water content is favourable for water resistance.

Appendix 4I. Effect of type of compaction on water resitance

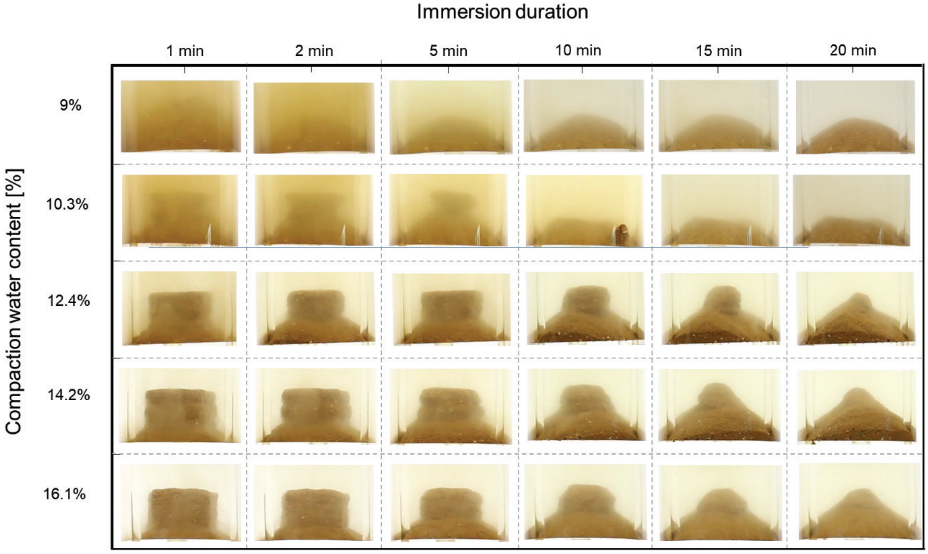


Figure 4I.1: Results from immersion test: Hand compacted rammed blocks with varying compaction water content

Appendix 4J. Reliability of MIP results

In order to test the reliability of results, the porosity measured from MIP was compared to the porosity measured by calculating the density and volume of CEBs. The result presented in Figure 5.9 shows a clear correlation in actual and MIP measured porosity. The porosity measured in the MIP test is 2.8-3.3% lower than the actual porosity. The under-estimation of porosity through MIP is in line with the observation and limitation mentioned for the MIP in Section 4.4.5.

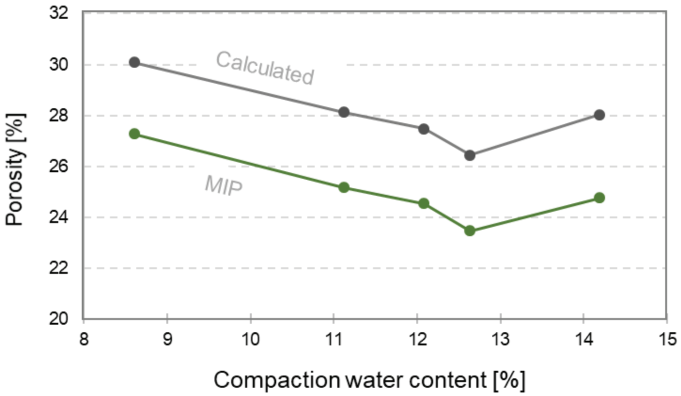


Figure 4J.1: Difference in porosity values of CEBs measured on whole block and a sample in MIP.

Appendix 4K. Influence of pre-wetting water content on the microstructural fabric (including swelling of clays)

To investigate the result of improved water resistance of CEBs with higher pre-wetting water content, an MIP test on a sample with 12.6% pre-wetting water content was conducted to understand if the microstructural fabric can explain this superior water resistance behaviour. The MIP result presented in Figure 5.21 shows intra-aggregate pores in the sample with higher pre-wetting water content, which has been also observed in several studies on compacted soil (Koliji et al., 2006; Romero, 2013; Romero et al., 2011). As compared to dried CEB, wet CEB shows an intra-aggregate porosity around the pore size of 0.1 µm. The drying process results in a reduction of porosity, which is caused by the disappearance of intra-aggregate pores and reduction in specific volume of meso-pores, although the size of the largest pore does not seem to change significantly in the process of drying. This indicates that the size of the macro-pore is not a dominant factor in providing better water resistance characteristics to CEBs of higher pre-wetting water content.

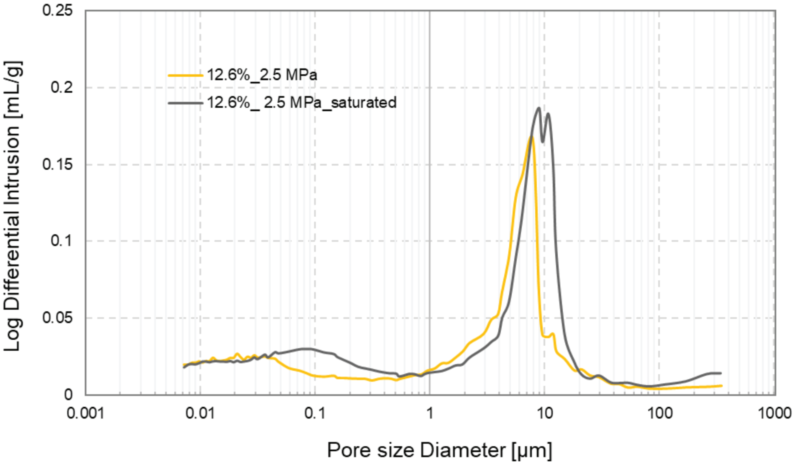
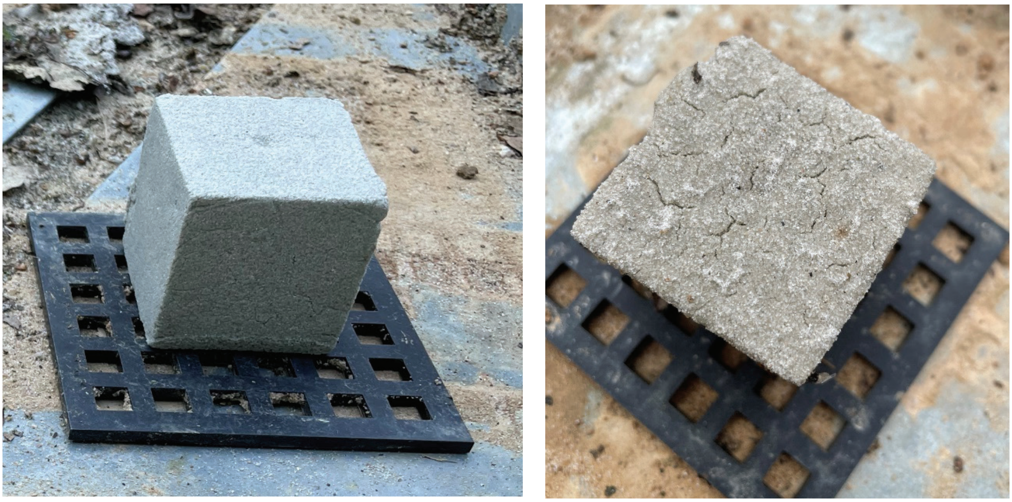


Figure 4K.1: Results from MIP test: CEB at 12.6% compaction water drying from saturated state to dried state.

The presence of intra-aggregate pores is due to clays, which swell in presence of water, as expected in CEBs with high water content. If the swelling of clays, had an appreciable effect on inter-aggregate porosity (meso and macro-pores), it would have been visible in MIP results. However, its absence either indicates that the swelling of clays does not change the macro-pore size responsible for water ingress or the limited presence of water (12.6%) does not make clay swell to their full potential. The process of immersion or water ingress through dripping saturates the soil, resulting in further swelling of clays. This could be possible especially in clays composed of swelling minerals, as in the clays used in this study. Therefore, swelling of clays could restrict the size of the largest pore resulting in a lower rate of water ingress.

Appendix 4L. Bentonite-sand CEB exposed to outdoor environmental condition



Block on day 1

Block on day 7

Figure 4L.1: Bentonite clay mineral-sand CEB kept outdoor for environmental exposure. The block used in rain test was dried in climatically controlled room for 3 months before keeping them outside. Outdoor exposure of 1 week resulted in crack on block due to daily variation in temperature and humidity. Bentonite minerals can swell and shrink considerably with changes in moisture content.

Appendix Chapter 6: Supplemental information to Chapter 6 "Insights into the Water Resistance behaviour of Cow-dung Stabilised Compressed Earth Blocks "

Appendix 6A: Cow-dung as a flooring material in Demographic and Health Surveys (DHS)

Table 6A: Information on households with dung flooring based on surveys carried out in various countries. Information extracted from (DHS, 2022)

Country	Survey	Households with dung floors [%]	Country	Survey	Households with dung floors [%]
Afghanistan	2015 DHS	0.1	Kenya	2014 DHS	17.7
Burkina Faso	2017-18 MIS	6.5	Kenya	2008-09 DHS	20.3
Burkina Faso	2014 MIS	7.5	Malawi	2017 MIS	6.3
Burkina Faso	2010 DHS	2.9	Malawi	2015-16 DHS	0.6
Burkina Faso	2003 DHS	1.4	Malawi	2014 MIS	3
Burkina Faso	1998-99 DHS	68.2	Malawi	2012 MIS	2.8
Burkina Faso	1993 DHS	67.2	Malawi	2010 DHS	2.6
Chad	2014-15 DHS	1.4	Malawi	2004 DHS	0.7
Chad	2004 DHS	0.4	Malawi	2000 DHS	2.5
Ethiopia	2019 DHS	10.4	Nepal	2016 DHS	6.8
Ethiopia	2016 DHS	33	Nepal	2011 DHS	0.4
Ethiopia	2011 DHS	34	Nepal	2006 DHS	7.2
Ethiopia	2005 DHS	25.4	Pakistan	2017-18 DHS	2.5
Ethiopia	2000 DHS	39	Pakistan	2012-13 DHS	1.8
Ghana	2019 MIS	0	Uganda	2018-19 MIS	18.9
Ghana	2016 MIS	0.1	Uganda	2016 DHS	15.3
Ghana	2014 DHS	0.7	Uganda	2014-15 MIS	24
Ghana	2008 DHS	1.1	Uganda	2011 AIS	33.4
Ghana	2003 DHS	1.3	Uganda	2011 DHS	27.9
Ghana	1998 DHS	3.7	Uganda	2009 MIS	39.7
Ghana	1993 DHS	2.6	Uganda	2006 DHS	37
India	2015-16 DHS	0.7	Uganda	2004-05 AIS	19.8
India	2005-06 DHS	1.2	Uganda	2000-01 DHS	26.6
Kenya	2020 MIS	6.6	Uganda	1995 DHS	20.9
Kenya	2015 MIS	10.3			

Appendix 6B: Information on cow farm, cow and cow-dung

Farm	
Farm name	Hoeve Biesland
Type of farm	Biological
Location	Delftgauw
Distance from the lab	4.5 km

Cows	
No. of cows	170
Breed	The cows are mixed breed (from france) for optimising for milk and meat both
Primary purpose	Used for milking and later sold for meat
Feed	Feed depends on the season. Apart from spring when cows can go to grassland for the day and eat grass, the food is supplied through automated systems, including robots. The dried straw (fibre) is supplied to a equipment installed at the roof. The protein is feed by self-driving robots. As compared to other farms, the feed is assumed to me more of less constant which is also reflected in the quality of cow-dung collected from the farm.

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Cow-dung	
Use	All the cow-dung is re-used as a fertiliser in the farm
Cow-dung collection system in farm	Automated wiping system installed on concrete floor. The cows spend all time in the shed which has a concrete floor in about 1/3rd of area. Most cows poop on the concrete floor (it is located in the area where robots throw the protein feed). The cow-dung collection system can be automatic or manually controlled.
Capacity of underground cow-dung storage facility	~750 m^3 (22m × 17m × 2 m)
Nature of fresh cow-dung	Cow-dung with cow urine and some water

Appendix 6C: Solid content in cow-dung

Table 6C: Solid content in cow-dung

Collection month	Sample	Date of collection	Date of testing	Average solid content [%]	pH
August 2020	CD_1day_aug	26-8-2020	26-8-2020	10.8	7.55
	CD_5day_aug	26-8-2020	31-8-2020	11.7	6.2
	CD_14day_aug	26-8-2020	9-9-2020	11.3	6.9
	CD_30day_aug	26-8-2020	25-9-2020	11.7	7.5
December 2020	CD_dec	9-12-2020	10-12-2020	9.9	7.7
March 2020	CD_mar	11-3-2020	11-3-2020	12.2	7.9

Appendix 6D: pH variation in time

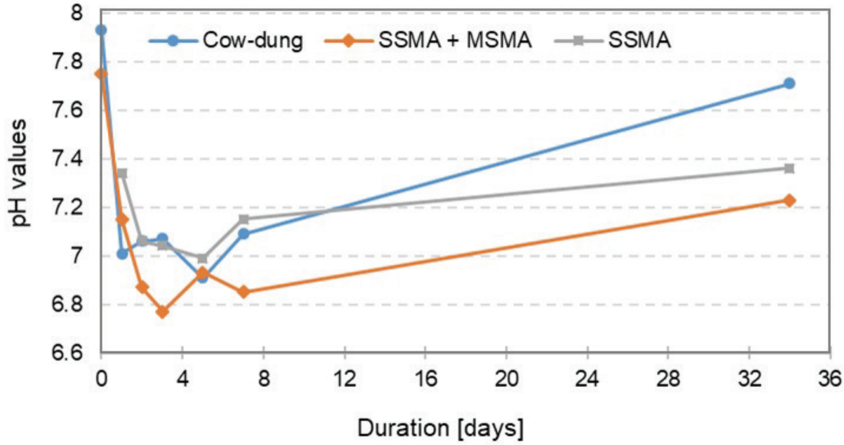


Figure 6D1: pH variation in cow-dung and microbial aggregates (SSMA and SSMA+MSMA) with time. The complete database for the pH test can be found in Appendix 6X1.

Appendix 6E: Storing of soil cow-dung mix

Figure 6E1: Soil cow-dung mix stored in a metal container and sealed with plastic fastened through rubber bands.

Appendix 6F: Harvard miniature compaction

The Harvard miniature compaction apparatus (Humboldt, USA) was preferred over the commonly used standard Proctor apparatus due to the limited required material (~130-160g) and limited effort required in compaction. The Harvard miniature compaction test was conducted following the procedure of Humboldt (2020). A compaction tamper of 9.07 kg spring was selected for compaction based on the consistency of results with the Proctor test (on soil). The mix was added in the mould and compacted in 5 layers, where each layer was tamped 25 times. If required, water was added to or evaporated from the mix. Water was added to the mixtures of soil with Fibres and MSMA, while evaporated from SSMA. As compared to the Proctor test, a slightly higher maximum dry density was observed in the Harvard miniature test (case of unstabilised soil, refer Chapter 4). In addition to providing information on the water content required for making blocks at optimum water content, the curves shown in Figure 6.6, was used to determine the quantity of soil required for the desired outcome of 40 × 40 × 40 mm^3 block size.

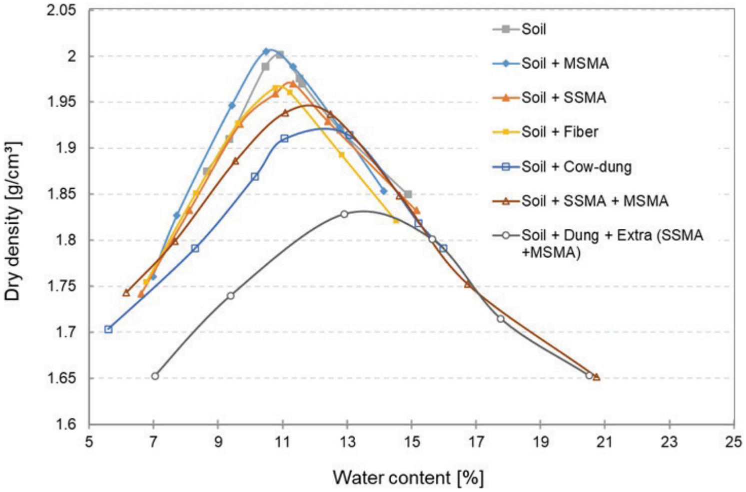


Figure 6F1: Relationship between dry density and water content for various mixtures determined by using Harvard miniature compaction apparatus. The supporting database is available in Dataset 6X1 (Kulshreshtha, 2022)

Appendix 6G: Fungus growth in soil cow-dung mixes

Figure 6G1: Growth of fungus in soil cow-dung mix with added microbial aggregates

Figure 6G2: Growth of fungus in soil cow-dung mix prepared with dry cow-dung

Appendix 6H: Precipitation and temperature data

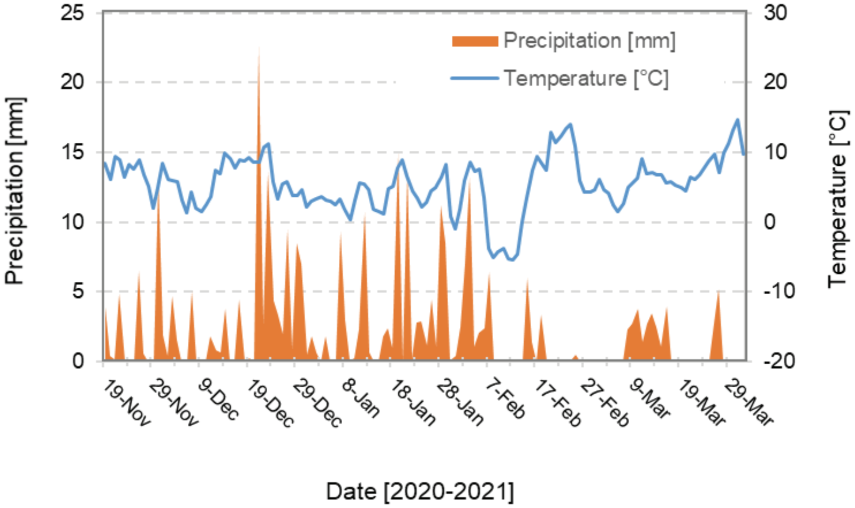


Figure 6H1: Precipitation and temperature data collected from KNMI (2022) for the nearest weather station (Rotterdam airport) to the outdoor space where a few CEBs were kept for 135 days. The complete data for plotting the graphs is provided in Dataset 6X4 (Kulshreshtha, 2022).

Appendix 6I: Folded capillary cell- used in Zeta potential measurement

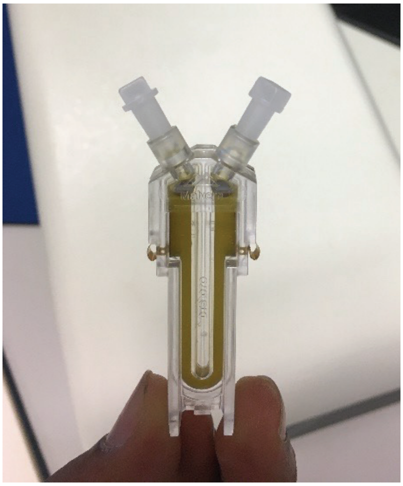


Figure 6I1: Folded capillary cell (DTS1070) filled with diluted microbial biomass solution. The cell was inserted in the equipment to measure Zeta potential and conductivity.

Appendix 6J: Results of outdoor exposure test

Table 6J1: Comparison of CD-CEBs and unstabilised CEBs that were exposed to outdoor environment

Sample	Sample ID	Mass: day 1 [g]	Mass day: 134 [g]	Mass loss [%]	Average mass loss [%]
CD-CEBs	C71	120.32	109.97	8.6	8.5
	C72	120.55	110.36	8.5	
	C76	120.28	110.11	8.5	
Unstabilised CEBs	17R	122.85	60.69	50.6	57.9
	17K	123.58	60.8	50.8	
	17P	122.92	34.01	72.3	

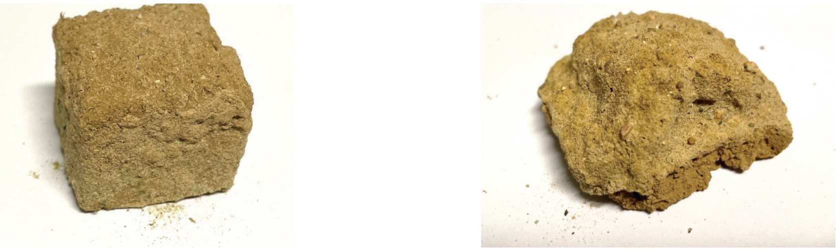


Figure 6J1: CD-CEB (left) and unstabilised CEB (right) after outdoor exposure of 134 days

Appendix 6K: Drip erosion test on CD-CEBs

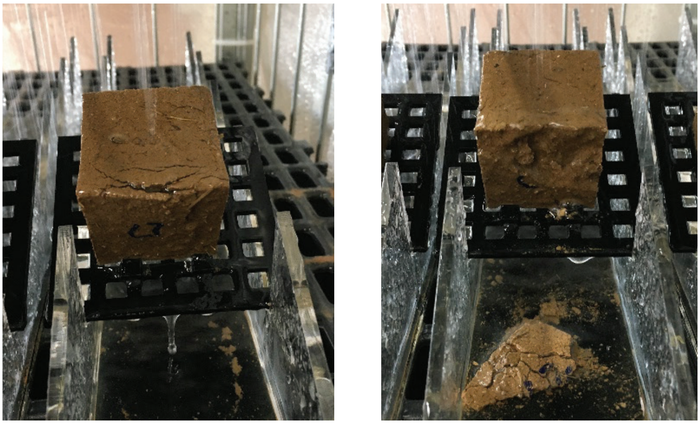
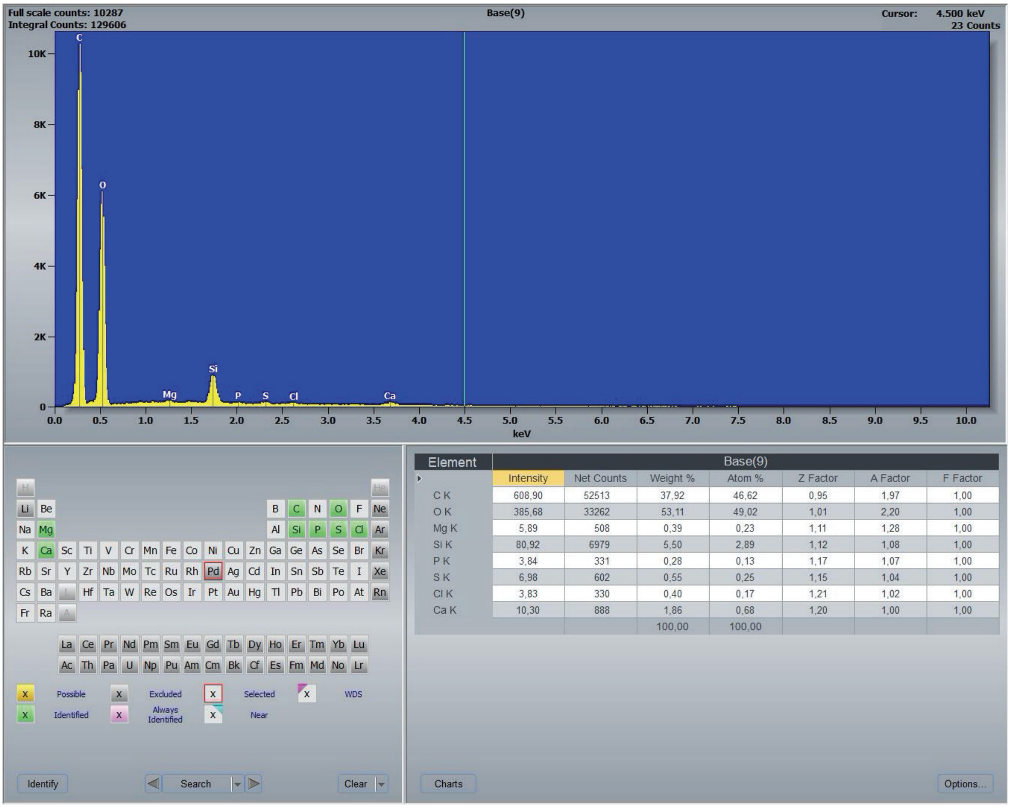


Figure 6K1: Drip erosion test on CD-CEBs dried for 7 days. The block around 59 mins showing cracks but no disintegration (0.5% mass loss) and the block with disintegration (5% mass loss). A duration of over 60 min would have been ideal for drip erosion test to capture the erosion characteristics of the material better. However, it was not possible due to limited time in lab due to covid restrictions.

Figure 6K2: CD-CEB (dried for 14 days) after drip erosion test showing no sign of cracks or disintegration as shown in CD-CEB of 7day drying duration (Figure 6K1).

Appendix 6L: ESEM-EDS on component of cow-dung



Full scale counts: 10287
Integral Counts: 129606

Base(9)

Cursor: 4.500 keV
23 Counts

Element	Intensity	Net Counts	Weight %	Atom %	Z Factor	A Factor	F Factor
C K	608,90	52513	37,92	46,62	0,95	1,97	1,00
O K	385,68	33262	53,11	49,02	1,01	2,20	1,00
Mg K	5,89	508	0,39	0,23	1,11	1,28	1,00
Si K	80,92	6979	5,50	2,89	1,12	1,08	1,00
P K	3,84	331	0,28	0,13	1,17	1,07	1,00
S K	6,98	602	0,55	0,25	1,15	1,04	1,00
Cl K	3,83	330	0,40	0,17	1,21	1,02	1,00
Ca K	10,30	888	1,86	0,68	1,20	1,00	1,00
			100,00	100,00			

Figure 6L1: Elemental analysis of undigested fibres extracted from cow-dung scanned at magnification of 125x

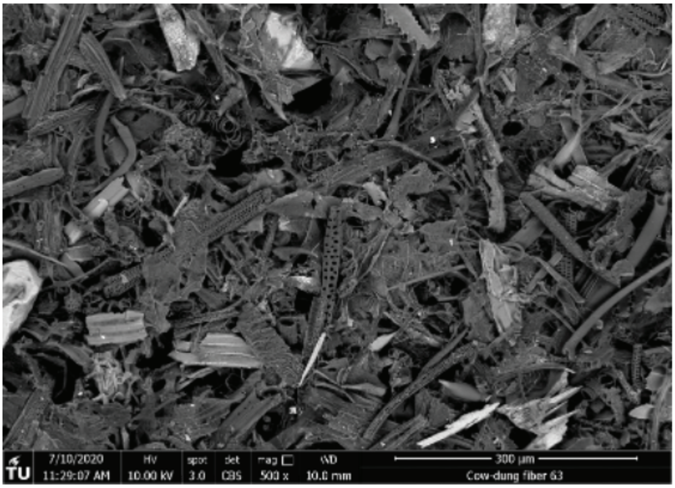
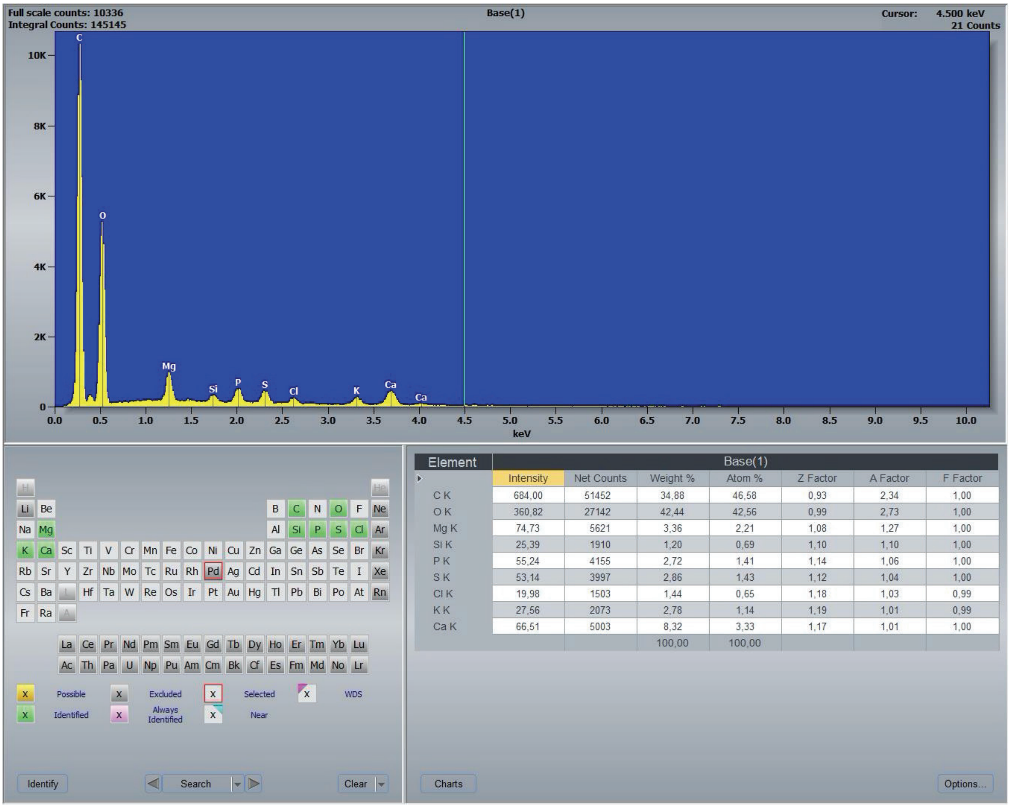


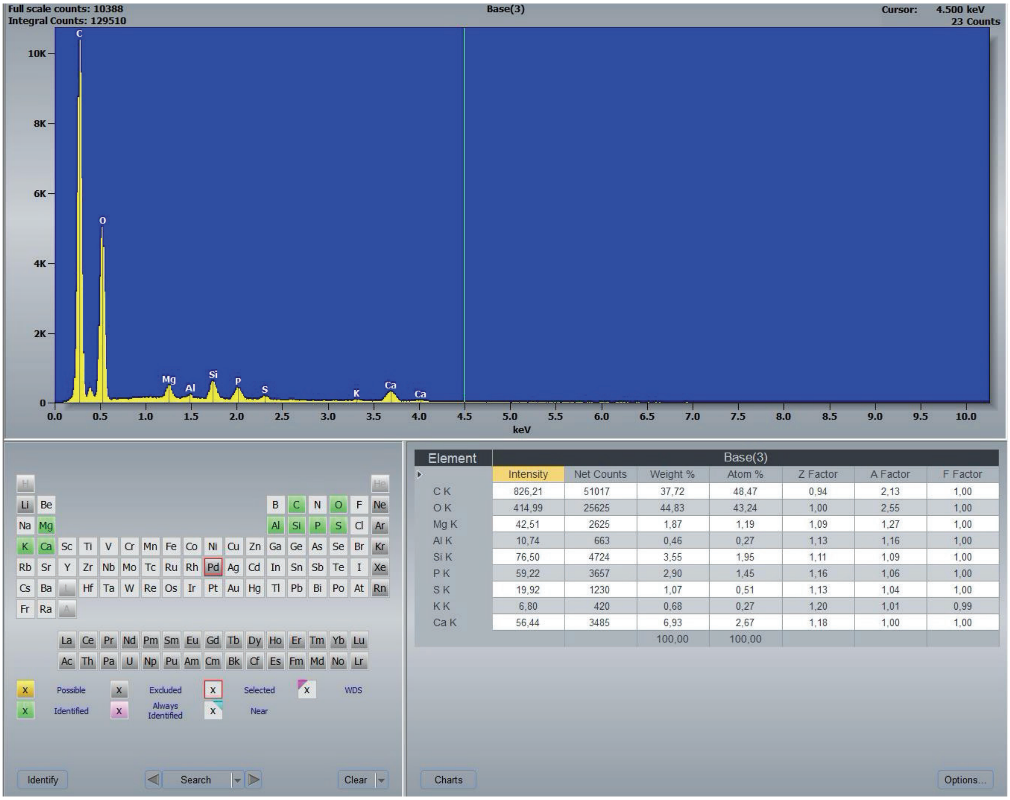
Figure 6L2: ESEM of fibres retained on 63μm sieve (size range 63-125 μm)



Full scale counts: 10336
Integral Counts: 145145
Base(1)
Cursor: 4.500 keV 21 Counts

Element	Base(1)						
	Intensity	Net Counts	Weight %	Atom %	Z Factor	A Factor	F Factor
C K	684,00	51452	34,88	46,58	0,93	2,34	1,00
O K	360,82	27142	42,44	42,56	0,99	2,73	1,00
Mg K	74,73	5621	3,36	2,21	1,08	1,27	1,00
Si K	25,39	1910	1,20	0,69	1,10	1,10	1,00
P K	55,24	4155	2,72	1,41	1,14	1,06	1,00
S K	53,14	3997	2,86	1,43	1,12	1,04	1,00
Cl K	19,98	1503	1,44	0,65	1,18	1,03	0,99
K K	27,56	2073	2,78	1,14	1,19	1,01	0,99
Ca K	66,51	5003	8,32	3,33	1,17	1,01	1,00
			100,00	100,00			

Figure 6L3: Elemental analysis of small sized microbial aggregates (SSMA) extracted from cow-dung scanned at magnification of 10 000x



Element	Base(3)						
	Intensity	Net Counts	Weight %	Atom %	Z Factor	A Factor	F Factor
C K	826,21	51017	37,72	48,47	0,94	2,13	1,00
O K	414,99	25625	44,83	43,24	1,00	2,55	1,00
Mg K	42,51	2625	1,87	1,19	1,09	1,27	1,00
Al K	10,74	663	0,46	0,27	1,13	1,16	1,00
Si K	76,50	4724	3,55	1,95	1,11	1,09	1,00
P K	59,22	3657	2,90	1,45	1,16	1,06	1,00
S K	19,92	1230	1,07	0,51	1,13	1,04	1,00
K K	6,80	420	0,68	0,27	1,20	1,01	0,99
Ca K	56,44	3485	6,93	2,67	1,18	1,00	1,00
			100,00	100,00			

Figure 6L4: Elemental analysis of medium sized microbial aggregates (MSMA) extracted from cow-dung scanned at magnification of 10 000x

Appendix 6M: Water resistance of CD-CEBs prepared with bentonite rich sandy soil

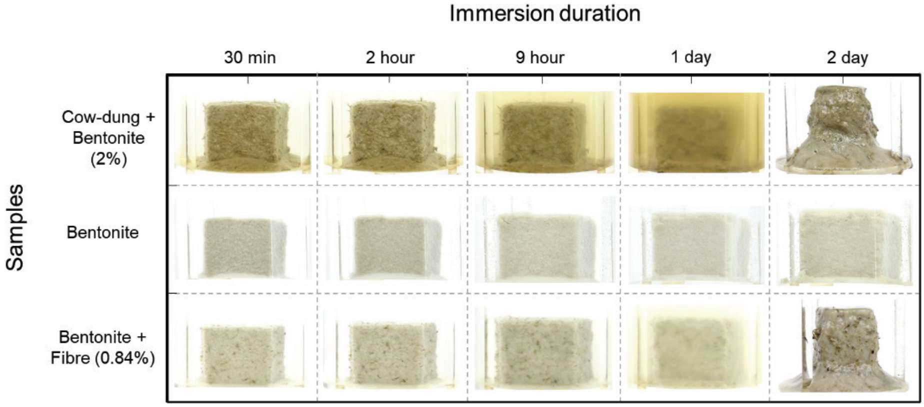


Figure 6M1: Time-lapse of disintegration of CD-CEBs prepared various combinations of artificially created bentonite rich soil.

Appendix 6N: Sand block stabilised with SSMA

Figure 6N1: Formation of groove on SSMA stabilised sand block due to impact of dripping. Note that the erosion on side of the block is not caused due to dripping action. The blocks were deformed with demoulding them.

Appendix 6O: Water resistance of cement stabilised CEBs

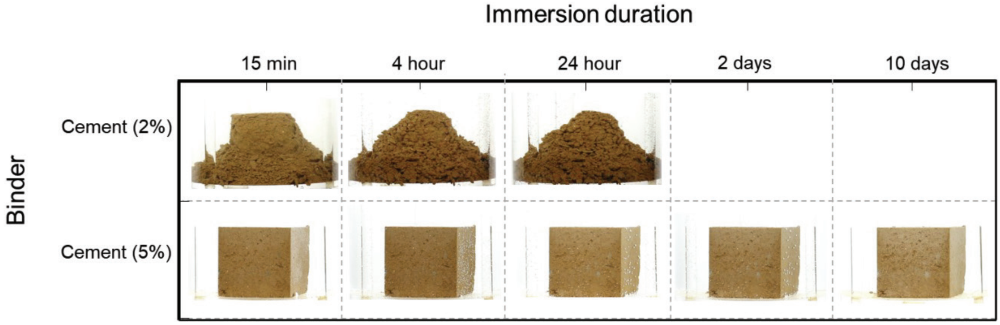


Figure 6O1: Immersion test on cement stabilised CEB.

Appendix 6P: Storage of cow-dung soil mix and its influence on water resistance characteristics

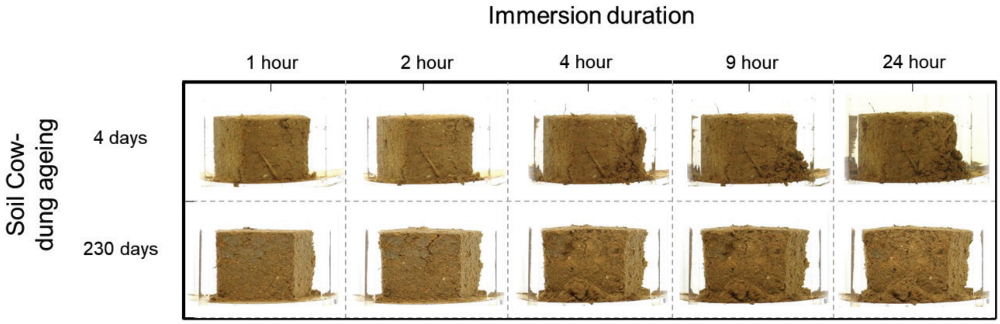


Figure 6P1: Immersion test on CD-CEBs prepared with cow-dung of varying soil-cow dung ageing duration. Cow-dung collected in March 2020.

Appendix Chapter 7: Supplemental information to Chapter 7 "Making an Impact on Earthen Construction Practice: A Science Communication Perspective"

Appendix 7A: Information on the survey group

Table 7A1: Information on survey group interviewed on the communication aspects of building with earth.

Identification	Region	Educational background	Experience level *
I1	North India	Civil Engineering	Beginner
I2	North India	Architecture	Advanced
I3	North India	Architecture	Beginner
I4	South India	Architecture	Advanced
I5	South India	Engineering	Beginner
I6	South India	Architecture	Advanced
I7	South India	Architecture	Advanced
I8	Western India	Civil engineering	Professional
I9	Western India	Architecture	Professional
I10	Eastern India	Architecture	Advanced

*Beginner: 1-2 years

Advanced: 2-5 years

Professional: >5 years

Appendix 7B: Source of learning for low-income households involved in self-construction

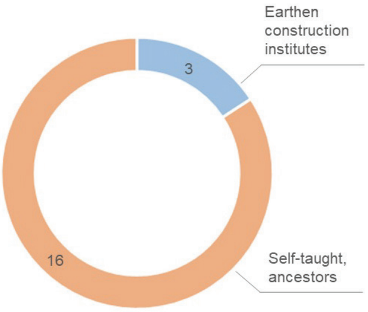


Figure 7B.1: The source of learning for low-income household involved in self-construction. Out of 19 people interviewed in field survey, 16 gained the knowledge to build with earth from their ancestors or learning from existing or abandoned building in their vicinity, whereas 3 were trained by earthen construction institutes as masons.

Appendix 7C: Knowledge dissemination route for earthen construction institutes

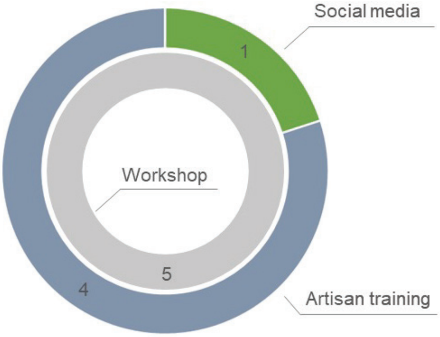


Figure 7C.1: The knowledge dissemination route for earthen construction institutes. All 5 institutes visited during field survey primarily disseminate knowledge through workshops. Although, 4 of them use artisan training and 1 social media as a secondary route to disseminate knowledge.

Appendix 7D: Influence of narration speed on rating

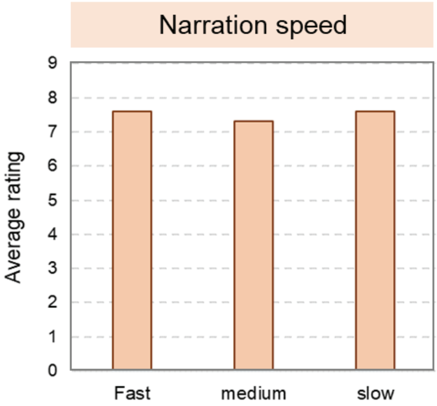


Figure 7D.1: Influence of video narration speed on average rating of videos

Appendix 7E: Number of views and its relation to the rated quality

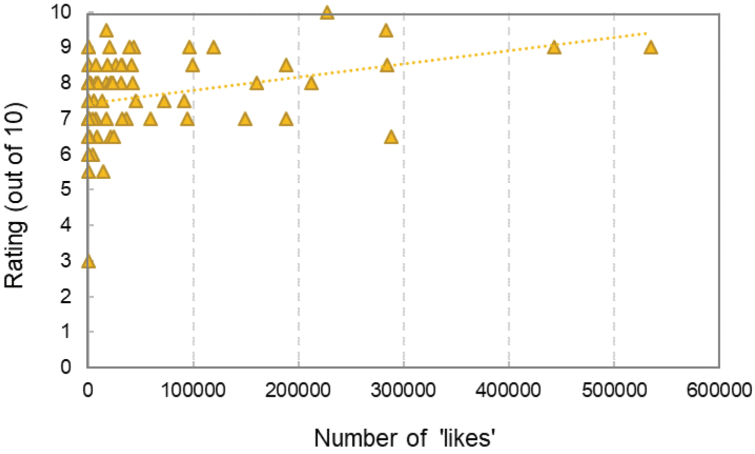


Figure 7E.1: Relationship between rating and number of 'likes' in 'popular science' category.

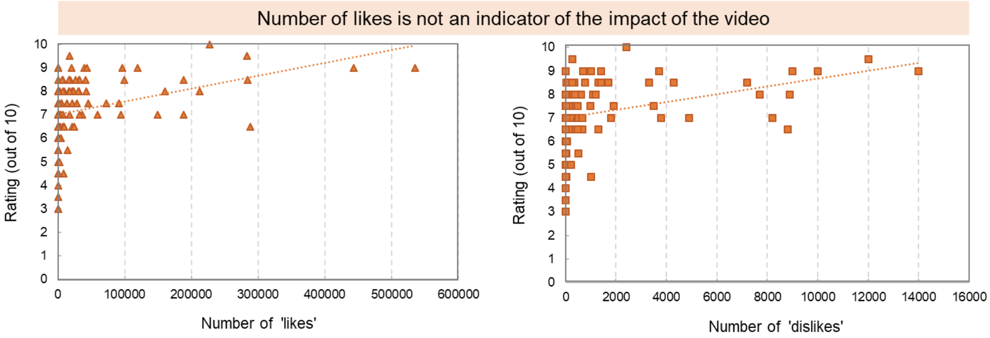
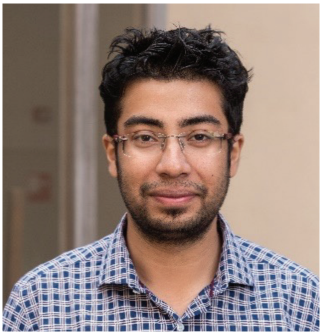


Figure 7E.2: Relationship between rating and number of 'likes and number of 'dislikes. Both likes and dislikes are positively correlated to assessed rating.



About the Author

Yask Kulshreshtha

Yask was born on 16th December 1990 in Kathmandu, Nepal as a citizen of India. His family moved back to India when he was just two years old. After graduating high school from Kendriya Vidyalaya, Yask attended Birla Vishwakarma Mahavidyalaya (BVM) Engineering college in Vallabh Vidyanagar, Gujarat to pursue a Bachelor of Engineering in Civil Engineering. During his studies, he was awarded the KVPY (Young scientist) fellowship from the Department of Science and Technology, Government of India. This fellowship provided him with an opportunity to conduct multiple research internships at Indian Institute of Technology Bombay. During these internships, Yask worked on ideas related to valorisation of food and marine waste in concrete, seeding his interest in the broad topic of sustainable building material. He obtained his Bachelor's degree in the year 2012.

In 2013, Yask moved to Netherlands to pursue Master of Science in Civil Engineering (Specialisation Geo-engineering) at the Faculty of Civil Engineering and Geosciences, Delft University of Technology. His passion for natural building material led him to develop a corn-starch based material, called CoRncrete. Yask further investigated this novel material as a master thesis topic and graduated within two years to receive an MSc degree with honours in 2015. In the following months, he extended his research work on CoRncrete and assisted in organising a summer school. After a brief stint as a researcher at the university, Yask went back to India for a 9-month long backpacking trip. During his journey, he was introduced to traditional earthen construction in India and visited rural areas across several regions of India to learn about it. The trip paved way to the development of the core idea behind his PhD thesis. After receiving the financial supported from the TU Delft | Global initiative on the proposed research topic, he re-located to the Netherlands in May 2017 to begin his position as a PhD candidate and Delft global fellow at the Faculty of Civil Engineering and Geosciences. In 2020, Yask received NWA idea generator grant to extend his research and apply it to the Dutch context. As a part of this research, he built a demonstration structure in The Green Village at TU Delft campus. Currently, he is involved as a material expert in a feasibility project to apply part of this research in the African market.