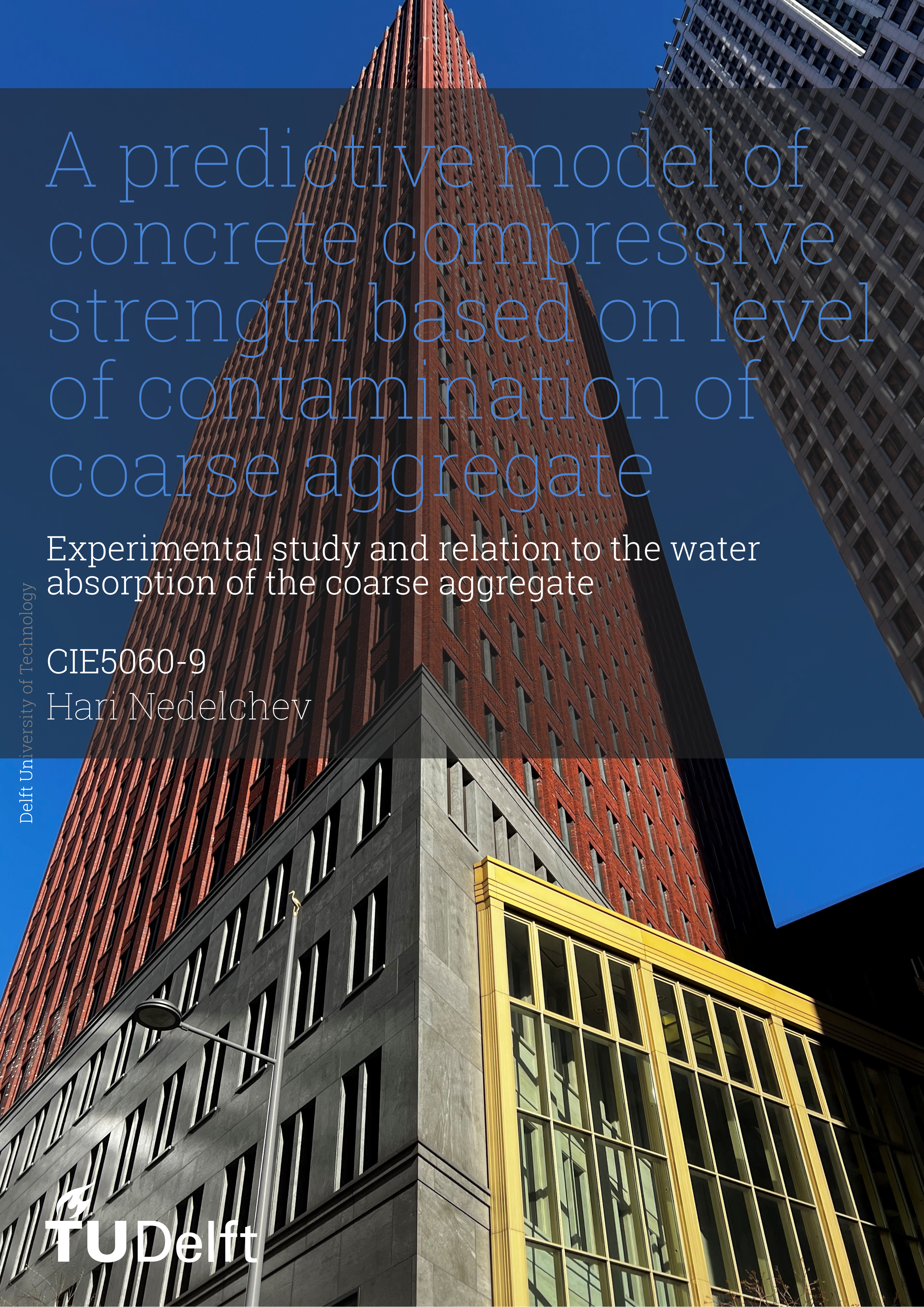

A predictive model of concrete compressive strength based on level of contamination of coarse aggregate

Experimental study and relation to the water absorption of the coarse aggregate

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Preface

This is the final chapter of a two and a half years long journey at the Technical University of Delft – this thesis project completes my Master's education in Civil Engineering which started in 2020. Despite its relatively short duration, this endeavour of mine has not been a smooth sailing whatsoever. Whether that has been influenced by the global pandemic followed by yet another economic crisis or by the challenges brought by studying in a different cultural and academic environment (we should not forget the hours spent in front of black screens, watching live lectures or discussing assignments, being in meetings..). Nevertheless, I took this path, well aware of what might be the consequences in such times. Now that I can finally see the light in the end of the tunnel, I can proudly say that I overcame all difficulties, all issues and challenges I was faced with and I am just one step away of obtaining my Master's diploma. This is the crucial moment to note that this journey of mine does not end here – this is merely its start. The construction industry is in dire need of change, we all have to start leading more sustainable lives so that our home can survive long after we are gone. This is exactly why I embraced this project – it is of high importance not only to me, but to the whole construction industry. Hopefully, this paper could assist or guide the ongoing researchers studying the recycled concrete and its potential so that in short time a proofed and finalized product is released on the market. Along with my previous education, my pure dedication to contribute towards a better future, I consider myself not only as the right student for this project, but also as the right candidate to continue working in the same direction after graduation.

This work could not possibly be done if it weren't for the chance I was given by my daily supervisors Ir. Ali Vahidi and Ir. Cheng Chang. It was they who introduced me to this specific topic, they helped me find my way in the unfamiliar at the times laboratories of TU Delft, they guided me and supported me throughout the project until it was finally done. I would like to express my gratitude to both of them, especially Ali who always found time to give an extra helping hand in the concrete laboratory or to check any of the samples when I didn't have the chance to do so. As my office mate, Cheng was always there for me not only for the technical components of the project, but also as moral support and even more importantly he was there to keep me on track and always aware of my role in the project. Of course, I cannot continue without expressing my gratitude towards my project coordinator Dr. Francesco Di Maio who aided me not only in the administrative aspects of the project, but we also shared numerous discussion on relevant topics and conversations triggered by experimental data I had established along the way. Finally, the person with the greatest importance to this project was Dr Peter Rem, the Head of the R&R department and my committee chair, the man whose work towards his field of expertise continues to bring benefits to the whole industry. Without him this project would not have existed and I would not have been able to jump aboard the R&R department's ship.

Last in this list but definitely first in my personal list of significance come my girlfriend, family and friends. Without them and their constant support, I would not have been able to walk this path in the way I managed to; they were always there to help me retain my motivation, to keep me sharp and confident and to provide a different look of any problematic situation I faced. I highly appreciate them and intend to continue expressing my gratitude not only when they find themselves in a similar situation, but always.

Delft, November 2023

Abstract

Recycled aggregate concrete is emphasized more and more nowadays due to its importance towards the construction industry and general welfare of our planet. Being such a significant feature with regard to universal sustainable development, every aspect of its properties should be evaluated, examined and possibly optimized so that in the end there is a well-known, well-described and ready to use product. This project aimed at correlating some of the established parameters of conventional concrete such as water absorption of the coarse aggregate fraction and the resulting compressing strength, only applied in the field of recycled aggregate concrete. Along with these two properties, a possible prediction model was sought for which would be able to forecast the mechanical strength of concrete based on its coarse aggregate composition.

A series of experiments were performed on samples fabricated for water absorption tests and compressive strength assessment. In total, 112 water absorption samples and over 250 concrete specimens were prepared and examined for the respective attribute. These samples used natural aggregate as the base of the coarse aggregate portion of the mix design, alongside a series of so-called contaminants which replaced the gravel in certain concentrations. These contaminants included bricks, ceramic tiles, glass, wood, gypsum, plastics (HDPE, EPS), mineral fibers and recycled sand concrete (RSC) and were entirely based upon the C&DW composition globally. Further investigation was done on the inclusion of air within concrete so that contaminated concrete results could be equated to this constant. All water absorption tests were performed according to the current EN 1097-6:2022 standards and concrete specimens were crushed after 7 and 28 days of curing in order to obtain their strength in compression. All concrete specimens were designed with water to cement ratio of 0.45 and cement CEM III A 52.5R was used throughout. The predictive model was initiated via the Minitab statistical software, while the final interface of the model being shaped using MATLAB.

The results indicated some interesting and promising trends. Starting with water absorption, it was shown that upon partial replacement of natural aggregate with any individual contaminant, the water absorption of the aggregate mix was proportional to the values of both materials. However, when two or more contaminants were present in the sample, the relation was no longer linear and it could not be properly predicted using equivalence conditions. It was proven that all contaminants except glass and plastics had a significantly higher water absorption values compared to natural aggregate which ultimately led to increased absorption of most prepared samples. Consequently, from both sets of experiments, it was evident that the water absorption of the coarse aggregate fraction was not the main contributor towards the strength development of recycled concrete. It had a minor influence, especially compared to the type of contaminant present and how much volume it took. Furthermore, samples with identical water absorption fabricated concretes with different strengths. In addition, samples with absorption beyond the acceptable range of 5% manufactured concrete with comparable or sometimes slightly better strengths with regard to the control one. Overall, plastics and wood had the most negative effect in terms of compressive strength, while bricks, tiles and glass seemed to affect this aspect in neutral or even slightly positive manner. EPS foam in very limited amounts (up to 0.5% of NA weight) yielded a notable 30 to 35% strength drop (28 and 7 days respectively), while on the other hand, brick replacing 20% of the NA improved the strength by approximately 7% after 7 days and 2% after 28 days. The number of contaminants present also played a role in the behaviour of concrete with all samples with comparable to control strength consisting of 1 or 2 contaminants. Recycled concrete aggregates in the form of crushed old sand concrete were used as partial to full replacement of the natural aggregate. The data indicated that the relation is perfectly linear in terms of replacement percentage and compressive strength – 100% RSC yielded 37.42MPa on average, 100% NA (reference mix design) achieving 42.02MPa after 7 days and all partial replacement of NA being linearly imposed within this range. All experimental results were equated to the extra air content within the mix with 100% RSC being equivalent to 2.5 to 4% of air, while 3% of air could be obtained by including 5.4% of gypsum, 1.3% of HDPE plastic or 0.1% of EPS foam (by weight replacement of NA). In the end, based on all experimental input, a predictive model was developed and optimized in several steps so that it was able to predict the water absorption of coarse aggregate, compressive strength after 7 days and equivalent air content based on the composition of the coarse aggregates. The model was validated by a total of 25 samples, including water absorption and compression tests, and the governing equations were provided in the closing chapter. Based on the path of project, it was apparent that there were aspects which could be observed in greater detail so that the behaviour of recycled concrete is better understood and the predictive model is expanded and all points were included in the recommendations in the end of the report.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
C2CA	Concrete to cement and aggregate
CA	Coarse aggregate
C&DW	Construction and demolition waste
CRCA	Concrete made from recycled coarse aggregate
CS	Compressive strength
EoL	End of Life
EPS	Expanded polystyrene
FA	Fine aggregate
fRCA	Fine recycled concrete aggregate
HDPE	High-density polyethylene
ITZ	Interfacial transition zone
LCA	Life cycle assessment
NA	Natural aggregate
PP	Polypropylene polymer
PU	Polyurethane
PVC	Polyvinyl chloride
RA	Recycled aggregate
RAC	Recycled aggregate concrete
RBA	Recycled brick aggregate
RSC	Recycled sand concrete
TU(D)	Technical university (of Delft)
WA	Water absorption
w/c	water to cement ratio

Symbols

Symbol	Definition	Unit
β_i	Volume fraction of each component i	kg/m^3
γ_i	Contribution of each component i towards the CS	%
δ_{air}	Extra air content added as volume replacement of CA	%
δ_{rca}	RCA Volume percentage replacement of NCA	%
η	Absorption capacity of the aggregates	%
ρ_a	Apparent particle density	kg/m^3
ρ_{rd}	Oven-dried particle density	kg/m^3
ρ_{ssd}	Saturated and surface-dried particle density	kg/m^3
ρ_w	Density of water at test temperature	kg/m^3
σ	Standard deviation in CS	N/m^2
σ	Standard deviation in WA	%

Symbol	Definition	Unit
a	Volume of air	kg/m^3
ASG_{rd}	Apparent specific gravity of the oven-dried particles	-
c	Cement content	kg/m^3
$f_c, f_{c,cube}$	Concrete compressive strength	N/m^2
P	Atmospheric pressure	atm
r	RCA replacement ratio	%
SG_{rd}	Specific gravity of the over-dried particles	-
SG_{ssd}	Specific gravity of the saturated and surface-dried particles	-
w_0	Initial water content required for 100% NA as CA	kg
w	Water content	kg/m^3
WA_{24h}	Water absorption after 24h immersion	%
$w/c_{(eff)}$	(Effective) Water to cement ratio	-

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1
Introduction

1.1. Background

It is well known that the construction industry is one of the sectors with the highest resources and energy demand globally. According to the recent report issued by the European Commission [1] construction sector accounts for 9% of EUs Gross Domestic Product (GDP). Furthermore, it contributes to approximately 50% of the overall energy consumption and around 33% of the water consumption within Europe. Construction and demolition waste (C&DW) makes up more than a quarter of the total waste generation in the EU. Thus, sustainable designs and practices should be implemented in order to reduce the environmental footprint of the industry. This has led to the recycling of construction materials after demolition of structures. As claimed by the same report [1], the level and quality of recycling and material recovery of C&DW in Europe varies considerably from one country to another and can be anywhere from less than 10% (Greece, Portugal, Spain) to over 85% (Belgium, Netherlands) [2].

Over the past years, people had attempted to improve the C&DW recycling and this led to the implementation of recycled aggregate concrete (RAC). This new material is made from crushed old EoL (End of Life) concrete particles found at the demolition site with the addition of new cement and any other additives. The EoL concrete ultimately act as the coarse and/or fine aggregate for the new concrete, effectively making the process more circular and sustainable. Studies [3, 4] have shown that this RAC is able to reach comparable strengths to the conventional concrete depending on factors such as the characteristics and condition of the crushed demolished concrete. However, at the moment, globally there is a limited number of companies that provide constant quality of recycled aggregates at a reasonable price. On average, 9.3% of the aggregates are recycled and re-used in the EU according to the recent annual review paper of the European Aggregates Association [5]. The prescribed standards of demolition and dismantling of structures are not followed strictly around the world since it is generally believed that there is no practical use of the demolished material.

What is more, there is insufficient information about the composition of the recycled aggregate available and the presence of various contaminants such as bricks, glass, wood, plastics and so on is not categorized. The effect those contaminants might have on the mechanical properties of the concrete is also not investigated thoroughly or contradicting results have been found in literature. For example, a study [6] reports that recycled fine aggregates are less likely to affect the long-term compressive strength, compared to recycled coarse aggregates. Furthermore, this study also suggests that the effect contaminants have on the compressive strength of concrete is almost insignificant. Contrary to that, there are other research papers [7] indicating that contaminants have an influence depending on their type and quantity. Moreover, other studies [8] state that there is variability in water absorption of recycled aggregate concrete (RAC) which leads to variability in compressive strength.

The discordance amongst data retrieved from various sources causes EoL concrete to be mainly used as backfilling and sub-base road construction [9], often mixed with waste materials like bricks or ceramic tiles, coming from the same structure. This process is not very "green" since as consequence raw materials still need to be used for the next batch of concrete. Despite the positive side that recycled materials serve a particular purpose in the road construction industry and that steel elements are retrieved, the main problem arises from the fact that road infrastructure requires less and less materials while the EoL concrete is continuously expanding in volume globally. Thus, it is of high importance that as many options as possible are considered for the application of EoL concrete so that the whole construction industry could lean towards a more sustainable future. As a consequence, this project aims at investigating aspects such as effect of contamination in recycled concrete and filling all knowledge gaps along the way.

There are numerous examples found in literature where researchers have tried to come up with a prediction of the compressive strength of RAC considering that this is the most significant property of the concrete. However, the major issues are that most scientific papers only provide theoretical models for predicting the strength based on several methods and different input, but none actually compare the obtained values with experimental results. Additionally, the role of contaminants is usually ignored to a certain extent and their influence is not analysed in depth, contrary to water to cement (w/c) ratio or cement type for example. Overall, there is inconsistency in the findings of the related projects and no real evidence on the overall effect of contaminated coarse aggregate. This ultimately results in no solid data to convince stakeholders to use the recycled aggregate in more construction projects. This could be changed if standards are implemented which allow the demolished material to be categorized and re-used accordingly, likely accompanied by certain financial incentives. This project aims at providing the data and the predictive model required to predict the compressive strength of concrete made from high quality recycled coarse aggregate with various levels and types of contaminants. This model could prove to be very useful in the near future should it be realized and could tip the scale towards the global implementation of recycled aggregate concrete not only in land filling and road construction, but also for higher-grade applications. The purpose of the model is mostly providing a link between the water absorption of the coarse aggregate portion and the resulting compressive strength of the recycled concrete. In other words, the project aims to simulate the recycled coarse aggregate coming from recycling facilities by adding controlled amounts of contaminants as replacement of the natural aggregate originally used as the main coarse aggregate.

Overall, this project attempts to scrutinize helpful data regarding the possible effects of contamination in recycled concrete. The starting point for this research are the broad topics of sustainability in construction industry and more specifically the implementation of materials such as recycled aggregate concrete. Since the nature of this project allows for a limited time and resources, the target of this research had to be aligned with what has been reported previously, what are the gaps and what was available in terms of facilities, equipment and materials. Hence, it was decided that a combination of experimental testing and predictive modelling would best fit the given description. To achieve this, it was ruled that a sufficient number of contaminants (attuned to the available time and resources) would be added to traditional gravel in order to investigate any noteworthy correlations and/or behaviour. In addition, the water absorption of coarse aggregates has not been inspected thoroughly as a contributor towards the compressive strength of recycled concrete and thus was also selected as one of the main aspects of this study. To tie everything up, a model taking into account all experimental data and providing forecasts to a wider range of parameters would be key to fully realising the objectives of this project. In Fig. 1.1 below, the narrowing process from the broad topic of interest to the project-specific objectives is illustrated:

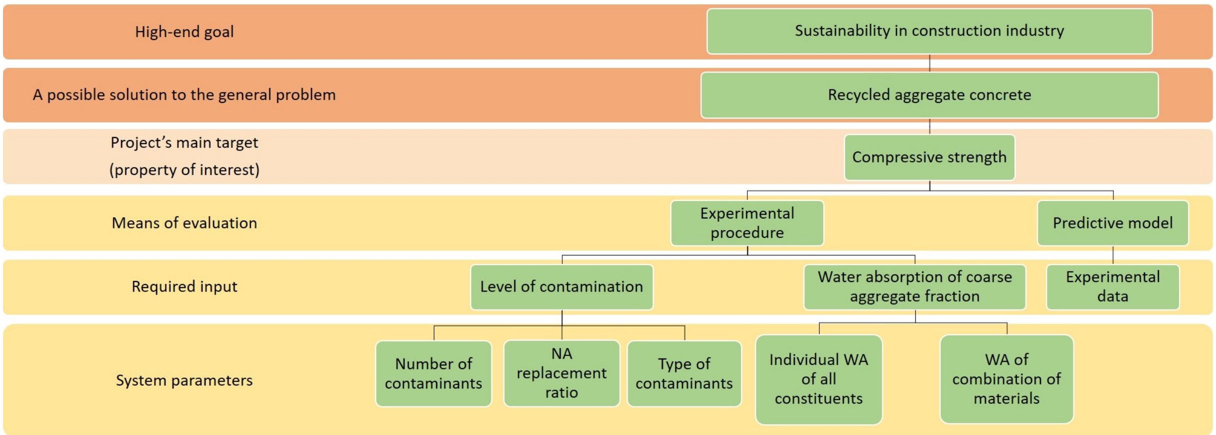


Figure 1.1: Project structure and derivation from the tendentious matter of sustainability in construction sector

The contaminants chosen for the study are the materials most often found in C&DW. According to [10], the recycled materials from C&DW include wood, metals (ferrous and non-ferrous), plastics, glass, paper, cardboard, drywall and concrete. Additionally, other sources [11] state that masonry also has a major contribution, especially in countries such as the Netherlands, Spain and Czech Republic. In the same source, gypsum is mentioned as one of the composing materials, which could be related to the drywall reference published in [10]. Another paper featuring a study on different C&DW samples [11] categorizes the composition as clean concrete, mixed aggregates (containing bricks, ceramic tiles, mortar), asphalt, newly cast concrete cores. Based on these reports [9, 10, 11], 8 main materials were selected. These materials cover brick, ceramic tiles, glass, wood, gypsum, plastics (HDPE, EPS), mineral fiber. In compliance with [12], some of the most widely used plastics in the construction industry include HDPE (High-density polyethylene), PVC (polyvinyl chloride), EPS (expanded polystyrene resin), PU (polyurethane insulation board), PP (polypropylene polymer). Furthermore, courtesy of Plastic Europe and their annual report for 2021 [13], Fig. 1.2 visualizes the use of plastics in several industries, including building and construction. Thus, it was opted for two of them (HDPE, EPS) to be part of the study. Mineral fiber was also included since in some of the reports [11] it is declared that there is an additional unidentified portion of mineral waste separate from the bricks, tiles and mortar group. Since mineral fiber has an application as thermal insulation in constructions and piping, it was concluded that it can be representative of its respective fraction. Lastly, no metals were entitled to be part of the study proceeding from the fact that ferrous metals (such as steel) are recycled and separated from the rest of the C&DW on-site [10]. Non-ferrous metals (aluminium, roofing sheets) are also recycled and transported to be re-used, while materials like wood, plastics, paper are usually incinerated. Due to the fact that the major portion of the C&DW is taken by secondary concrete [10, 11], it was rational to include crushed concrete aggregate as a contaminant at least to an extent which could be used to enhance any correlation between all results. Furthermore, from previous studies in TU Delft, it was known that the compressive strength of CRCA made with 100% RA is reduced by a maximum of approximately 30%. In the end, all results are compared with the inclusion of air in concrete. The air was simulated by adding of individual EPS foam elements (different from the use of the material as a contaminant) in order to examine any similarities between CRCA and concrete with larger air content.

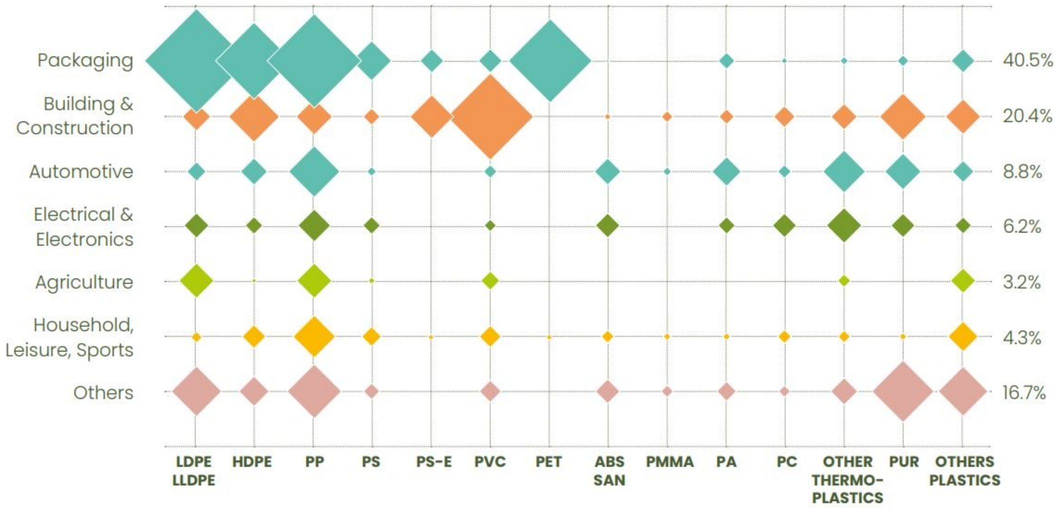


Figure 1.2: Plastics usage by segments and polymer type. Total: 49.1Mt. Data for year 2020. Extracted from [13].

Lastly, the idea behind using controlled amounts of contaminants was derived from ongoing studies [14, 15] based on SBS (sensor-based sorting) and LIBS (Laser-induced breakdown spectroscopy). These methods, currently still in development, allow the user to separate particles of different types and sizes using high-resolution CCD camera [14] or nanosecond pulse laser [15]. Apart from particle differentiation, the user is also able to attain the exact composition of a given sample and this has been an inspiration to this study. The output from another research [16] shows that the most advantageous technological routes of contributing towards a more sustainable construction industry involve recycling on-site and producing high-value secondary products. Following the C2CA project (Concrete to Cement and Aggregate) (c2ca.eu) funded by the European Commission (EC), this approach is most effective when it comes down to decreasing the environmental footprint based on a Life cycle assessment (LCA). In combination with the methods used to identify the components of the C&DW compound and the development of a predictive model, it is believed that we would be able to predict the strength of CRCA and the final result would be a completed full cycle emphasizing the circularity of the process.

1.2. Scope

This project aims to make the functional properties of RAC more predictable. For this reason, it is essential that the process of describing the properties of the recycled aggregates is simplified as much as possible. Thus, an important step towards achieving this goal is to reduce the complexity of the concrete design mix by excluding any nonlinear functions that might relate the input parameters (for example water absorption of the concrete mix, water to cement ratio and cement content) and the desired output (compressive strength of the concrete after a given period of time). In other words, all contaminants (or other constituents of the study) which bring excessive complexity to the potential predictive model to be developed will be disregarded.

The main focus of this study falls onto the effect contaminants have on the water absorption of the coarse aggregate and subsequently on the compressive strength of the concrete containing them. It should be mentioned that coarse aggregate is one of the four main ingredients for making concrete (rest are fine aggregate, water, cement) and usually makes up for 40 to 50% of the weigh of concrete. Another important property of the coarse aggregate, sometimes referred to as gravel, is that it contains particles with sizes between 4 and 20mm in diameter and has a water absorption of no more than 3%. Concrete made from secondary materials is generally referred to as RAC (recycled aggregate concrete), however in this project a more specific type of recycled concrete is considered – concrete made from recycled coarse aggregate (CRCA), meaning that only the contamination of the larger aggregate particles is of interest. This is done to limit the diverse factors that could influence the behaviour of the obtained concrete. As mentioned, the aim is to establish a strong connection between the water absorption of the coarse aggregate content of the CRCA and the resulting compressive strength under various conditions. These conditions include different number and different quantities of contaminants present in the mix design. In pursuance of the broader picture, a combination of these conditions can be implemented resulting in numerous different concrete mix designs of interest to this study. To overcome the large number of testing specimens, a proper approach in the form of random sampling method could be used to narrow down the contaminants with major contribution and their contents of interest within the mix. Based on these results, a predictive model correlating the water absorption, compressive strength and level of contamination should be developed to complete the study.

The contaminants used throughout the research are tailored to comply with what is more likely to happen in reality; they denote the materials that are most often found in C&DW and predominantly contribute to its composition. As mentioned previously, they include (but are not limited to) brick, glass, wood, gypsum, ceramic tiles, plastics (HDPE, EPS), mineral fibers. Additionally, sand concrete is also featured as part of this study with comparative purposes.

It is also recognized that there are other contributors to the mechanical behaviour of contaminated concrete. For example, shape and size distribution of the (coarse) aggregate, type of cement of the parent and new concrete, strength class of the old concrete, water to cement ratio are only some of the aspects that could fully describe and categorize the behaviour of RAC. This project does not aim to provide in-depth details regarding each one of those aspects, however if during the course key relations are obtained, then side studies could be suggested or performed for better understanding of the overall problem.

1.3. Aims and objectives

This research plays a key part into the broader topic of CRCA and factors that have an effect on its structural behaviour. The primary goal of this project is to establish insight onto the connection between the water absorption of coarse aggregate and the compressive strength of CRCA. By means of experimentally evaluating the water absorption of various contaminated coarse aggregate samples, designed in a controlled environment with the sole purpose to simulate real-life conditions, it is sought to determine a strong connection between the theoretical background and laboratory tests. Naturally, the desired outcome is to link the obtained datasets to practical solutions by developing a predictive model which could mitigate the current issues regarding C&DW and contribute to a more circular construction industry. In order to achieve the ultimate goal of the research, namely to establish the connection between level of contamination of RCA, water absorption of RCA and the compressive strength of CRCA, the following objectives need to be met:

- Obtain a broad range of water absorption values for a set of recycled aggregate samples;
- Include all contaminants as replacement to the natural aggregate individually and in groups;
- Define a wide range of CRCA design mixes and narrow down the test samples via random sampling method;
- Perform a series of compression tests on concrete specimens with known degree of contamination and water absorption levels;
- Relate all experimental results with existing literature;
- Develop a predictive model and validate it with more random sampling tests;
- Determine which other parameters (might) have a significant influence on the behaviour of CRCA.

1.4. Research Questions

The knowledge gaps which include the relation amongst the water absorption of the contaminated coarse aggregate and the compressive strength of the concrete raise questions such as:

1. Is the water absorption of recycled aggregate a linear function of the content of relevant contaminants in the aggregate for a predefined range of allowed water absorption levels from 0 to 5%? Does the relation also hold true for values beyond this range?
2. Do recycled aggregate with identical water absorption and different compositions deliver comparable compressive strengths?
3. Does the estimated water absorption give accurate predictions of the water absorption in practice? Does labelling a given material sufficient to describe its coefficient in the water absorption calculation or does this coefficient vary in practice for the same material?
4. Is it possible to predict the deviation between the simple model prediction based on a given input from the concentration of major components? Is it possible to develop a correction which simplifies the model and makes it linear at all times?
5. Which are the main parameters affecting the compressive strength of concrete made from RCA and what is their overall effect?
6. Is it possible to include crushed concrete aggregates in a way that is beneficial to the compressive strength of concrete?

1.5. Project Outline

Based on the project's definition and nature, there were four main phases defined initially (Phases 1, 2, 3 and 5). During the course of the project, an alternation in the initial schedule has been made, incorptorating another phase (Phase 4) which required completion prior to Phase 5. Each of those phases had its own individual contribution and some entirely relied on the input of the previous one. Below in Fig. 1.3, a Gantt chart describing the dependency and distribution in time of all phases is presented:

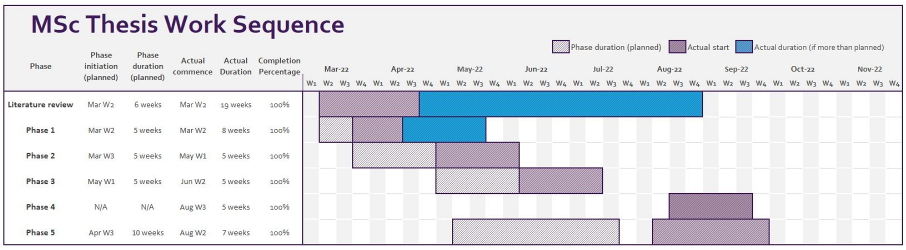


Figure 1.3: Project work sequence (planned and actual).

Below all phases are briefly explained:

- Literature review: The initial planned duration for literature review is as recommended by several academic sources. However, due to the variety of different components of the project and the different result sets after each new phase, more sources in literature had to be investigated. The extensive literature review was still done in the initially planned timeframe.

- Phase 1: This phase includes the initial water absorption testing - all materials which need to be tested individually and also in combination with coarse natural aggregate only. It was started slightly later than planned due to the lack of certain materials in the laboratory.

- Phase 2: This stage of the project features the first step of a random sampling method applied to resolve an issue with a large amount of possible combinations of aggregate and contaminants. The exact procedure and reasoning behind this method are given in Section 4.2.2. It also includes more water absorption tests performed on the chosen samples. It commenced later than expected due to the detailed analysis of the results of the previous phase and due to the time it took to optimize the control concrete mix design.

- Phase 3: This is the second step of the random sampling method. It is entirely dependant on the previous phase since it utilizes its result as input for more relevant settings. Similarly to the previous step, it is also described in greater detail in Section 4.2.2.

- Phase 4: This step was included post factum. It has to do with the final comparison of the results to one constant – in this case the chosen parameter was air in the form of individual EPS foam particles. Several group sizes were used and more specimens were cast and tested for their strength – all relevant information is communicated exhaustively in Section 4.4.

- Phase 5: This phase is mainly concerned with the development of the predictive model of the project. The initiation is possible relying on the results from Phase 2 on a more basic level, while the data from Phase 3 has the greatest weigh on the model's settings. The validation of the model, which is also part of this phase, is done once again by using random sampling method to come up with an arbitrary number of samples in order to compare the model's prediction and the actual experimental behaviour. The initiation of this phase was delayed in time due to the nature of the results and the need to perform more laboratory experiments. More information of the development of the predictive model can be found in Section 5.

1.6. Thesis Outline

The outline of the project follows the hereunder structure: In the next segment, Chapter 2, the theoretical background in the form of literature study is examined and discussed. The chapter mentions important aspects of the project found in similar studies - water absorption of natural aggregates, existing relations between water absorption and compressive strength of concrete, general information regarding the RAC and its applications in the construction industry, development of analogous predictive models, properties of materials found in C&DW. The next section, Chapter 3, explains the methodology used to carry out the experimental procedures throughout the project. Then, in Chapter 4, all experimental results are presented, examined and compared to the theory, as well key relations are extracted in aid of developing a predictive model. In-depth analysis of different water absorption datasets is considered, relating all to the rest of the project deliverables. Chapter 5 outlines the process of creating and refining predictive models and their validation. The conclusion and recommendations for future work are manifested in Chapter 6 which concludes the main body of the thesis report.

2
Theoretical background

2.1. Introduction
Due to the nature of this project, finding relevant published information is very beneficial, however it doesn't carry as much weight as per usual. In other words, there are aspects which need more in-depth review such as the individual role of contaminants, their properties, certain mechanics of concrete production like hydration process, water intakes, cement used and water to cement ratio effect. Naturally, studies on recycled aggregate concretes and their applications are also very favourable. It is advantageous if information regarding a predictive model linked to concrete production is harvested and used later in the project. Overall, it is important to consider and assess diverse data insightful on each of the individual constituents of this research and if possible to collect information concerning a blend of components. Hence, in this chapter, each new section denotes one of the main modules and starting points for this study while any subsection looks into more detail at their corresponding topic.

2.2. Properties of conventional concrete
Conventional concrete is made out of four main ingredients - cement, water, coarse and fine aggregates. Furthermore, there are many other constituents such as air entrainers, plasticizers and superplasticizers, retarders, stabilizers, cement additives such as slag, fly ash and many more which all have a certain effect on the properties of concrete. Below, the substantial elements are elaborated together with some of the relevant properties of concrete for this research.

2.2.1. Cement
Cement is the most important and most expensive component of a concrete mix design. The different cement options directly affect the mechanical properties of the resulting concrete. Thus, it is of high importance to investigate the variations and the consequent effect each one might carry to the concrete design. In order to perform this task, first the cement classification must be explained. Relying on existing standards, NEN-EN 197 [17], there are five common cements which are grouped as follows: CEM I (Portland cement), CEM II (Portland-composite cement), CEM III (Blast furnace cement), CEM IV (Pozzolanic cement) and CEM V (Composite cement). Any additives to the cement are specified after the initial cement notation and their amounts are prescribed with A, B and C – corresponding to the ratio of main components. The strength class of the cement ranges from 32.5 up to 52.5 with step size of 10; three rates of hydration are available: Class N denotes ordinary early strength, class R with high early strength and class L with low early strength, the latter applicable only for CEM III. The full characteristics of

cement classification and nomenclature are available in the current standards NEN-EN 197-1 [17].

Whenever cement is mixed with water, cement paste is formed which ties the aggregates together by filling the surface voids of the particles. As soon as water is present in the mix, the cement hydration process begins. This process is complex and has been examined extensively in literature. A very simplified schematic (Fig. 2.1), courtesy of [18], illustrates how the process could be split into four main stages. The main deliverables extracted from this study include the following:

- As long as there is water/moisture within the concrete, in theory it will always increase in strength;
- For practical reasons and as empirically established, it is considered that concrete reaches the majority of its strength after 28 days of curing;
- Cement hydration is linked to heat release with especially high rate between the third and tenth hour (on average) – this stage is known as the acceleration stage and denotes the initial setting of concrete;
- Factors such as water temperature, environment temperature, cement and water content, type of aggregate could affect the process by slowing it down or speeding it up;
- If the reaction occurs too quickly, then residual tensile stresses could develop in time which could cause cracking of concrete – to mitigate this the cement type should be properly chosen.

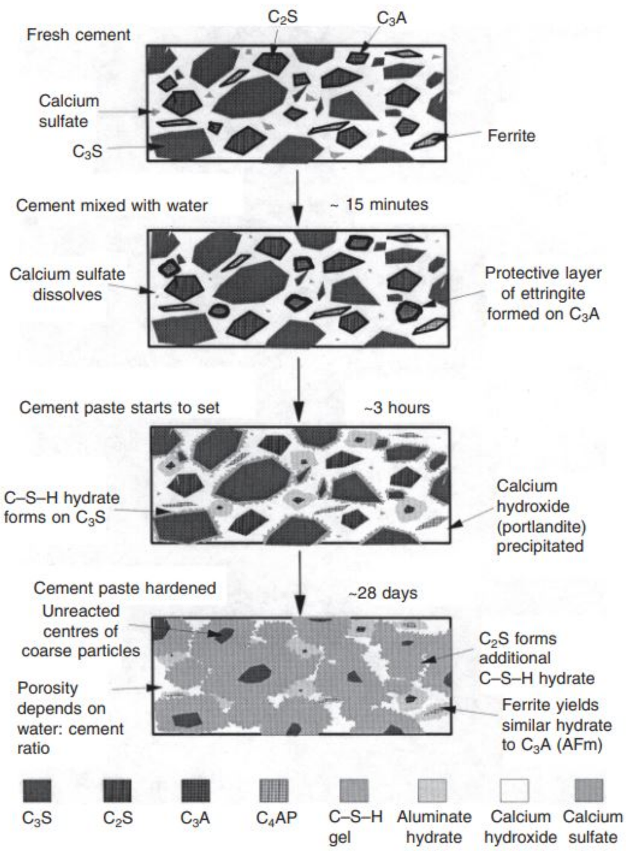


Figure 2.1: Cement hydration process in four main step. Retrieved from [18].

Deriving from the last item mentioned in the above list, low heat cement such as CEM III reduces the heat dissipation throughout the hardening process and helps preventing the crack formation in later stages. Additionally, as mentioned previously, water is required so that the hydration of cement occurs and any strength growth is to be expected. On the other hand, it is also reported that cement is directly connected to compressive strength of concrete. Consequently, a very importance parameter of each concrete mix design is established – the water to cement ratio (w/c). Even more than 100 years ago, there was a formulated law governing the compressive strength of cement paste based on the cement and water contents [19]. The law could be transformed to resemble Eq. 2.1:

$$f'_c = \frac{k}{1 + (\frac{w}{c})^2} \tag{2.1}$$

where f'_c is the compressive strength of fully hydrated cement paste [MPa] and k is a constant [MPa].

From the equation, it is obvious that the lower the w/c is, the higher the resulting strength is. Concurrently, one cannot reduce this value infinitely and expect to obtain a strong design. Later on it was discovered that the lowest ratio required to fully hydrate Portland cement (CEM I) is 0.42, courtesy of the infamous scientist John Powers, creator of the Powers' model. After numerous theoretical and experimental studies, w/c ratios in the range between 0.40 and 0.60 dictate the current concrete production, fluctuating due to the cement type used. Naturally, it is more advantageous to use lower w/c due to the improved strength and overall more sustainable design. Nevertheless, such concretes should be dealt with great care, paying extra caution on the curing conditions and providing sufficient water so that shrinkage does not occur at early stages, compromising the durability of the concrete.

2.2.2. Aggregates

On average, 70 to 80% of the concrete mix is taken by aggregates. There are two types of aggregate used for conventional concrete – fine and coarse. Fine aggregates have particle diameter of 4mm (Eurocodes), 4.75mm (American Standards ASTM), 5mm (British Standards BS) or less, while coarse aggregates are comprised of larger particles [20]. If natural aggregates are used then the fine portion is usually referred to as sand, while the coarse fraction is known as gravel (there are other type of natural coarse aggregates such as granite, basalt, marble and others). Natural aggregates are extracted from river beds, sea beds, mountains, deserts. The importance of aggregates comes from the fact that different sizes and surface textures result in different bonding with the cement paste. Gravel for example has smooth surface with limited amount of voids – resulting in good workability of fresh concrete but not as efficient bonding with the cement paste. Crushed stone or recycled aggregates are much more porous and rough allowing the paste to penetrate within the particles and to obtain a stronger bond. On the other hand, this means that the workability will not be as good or that more cement has to be used. The coarse aggregates are the load bearing framework of the concrete and usually withhold more stress compared to the cement paste [20]. Sand particles are required so that there are no voids in the concrete mix, which could lead to the so-called segregation of concrete.

An important aspect when discussing aggregates in recycled concrete is trying to understand what happens when a foreign particles replace natural aggregate particles. It is well known that natural aggregates act as inert fillers – they do not have chemical reactions with cement, do not hydrate, do not swell or shrink. As mentioned previously, the type of aggregate could also influence the performance of both fresh and hardened concrete, especially water absorption, porosity, particle grading, overall weight and density of concrete, elastic modulus, crushing and compressive strength. Therefore, it is of utmost importance to understand how the particle replacing the natural aggregate will alter these properties. For example, glass is known to contribute to Alkali-silica reaction (ASR), which is one of the main disruptive mechanisms in concrete. Since glass particles could be easily found in C&DW, then it could be expected that ASR can occur in recycled concrete, which could help deteriorate the concrete with time. As reported by Yuan et al. (2021) [21], lightweight aggregates (dry bulk density below 1200kg/m^3) produce lighter material with better thermal insulation properties than conventional normal weight aggregates. The downside of using such aggregate is that they manufacture weaker concrete with lower elastic modulus and higher creep and shrinkage. In other words, if natural aggregate is replaced, it is always rational to determine the sulfate and chloride contents of the new material so that any degradation of the resulting concrete is anticipated. Moreover, there are materials, referred to as "deleterious substances", which can be minor constituents in aggregates [21]. These substances could be detrimental to the workability, setting and hardening, as well the durability of concrete. Such materials could include organic impurities, silt, shale, coal, lignite, some lightweight materials, clay lumps and friable particles, chert and alkali-reactive aggregates. Overall, foreign particles used instead of conventional gravel could delay setting and hardening of concrete, reduce strength by interfering with cement hydration process, result in volume changes due to certain chemical reactions (such as ASR) and generally cause deterioration [21].

2.2.3. Air content

Air is incorporated in concrete via several methods, most often by using air-entraining admixtures. However, air inclusion could also be accomplished via a different approach. The concrete recipe could be designed in a way that accounts for a fraction of the volume dedicated to air and therefore the rest of the components could only fill the remaining volume. Air is included as it can bring better workability by reducing the friction between cement particles, as well as conserving water within [20]. It could also improve frost resistance and impermeability, however there is a price to be paid and it all comes at the cost of impaired compressive strength (CS). It is known that 1% of air (vol.) could lead to 4 to 6% of CS decline [20]. Zeng et al. [22] have reported that atmospheric pressure also governs the formation of air bubbles. At low pressures (0.7 P), the initial air content of fresh concrete is revealed to be 13.8 to 41.3% lower than at 1.0 P due to the higher surface tension of air-liquid surface. Furthermore, the compressive strength of concrete at 0.7 P is 15 to 20% lower than that at 1.0 P – this is explained by the higher content of air voids in the 400 to 2400µm region.

2.2.4. Water absorption

When discussing the role of water to the strength growth and its importance for the cement hydration process, it is also key to mention the role of the water absorption properties of both the ingredients and the resulting concrete. It is known that different amounts of water lead to different strength developments and could also affect the residual stresses. This is why the water absorption properties of the aggregates have to be examined prior to their inclusion in the mix. Since coarse aggregates compose the major part of the aggregate portion, they possess higher weight in terms of the overall water absorption of the constituents. Natural coarse aggregates like gravel possess a well known range of values of WA and are mostly between 0.5 to 2.0% [23]. This is correlated with governing codes of practice and/or construction standards where most often the limiting value is anywhere between 3.0 and 3.5% for coarse aggregate. This practically disallows the use of most recycled aggregates since it is widely reported that they have significantly greater absorption compared to NA, very often higher than 5.5%. On the other hand, there must be a reason of this imposed limitation – according to Zhang and Zong [24], this is due to the possible durability issues. They state that durability is concerned with the ability of penetration of a fluid within the microstructure of concrete, known as permeability. Highly permeable concretes allow harmful substances within the concrete which leads to deterioration. Additionally, high permeability is usually related to more porous particles, i.e. particles which contain more pores or voids on surface level. Consequently, porous elements such as recycled coarse aggregates are associated with higher absorption capacity and this arises the issue of using such materials. The authors of [24] also suggest that proper curing conditions (effect of external elements) such as suitable temperature and humidity have to be ensured in order to prevent durability problems at later stages. It is also principal to note that different conditions such as atmospheric pressure, pre-wetting methods, initial moisture content could affect the results of standard water absorption tests as reported by Khoury et al. [25].

Water absorption is also evaluated in later stages over the hardened concrete element, not only on its aggregate contents prior to casting. This absorption is categorized by the water flow into unsaturated pores due to pressure difference caused by capillary forces [26]. A study by Maghfouri et at. [27] has investigated the role of 28-day water absorption of concrete compared to its compressive strength. As it turned out according to the research, lightweight concrete (more porous aggregates used) resulted in much higher values of WA along with lower strength growth compared to normal weight concrete. Nonetheless, lightweight concrete was reported to reach feasible strength values, accepted by design codes, despite being classified as problematic in terms of long-term durability due to the higher 28-day WA [27].

2.2.5. Compressive strength

This is the most important property of concrete – it is well known that concrete as structural material is mainly used to produce elements able to withstand great axial stresses. Since unreinforced concrete is considered as brittle material, it is of high importance to be able to reach designed strengths in order to prevent brittle failures. All previously mentioned parameters influence the development of compressive strength and hence it is vital to understand how do the contaminants join in the story of recycled concrete.

2.3. Properties of contaminants

In the next sections, each contaminant chosen for this study is examined into detail and all relevant properties, functions or consequences of using it are mentioned. The review also focuses on determining specific values of water absorption, density and possibly crushing and abrasion values, as well as behaviour under axial compression. While for some materials all properties are listed and/or widely available, for others the latter might not be applicable. In such cases, it is important to consider qualities close to the desired and if this is also not possible, then any key characteristics that might affect the recycled concrete.

Prior to looking at each contaminant, it is crucial to define an estimate of the fraction each material occupies within C&DW. Clearly, these values differ based on location, time period and investigation method and categorization, however for this research they are relevant only in terms of what amounts of each could be expected within the recycled aggregate portion if almost no refinement is applied. Judging from all previously mentioned papers [9, 10, 11], as well as a study carried out in South Africa [28], it can be concluded what these volume fractions are on average. In Fig. 2.2 below the data is envisaged and it can be seen that a significant share, around 70%, of the demolished material is taken up by old concrete waste and masonry products. Other materials occupy around 30% of the total volume and the largest fragments pertain to non-categorized waste, plastics and timber. Glass and gypsum are found in smaller quantities compared to the rest.

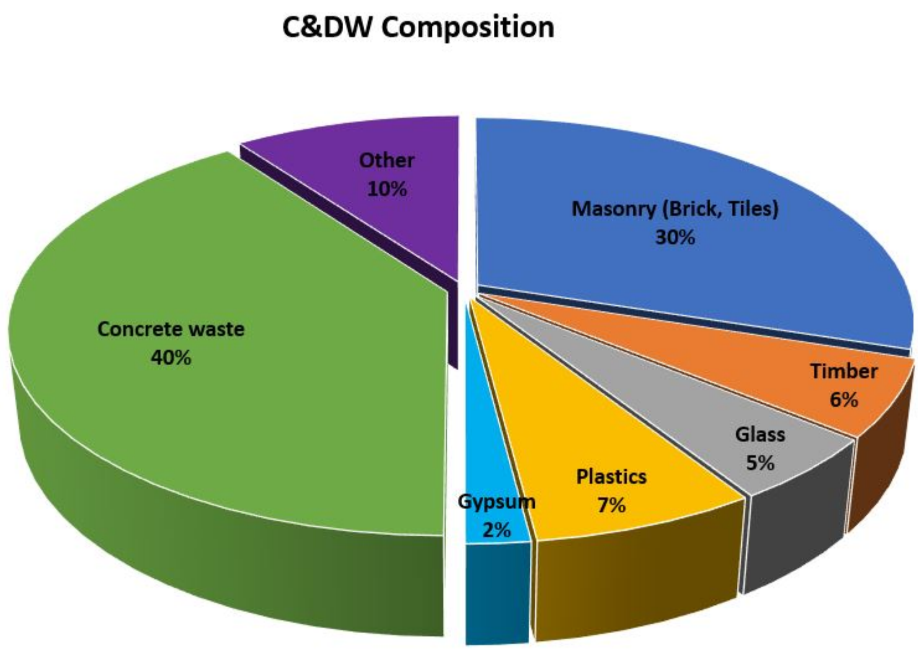


Figure 2.2: Approximate composition of C&DW globally as reported in literature

Brick

There are multiple examples available in literature of people using bricks in various forms as part of concrete mix design. Brick, surface-treated or not, crushed into fine or coarse aggregate size, has been one of the main materials evaluated when describing possible recycled aggregate concrete. For example, Kasi (2016) [29], who investigated the use of recycled brick as coarse aggregate in concrete, prepared recipes containing 0 up to 100% volume replacement of natural coarse aggregate, with a step size of 25%. The main outputs of his study include 12.85% water absorption of coated recycled brick aggregate (coating is done to limit the water absorption of standard recycled brick) and significant difference in terms of compressive strength of the resulting concretes: for the control mix with 100% NA, the 28-day strength was reported to be 25.25MPa, while for the 100% RBA (recycled brick aggregate) the value was 7.25MPa. This denotes a difference of over 70%. The intermediate points however yielded more interesting results – it is evident that concrete with 25% RBA replacement reached the same compressive strength as the control design (25.15MPa). At 50% replacement, the difference with reference was approximately 30% (17.35MPa), while at 75% RBA the loss of strength was nearly 60% (10.82MPa). The tests were carried out for mix designs for M20 concrete (results mentioned above), as well as for M15 grade, however the relation was almost equivalent. Fig.2.3 below illustrates the aforementioned correlation in terms of compressive strength relative to the reference concretes with 0% brick content:

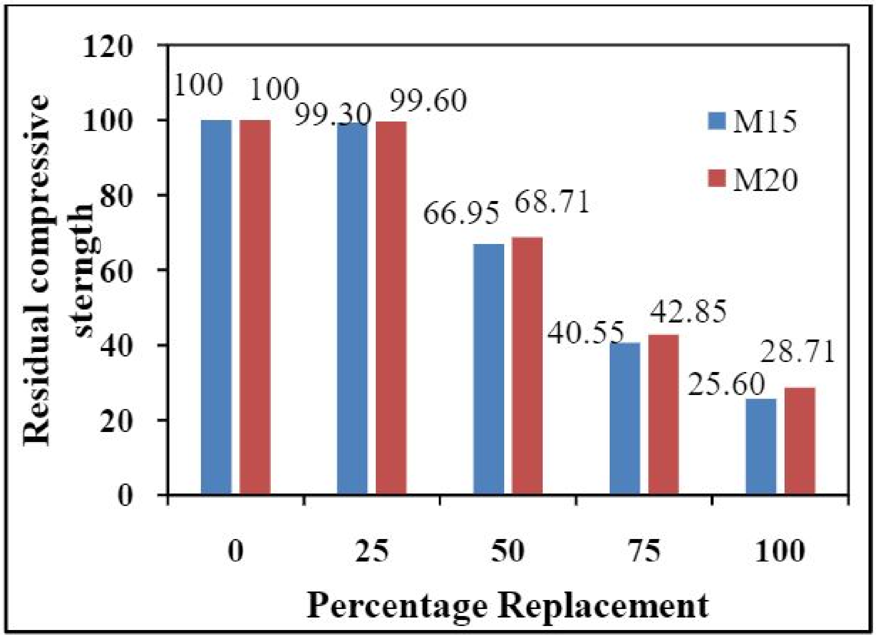


Figure 2.3: Residual compressive strength variation for different NA replacement. Courtesy of [29]

Another research [30] reported an extensive dataset regarding the use of recycled bricks within concrete design. Scrutiny indicates that for lower w/c ratios (equal to 0.45), the recycled coarse brick aggregates showed improvement in compressive strength compared to first-class brick aggregates used commonly in the authors' country Bangladesh. The latter statement did not hold true if the w/c was 0.55 – in such cases the workability, strength and elastic modulus of the first-class brick aggregate concrete were significantly better. These findings would suggest that the higher water absorption of recycled aggregates contributes towards the gradual release of moisture in the concrete in cases when more water could be incorporated (lower w/c) and therefore improves the cement hydration and subsequently the strength development. In addition to this, replacements of first-class bricks with recycled didn't carry any remarkable reductions in strength as reported by [30], which comes as proof to the previous statement.

From a previous project carried out in the laboratories of TU Delft, it was estimated that recycled bricks sourced from a local Dutch company had about 20% water absorption value. Other studies such as the one of Milevi et al. [31] confirm that absorption of recycled crushed bricks is in the magnitude of 22 to 25%. Moreover, they also suggested that bricks become fully saturated with water after 30 minutes of submersion and remaining in water for further 24 hours only increased the value by around 2%. The same research also provided guidelines for the expected difference in compressive strength of concrete made entirely with natural coarse aggregate and one made with recycled bricks as the CA. The drop in strength was approximately 20% after 28 days – 46.88MPa (control) and 35.75MPa (bricks).

In addition, Cachim [32] completed a research on recycled concrete made with brick as replacement of coarse aggregates. The two types of bricks used in his experiments reached 15.81 and 18.91% of water absorption, while their crushing strength was reported to be 30.8 and 27.3% – in comparison the NA in that particular project was evaluated to have 1.33% WA and 21.6% crushing value. Dry density of bricks was between 1805 and 1928kg/m^3. The conclusive comments of the author expressed that up to 15% of bricks as NA substitute did not lead to a strength reduction, while larger amounts such as 30% could bring losses up to 20% depending on the brick type. Furthermore, crushed pre-saturated bricks were said to provide extra water for cement hydration and this moisture did not affect the optimal initial w/c ratio.

Wood

A comparative study on three types of wood [33] evaluated the water absorption of the woods at different soaking periods. According to this research, after 1 day of immersion in distilled water, the moisture content for two of the three types was nearly 60%, while the third one (hardwood specimen) reached 20% absorption. Furthermore, the absorption rates differed for each wood and this was explained by the diffusion phenomenon - the moisture diffusion into the wood occurred due to the moisture gradient between the surface and the core. Moreover, the rate of water absorption depended on the difference between the saturation water content and the water content at a given time. Each wood specimen had a different set of properties, including amount and size of cellular cavities, where the interstitial water is contained, and this arose the difference in absorption rates for each wood type.

Another published paper [34] reported WA of various raw materials after 24 hours of soaking time – it is evident that a mix of wood particles reached almost 53% value, while MDF and plywood went up to 74 and 79% respectively. Plotze and Niemz [35] have scrutinized a thorough dataset of timber samples which have been experimentally tested for porosity and density. From their data it can be seen that the total porosity of a wide range of specimens fall between 22.1 and 73.68%, while on average this value is in the magnitude of 54.0%. Consequently, the higher the porosity, the larger the volume of voids as per definition. The volume of voids is directly linked to water intake properties of any material, including wood as also stated by [36]. In their publication, it is evident that the higher the amount of permeable voids, the higher the water absorption. However, it should be noted that wood expands while absorbing moisture, therefore resulting in the ability to captivate larger amounts of moisture compared to its dry conditions. According to [37], differences in density and void volume (porosity) could arise from differences in the anatomy of the wood modified by the effect of extractives. A previous study by Mantanis et al. (1995) [38] has revealed that on average extractives take up 2 to 10% of the initial volume of wood, with the exception of tropical species which can contain 20-25%. Taking this into account, it can be concluded that the general law linking porosity, volume of voids and water intake should be slightly modified for timber specimens due to their emphasized shrinking and swelling properties when exposed to certain environments.

Glass

Glass or glass wastes have also been used in the past for making concrete as reported by [39]. The authors divulged some of the advantages of using glass within recycled concrete and they included potentially better resistance to freeze-thaw cycles, drying shrinkage and abrasion derived from the low porosity and limited water absorption. On the other hand, glass was said to cause expansion and cracking likely due to dissolved amorphous silica under alkaline conditions, forming alkali-silica reaction gel (ASR) which absorbs water and expands, leading to higher tensile stresses and subsequently cracks. The same study reported water absorption of recycled glass waste of 0.1%. Furthermore, results showed that the usage of recycled glass particles leads to insignificant decrease of compressive strength – a reference 100% NA-made concrete reached nearly 29MPa at 7 days and just over 37MPa after 28 days, while recycled concretes with contents of 33%, 66% and 100% glass as CA gave rise to values of 28, 26 and 25MPa after 7 days and 35, 32 and 32MPa after 28 days correspondingly. This came to prove that using recycled materials could even be beneficial in terms of strength development in concrete in addition to the decreased amount of plasticizer required in order to keep the came workabillity of the fresh concrete.

Another paper [40] reported a wider range of WA values for recycled glass particles – from 0.03% up to 1.45%, density between 1550 and 2470kg/m^3 and abrasion resistance of 30 to 38% (LA coefficient). In this study, a comparison between the incorporation of glass in recycled concrete was made, derived from various sources from literature. The results, as presented in Fig. 2.4 were contradicting, nearly half reporting a positive trend in workability as more glass particles were added or positive effect over the compressive strength of concrete with glass aggregates. The remaining projects however stated the opposite. The authors tried to explain why these differences occur – some of the glass specimens had higher friability and lower density, leading to lower strength (Mardani-Aghabaglou et al. (2015)). The rest of the papers which reported reduced strengths were likely due to the weaker ITZ, caused by the smooth surface and sharp edges of glass, as explicated by the authors. In contrast, the positive effect achieved in the rest of the studies was unraveled to be based upon the presence of fine glass particles (<0.825mm), which were said to promote the long-term strength of concrete through pozzolanic reactivity, formation of dense microstructure around the ITZ and the contribution of silicate species from glass in the CSH gel formation.

Source	% of sand replacement with glass aggregate	W/C ratio	Effect on workability	Effect on compressive strength
Małek et al. (2020)	5, 10, 15, 20	0.49	↓	↑
Bisht and Ramana (2018)	18, 19, 20, 21, 22, 23, 24	0.40	↓	↑ up to 20% ↓ beyond 20%
Liu et al. (2018a)	30, 60, 100	0.66	—	↓
Liu et al. (2018a)	20, 40, 60, 80, 100	0.51	—	↓
Olofinnade et al. (2016)	25, 50, 75, 100	0.50	↓	↓
Afshinnia and Rangaraju (2016)	20	0.45 and 0.31	↓	↓
Adaway and Wang (2015)	15, 20, 25, 30, 40	0.41	↓	↑ except for 40% replacement
Mardani-Aghabaglou et al. (2015)	15, 30, 45, 60	0.45	No significant change	↓
Abdallah and Fan (2014)	5, 15, 20	0.55	↓	↑
Du and Tan (2014)	25, 50, 75, 100	0.49, 0.38, 0.32	No clear trend was found	↑
Tan and Du (2013)	25, 50, 75, 100	0.485	↓	↓
de Castro and de Brito (2013)	5, 10, 20	0.55–0.58	↓	↓
Ali and Al-Tersawy (2012)	10, 20, 30, 40, 50	0.40	↑	↓
Borhan (2012)	20, 40, 60	0.55	↑	↓
Ling and Poon (2011a)	25, 50, 75, 100	0.45	↑	↓
Ling et al. (2011)	25, 50, 75, 100	0.40	↑	↓

↑, means a positive trend in the result; ↓, means a negative trend in the result; — means not reported.

Figure 2.4: Contrasting results in affected concrete properties by the use of glass aggregate as reported by [40]. Retrieved from [40].

Conducted studies [41] on the same topic of incorporating glass with the aggregates of concrete communicated that up to 50% of replacement with coarse glass particles led to drop of maximum 22% of CS. Furthermore, if 100% glass was used for the fine aggregate fraction, then only 17% decline in strength was expected after 28 days. In the end, it was concluded that coarse glass particles reduced the CS due to the smoothness of the glass surface which interfered with the bonding between the aggregates and the cement paste.

The moisture absorption of glass was reported to be within the range of 0.15% to 0.23% according to [42]. In their research, over 15 different samples with different thicknesses and different properties were tested for their water absorption. Some specimens were treated with external materials or had inclusion of composite materials. Thus, the results of this research are only indicative and should not be taken into account before relatable results are found in literature in terms of water absorption of glass only. Nevertheless, the standard deviation from the numerous experiments in this research was estimated and it turned out to be 0.02% and the values are presented in Table 2.1:

Table 2.1: Water absorption of glass as reported by [42].

Extracted WA values [%]			
Size group	E-glass/polyester	ECR/Epoxy	ECR/Vinyl Ester
1mm	0.22	0.23	0.19
2mm #1	0.22	0.22	0.18
2mm #2	0.21	0.22	0.18
2mm #3	0.21	0.22	0.18
4mm	0.20	0.18	0.15
Mean = 0.20%; Standard deviation σ = 0.02%			

These results however focus on clean or surface treated glass particles. In reality, the recycled glass coming from plants is more contaminated with fine particles like dust, which could affect the water absorption values. Related to this, another research [43] disclosed that WA of recycled glass was around 0.40 to 0.43%. Another output from this project was that nearly 30% of glass as NA replacement produced concrete with comparable strength independent of the grade design. Additionally, the drying shrinkage was constantly reported to be decreasing due to the lower absorption levels of glass – an effect more visible at larger replacement rates of NA.

Amlashi et al. [44] also examined the re-use possibilities of glass. They looked into the common experiments used in pavement and highway engineering and therefore tested recycled glass for its LA abrasion value. The end result showed that commonly reported values fell within the range between 23.0 and 42.0%, most times between 25.0 and 30.0%.

Gypsum

One of the first properties of gypsum that comes to mind when studying its water absorption potential is that is widely believed that gypsum dissolves in water. Consulting with research papers on this topic, it was seen that this was only partially true – Lebedev and Kosorukov [45] stated that the solubility of gypsum in water at 25^{o}C was approximately 0.0147 to 0.0161 M. They also mentioned that in other studies, the same property, expressed in units of grams per liter [g/L] rather than molar scale [M], was around 2 g/L at 25^{o}C. Comparing this data to the available values for sodium chloride (main composing substance of regular cooking salt), it is clear that gypsum is approximately 180 to 250 times less soluble in water – 1g of NaCl dissolves in 2.8mL of water or solubility equal to 36.0g/100g of water [46]. Another paper [47] suggested that the solubility of gypsum was slightly higher and equated to 140 times lower than common salt. Nevertheless, it is obvious that there must be some losses in terms of dissolved gypsum particles within the concrete mix, however these losses should be limited and should not interfere significantly towards the performance of RAC. On the other hand, this is an important property to take into account and examine when analysing water absorption results of samples containing gypsum.

Examining the recycling aspects of gypsum and gypsum products and their potential use in concrete, several studies are available to provide more insight on the topic. While most researchers such as [48, 49] included gypsum as replacement of cement, others such as Lushnikova and Dvorkin [50] investigated the applications of gypsum as a construction material in more depth. In their publication, they stated that gypsum itself was able to reach 17MPa of compression and 2MPa in tension. Another study [51] revealed that cubic specimens made out of recycled gypsum from plasterboard sheets yielded compressive strength values above the 8.4MPa mark which is considered the lower limit for commercial gypsum classification in Brazil according to local standards [52].

Nonetheless, it seems as though gypsum has been incorporated within concrete mix design mainly in the form of cement replacement. The consequences it might carry if added as aggregate replacement have not been evaluated by researchers and are yet to be analysed.

Ceramic tiles

According to the ISO-13006 [53] standard, ceramic tiles used in construction are divided into three categories based on their water absorption values - low, medium and highly absorbent. The water absorption ranges for each category are the following: below 3% (low), 3 to 10% (medium) and more than 10% (high). It should be mentioned that this division is only valid for the tiles themselves, while in reality in C&DW the tiles are usually found with hardened mortar attached to their back side, referred to as adhered mortar. Thus, the water absorption of recycled tiles is expected to be higher than the stated ISO values.

A study on properties of concrete made with ceramic wastes [54] looked into the option of including these secondary materials in order to decrease the overall cost of concrete and to improve the environmental footprint of the construction industry. In this study, Pacheco-Torgal and Jalali recorded the density of the coarse proportion of the ceramic waste, as well as the water absorption and the compressive strength of concretes made with certain amounts of ceramics. The density was reported to be 2263kg/m^3, WA of 6.0% and 10 to 15% higher compressive strength at 28 days for concrete with 20% coarse ceramic waste as replacement to the natural coarse aggregate. Another study [31], which investigated the inclusion of bricks and tiles in concrete, reported that at 28 days, a 33% drop in compressive strength was expected for a concrete made entirely with recycled tiles as aggregate (31.56MPa) compared to conventional NA concrete (46.88MPa).

Continuing in the same direction, Pitarch et al. [55] also replaced natural aggregates with ceramic waste. In their publication, they disclosed that the WA of the coarse ceramic waste material could extend to 15.76% and attain densities around 2300kg/m^3. Comparing the CS for control specimens and samples with 14, 20 and 30% of coarse ceramic waste instead of NA (%wt), it was evident that up to 20% inclusion of ceramics improved the strength, while 30% nurtured comparable results – 31.51/37.80MPa (control, 7/28 days), 33.25/38.51MPa (14%wt), 33.75/40.21MPa (20%wt) and 31.36/38.25MPa (30%wt). Slightly lower values were achieved for the same fraction replacements of sanitary ceramic waste instead of the tiled version, but nevertheless very close to the control levels (up to 12% decline in strength). The results are illustrated in Fig. 2.5, where TCW denotes tile ceramic waste and CSW sanitary ceramic waste. RCB samples are not relevant in this case.

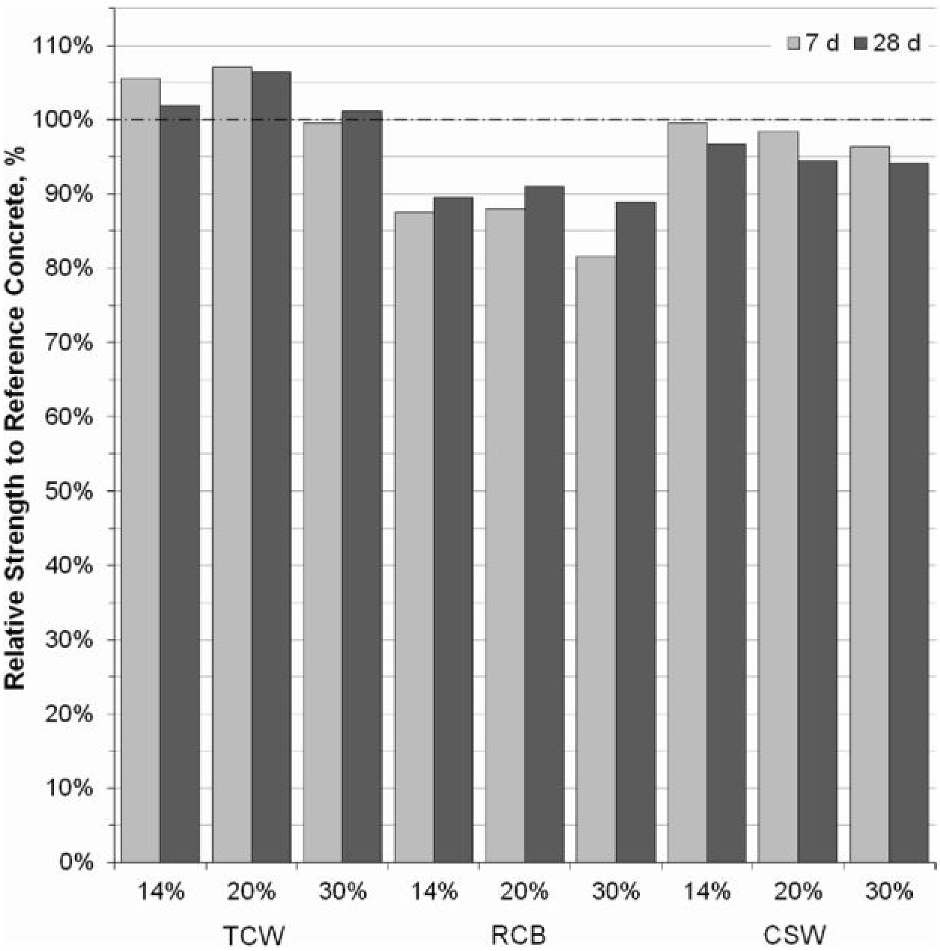


Figure 2.5: Relative compressive strength of ceramic waste concretes in comparison to natural aggregate concrete. Retrieved from [55]

Furthermore, Mangi et al. [56] published a very extensive research on the incorporation of ceramic tiles and marble wastes in concrete. Courtesy to their paper, Fig. 2.6 illustrates how different amounts of recycled ceramics affect the control concrete if added as coarse aggregates as reported by various resources.

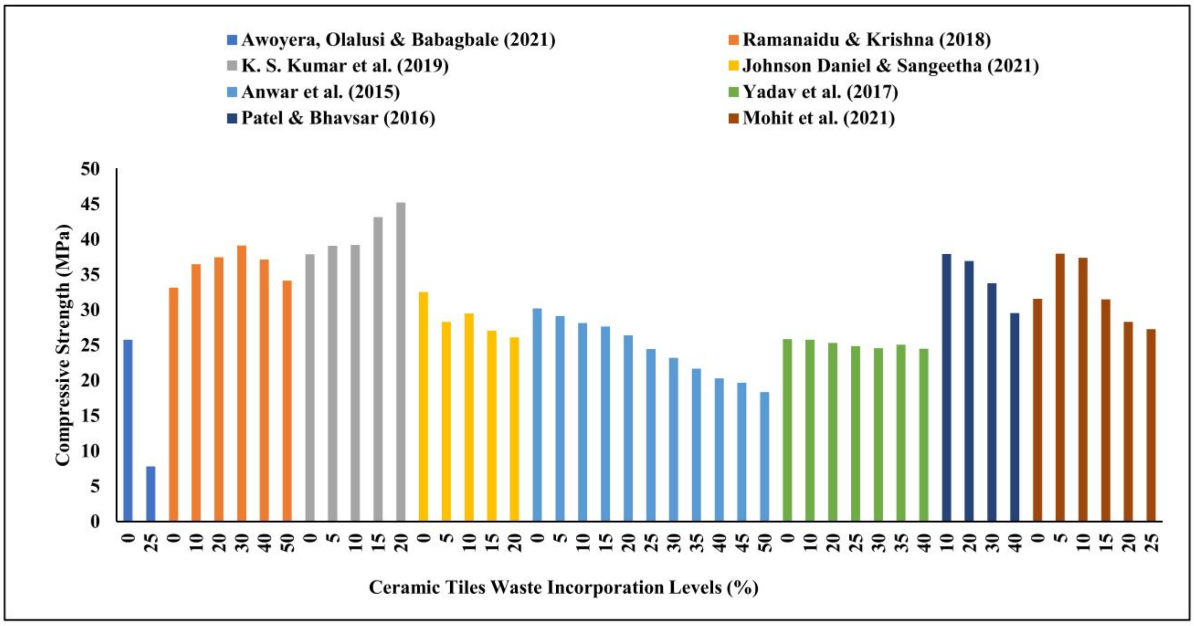


Figure 2.6: Compressive strength of concretes with ceramic wastes as CA. Extracted from [56]

From the above schematic, it can be concluded that in the majority of cases ceramic aggregates deteriorate the compression, regardless of their replacement fraction. There are records however of up to 30% replacements which did not follow this trend and rather manufactured concretes with higher strengths than the reference, however it is clear that generally the overall effect is slightly negative. On the other hand, a minor decline in strength should be compensated by the more economic and sustainable design, as well as the lighter overall concrete. Another study [57] confirmed the universal tendency of slight decrease of CS with possible improvement if certain conditions apply – it was indicated that for 50% replacement level, the relative CS was 83% of the control value, while for 100% replacement the CS was 72%. Additionally, if the w/c was altered to from 0.65 to 0.55, then there was an increase of CS of 9% for all samples, indifferent of the replacement levels.

Based on these statements, it can be summarized that generally ceramics tend to have lower WA compared to bricks, but still significantly higher compared to NA. Therefore, if any positives are to be extracted from the inclusion of tiles, then the w/c should be kept relatively low so that similarly to bricks water is released gradually with time, assisting the cement hydration and strength development. Thus, all instances where negative trends in compressive strength are observed are likely due to these reasons – excessive w/c ratio or possibly significantly lower WA of the ceramic used.

Plastics (HDPE, EPS)

In compliance with the dataset accessed online [58], the 24-hour water absorption of a wide range of plastics could be visualized. As mentioned previously in Chapter 1, the WA of some of the plastics is of greater importance compared to others. These plastics include PVC, HDPE, PE, PET, Polycarbonate, PS, EPS, PP. For this reason, their WA ranges are extracted from the database and presented below in Table 2.2. According to these values, the mean WA and the standard deviation of all relevant plastics is calculated and also presented in the aforementioned table. The water absorption of all listed plastics has been evaluated relying on the procedure outlined by ISO 62 [59] or ASTM D570 [60] standards.

Table 2.2: Water absorption of plastics as reported by [58].

Plastic type	Minimum WA [%]	Maximum WA [%]	Deviation σ[%]
PVC	0.04	0.40	0.18
HDPE	0.005	0.01	0.03
PE	0.02	0.06	0.02
PET	0.10	0.20	0.05
PC	0.10	0.20	0.05
PS	0.01	0.07	0.03
PP	0.01	0.10	0.05
Mean:	WA = 0.10%		$\sigma = 0.06\%$

Another study [61] based on concrete plates made from recycled aggregates and recycled plastic showed the fluctuation of the water absorption with evolution of the proportion of plastic to concrete. It is important to mention that in this research the water absorption measured was of the resulting concrete specimen and not based on the absorption of the coarse aggregate. Nevertheless, results showed an initial drop of the absorption as the fraction of plastics rose until the point of 50% replacement when the absorption started to increase. The reported values for water absorption of conventional concrete are between 3 and 6.5% as indicated by [62], while the absorption of the plastic-concrete specimens are given in Fig. 2.7. It is evident that despite the drop in absorption, likely due to the nature of plastic and its reported low water absorption, the combination of recycled concrete and plastic resulted in comparable values approximately between 2.5 and 7.5% as stated by Wei et al. [61].

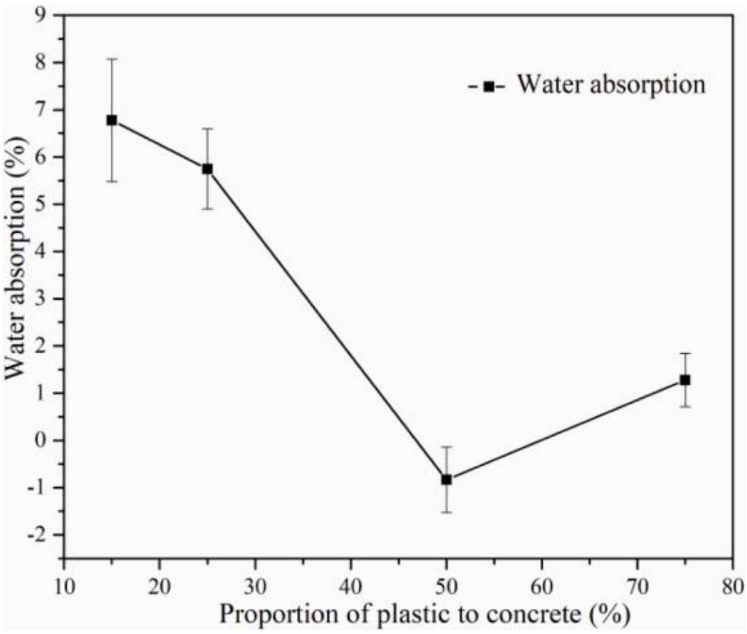


Figure 2.7: Water absorption of recycled plastic-concrete plates as reported by [61].

A survey on eco-friendly concrete [63] implemented recycled PET bottles in the mix design. The authors reported several properties such as 0.49% WA of PET as well as 1410kg/m^3 dry density. What is more, weight replacements of 10 up to 50% of NA were investigated. The output displayed that up to 20% of mass replacement led to negligible change in compressive strength as depicted in Fig. 2.8. Larger contents on the other hand declined the strength rapidly. Tensile and flexural strengths were affected more noticeably even with smaller amounts of PET added. As a general conclusion it was reported that PET bottles could be used for concrete making because they made overall lighter end material. Special care should be taken to properly select the desirable replacement rates and despite poorer mechanical properties, the concrete could be used for lower grade application.

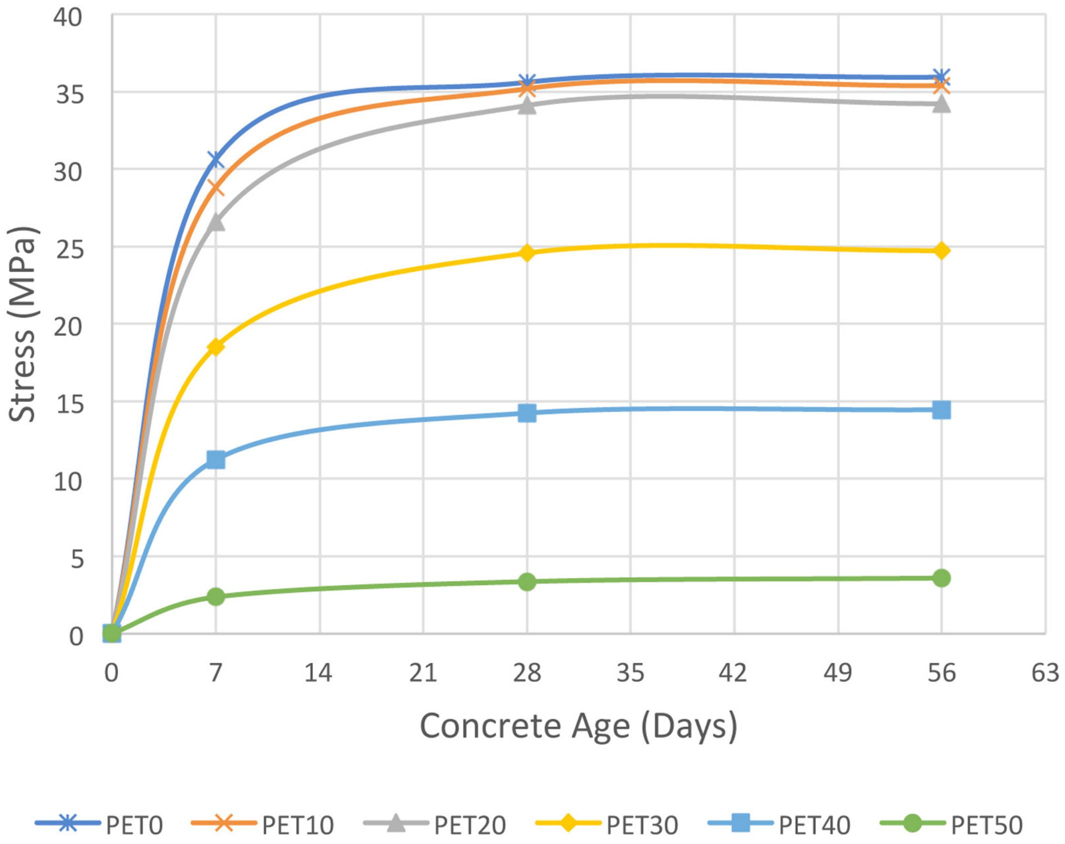


Figure 2.8: Strength development of PET-enhanced concrete. Courtesy of [63]

A similar survey on the same topic of recycled plastic concrete [64] provided different results in terms of compressive strength. Siddique et al. [64] claimed that 10% of plastic aggregate content reduced the strength by approximately 30%, while 50% replacement gave rise to a concrete with over 60% weaker compression, regardless of the design w/c ratio. Nonetheless, introducing plastic in concrete could induce lower shrinkage and enhanced impermeability, as well as reduced bulk density. Based on this, it is possible that a more sustainable concrete design with possible applications in marine construction is feasible.

Mineral fibers

According to a study [65], the water absorption of mineral wool insulation after 24 hours was approximately 100%. Another study [66] conveyed that mineral wool with density of $69kg/m^3$ had a water absorption of around 75% after 1 day.

Ramirez et al. [67] studied the behavior of concrete with recycled mineral wool fibers as additive. The reported analysis featured higher flexural strength of mineral fiber enhanced concrete compared to conventional NA concrete. 30%wt replacement of three types of mineral fibers (rock wool waste, fiberglass waste and mixed waste of mineral wool) provided better performance – 6.6MPa (reference) compared to 6.7MPa (mixed waste and fiberglass waste) and 7.1MPa (rock wool waste). If the replacement levels were increased to 40%, then there was a drop of flexural strength for fiberglass and rock wool specimens, however the mixed waste exhibited an improved value. If 50%wt were included, then there was a clear linear trend for the mixed waste samples reaching near 7.3MPa of flexural strength, 10% higher than control specimens. In terms of compressive strength, mineral fibers deducted from the NA concrete and the larger the amount of fibers in the mix, the greater the drop was (12% up to 27% decline).

Another survey [68] on recycled sand concrete (mortar) made with mineral fibers verified the reported results from [67] regarding the effect on compressive and flexural strengths. Their output is summarized in Fig. 2.9. Each sample apart from the reference (REF) was made using fine recycled concrete aggregates. REF R utilizes 100% fRCA and no fibers were included in the paste, each of the next specimens denotes the volume replacement of filler with waste fibers (5, 15 and 25%).

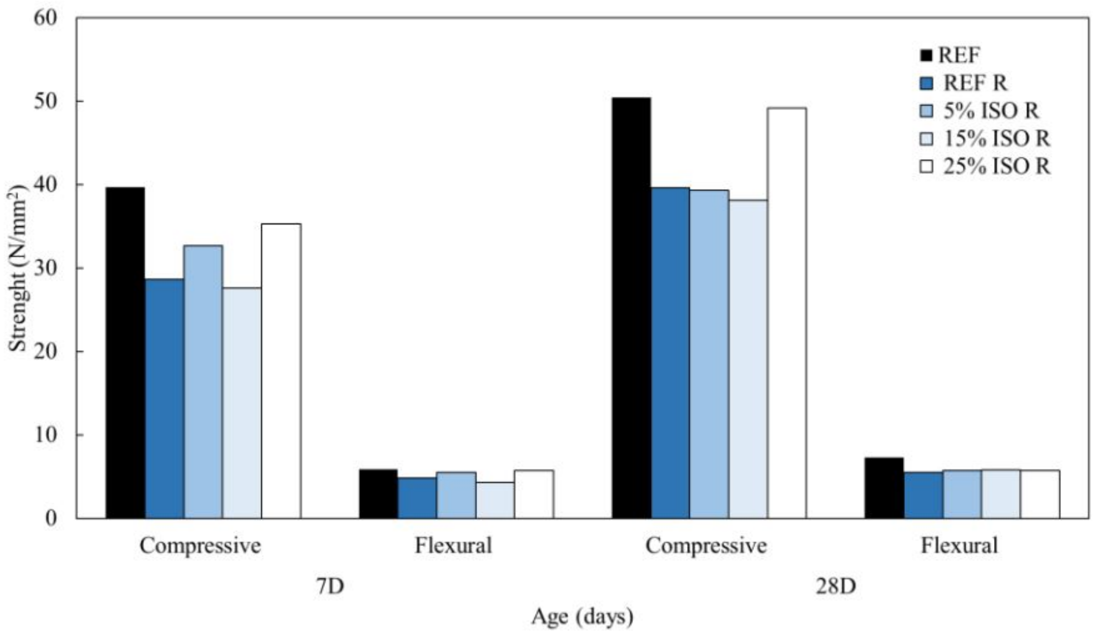


Figure 2.9: Flexural and compressive strengths of fiber-enhanced RAC after 7 and 28 days. Retrieved from [68].

From the figure it is clear that there was insignificant change in terms of the flexural strength and judging from previous sources this could be due to the fRCA rather than the mineral fibers. The compression aspect presented curious outcome – 25% of aggregate replacement recorded a higher value compared to fRCA-only (REF R) samples. The authors explained this by the possible achievement of an optimal filler grain size curve or because waste fiber particles filled interstitial voids between the paste and aggregates, forming a denser microstructure. Another output of this research was that mortars with waste fibers included gradually increased their durability and performed better under frost cycles compared to control mortar.

Additionally, Ferrandez et al. [69] fabricated concretes with two types of RAs and added different amounts of mineral wool to each. From Fig. 2.10 which displays the comparison between all samples, it is clear that the inclusion of mineral fibers improved the flexural strength and overall didn't affect the compressive strength significantly. This study also corroborated that mineral fibers led to decreased shrinkage of the concrete.

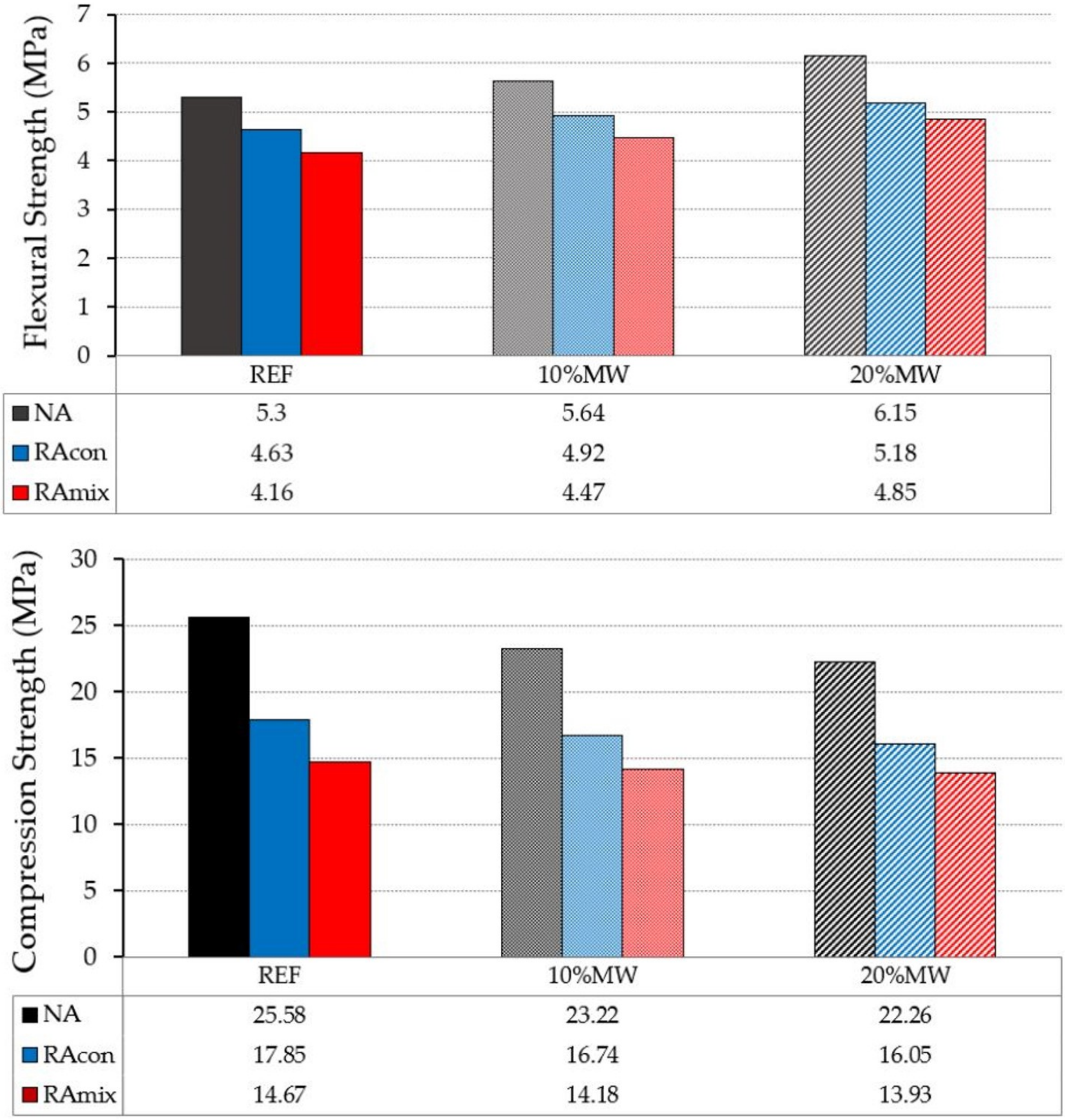


Figure 2.10: Intrinsic proprties of RAC utilizing 10 and 20%vol of mineral fibers as replacement of the aggregates. Retrieved from [69].

2.4. Properties of RAC

Malesev et al. [4] investigated the properties of RAC. Some of their statements included that the RA had much higher WA compared to NA due to the content of adhered old mortar to the particles. The amount of the attached mortar was said to range between 25 and 65% in volume and the the higher the cement mortar content, the larger the absorption. Moreover, the porosity of the RA was affected by the water to cement ratio of the original concrete. It was also reported that the amount of attached mortar depended on the crushing method in the recycling process and researchers [70] have recommended that the amount of RA in concrete should be maximum 20 to 30% in order to maintain water absorption of aggregates of less than 5%. Furthermore, the bulk density of RA was reported to be on average 10% lower compared to NA.

A study [71], published in the Institution of Civil Engineers (ICE) magazine delineated that the water absorption of coarse recycled concrete aggregates was in the magnitude of 5.4%. The recycled aggregates were said to originate from a concrete with strength class C25/30. However, this study only featured 8 to 20mm particle fraction of the coarse aggregate which signifies that the water absorption of 4 to 16mm fraction could be different, likely higher. In the same research recycled coarse aggregates (not necessarily originating from old concrete) were reported to reach water absorption values up to 10%.

Another study [72] deemed the standard water absorption tests not entirely accurate for recycled aggregates. They provided the following three reasons why a new method of testing should be incorporated:

- Drying at 105±5°C might remove water chemically incorporated in the adhered mortar;
- Soaking time before reaching full saturation varies according to the presence of cement paste on the surface of aggregates;
- Reaching surface-dry conditions by drying the aggregates with a cloth/towel might result in detached cement particles which would ultimately reduce the oven-dried mass of the sample.

The same research suggested an innovative new method, called "real-time assessment of water absorption" to evaluate the absorption of the recycled aggregates. The results revealed that an average WA value of 5.83% was achieved after 96 hours of soaking and 8.74% after 120 hours of soaking. However, the composition and size distribution of the samples were not stated, it was only reported that the new method is suitable for aggregate sizes from 5 to 40mm.

Regarding the suitability of RCA as a natural aggregate replacement, a study [73] has been published, exploring the compressive strength of concrete made from recycled C&DW materials. The samples which completely replaced the natural coarse aggregate by RCA tended to always be within close proximity of the control specimens, comprising of natural aggregates only. The only major difference came at 90 days strength when the reference concrete reached a value of 72.2 MPa, while the CRCA went up to approximately 67 MPa. The CRCA (made with 100% CA replacement and 0% FA replacement) was also reported to be the most suitable and green option amongst the rest of the samples (100% NA (fine and coarse); 100% RA (fine and coarse)). This study also stated that was not recommended to replace more than 30% of coarse aggregate in terms of weight, however it proved to carry a positive effect despite reaching values beyond this point.

Nedeljkovic et al. [74] carried out experiments regarding the physical properties of RAC made with fine recycled concrete aggregates (fRCA). One of the relevant outputs from their study was the reported water absorption range of concrete made with fRCA - values varied from 4.28% up to 13.1%, with an average of 8.4%. They compared these values to the reported WA values for natural fine aggregate (sand) which were in the magnitude between 0.2 and 4.1%. It was also estimated that the fRCA had lower densities compared to sand – 1630 to 2560 kg/m^3 fRCA and 2530 to 2720 kg/m^3 sand. The high water absorption of fRCA was due to the higher content of pores and rougher surface texture compared to sand. This directly affected the effective w/c ratio and resulted in worse consistency of the fresh concrete mix. The decreased workability was also explained by the adhered mortar on fRCA particles which introduced more interfacial transition zones (ITZ). This in turn affects the properties of concrete, including compressive strength. Furthemore, Bu et al. (2022) [75] have summarized that the durability of concrete made from fRCA is highly dependant on the quality of the fRCA, which is influenced by the amount of adhered mortar on the particles. They also announced that the average water absorption of fRCA could reach about 8.4%, however the higher the old mortar attached, the higher the porosity and the water absorption.

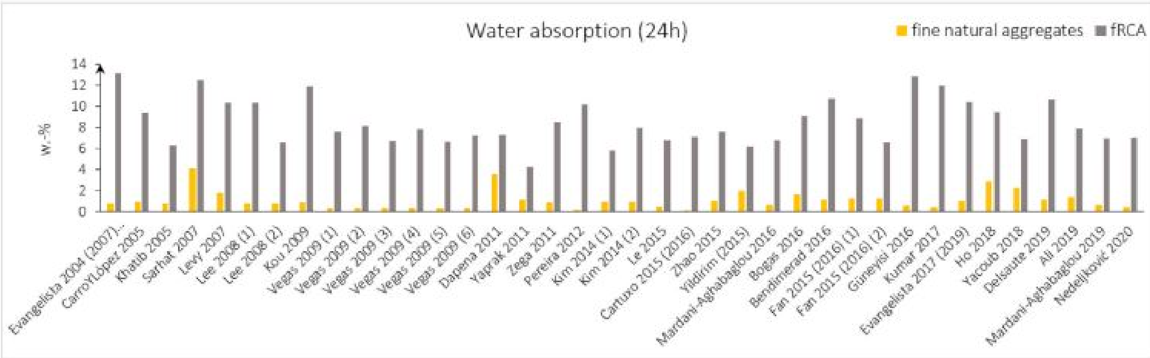


Figure 2.11: Comparison of water absorption values for natural aggregates and fRCA as reported by literature sources. Extracted from [74].

Crushing and Los Angeles (LA) abrasion tests determine the durability of aggregates. According to [76], RCA reached higher values in both tests compared to NA, which ultimately meant that a larger amount of fine particles broke off. It was stated that RCA reached 23.1 to 24.0% in crushing tests and 26.4 to 42.7% in LA abrasion tests. Compared to this, NA had 13.0 to 15.7% crushing values and 11.0 to 22.9% LA abrasion values which were significantly lower. The breaking off of fine particles was explained by the presence of adhered mortar in the ITZ, which is the weaker part of the concrete. Thus, it was believed that the attached mortar was possibly the reason for lower compressive strength due to the fact that it's most likely to detach and create a weak link within the concrete specimen. The researchers also indicated that concrete made from 100% RCA replacement to NA (coarse) was 20 to 25% weaker in terms of compression compared to concrete made from natural aggregates only. Additionally, mixes with 50 to 100% NA replacement required a 4 to 10% lower w/c ratio to obtain the same strength as the reference specimens. Other similar studies were references in the paper [76] where comparable results were also mentioned - 25% strength reduction for 50% NA replacement and 18% decrease in strength for mixes with 15 to 30% RCA inclusion.

Another important aspect of RAC is the altered ITZ. The intrinsic properties of recycled aggregates including WA and porosity could majorly affect the ITZ as reported by [77]. This change could directly influence the mechanical properties of the RAC. Thus, it is essential to investigate the effect of each contaminants on the ITZ so that further insight could be gained on the possible consequences. The same study examined the compressive strength of several RAC and it was evident that concretes with 100% recycled concrete aggregates or with 100% recycled concrete block aggregates had comparable strengths after 7, 28 and 91 days. This confirmed other findings of 3 to 8% enhancement compared to NA concrete as reported and referenced in the study [78, 79]. The authors explained this positive effect by the stronger bond achieved between the cement and the recycled aggregates which compensated the lower intrinsic strength of the RAs. Moreover, factors such as the saturated (water) curing, internal curing coming from the higher moisture content of RAs and the enhanced interlocking could play an important role of the enhanced performance. It was also reported that this statement also holds for bricks and brick-aggregates, however due to the lower intrinsic strength, the overall positive effect could be negated. The same study also provided an in-depth inspection of the morphological structure of all types of RAC examined – a summary is presented in Fig. 2.12.

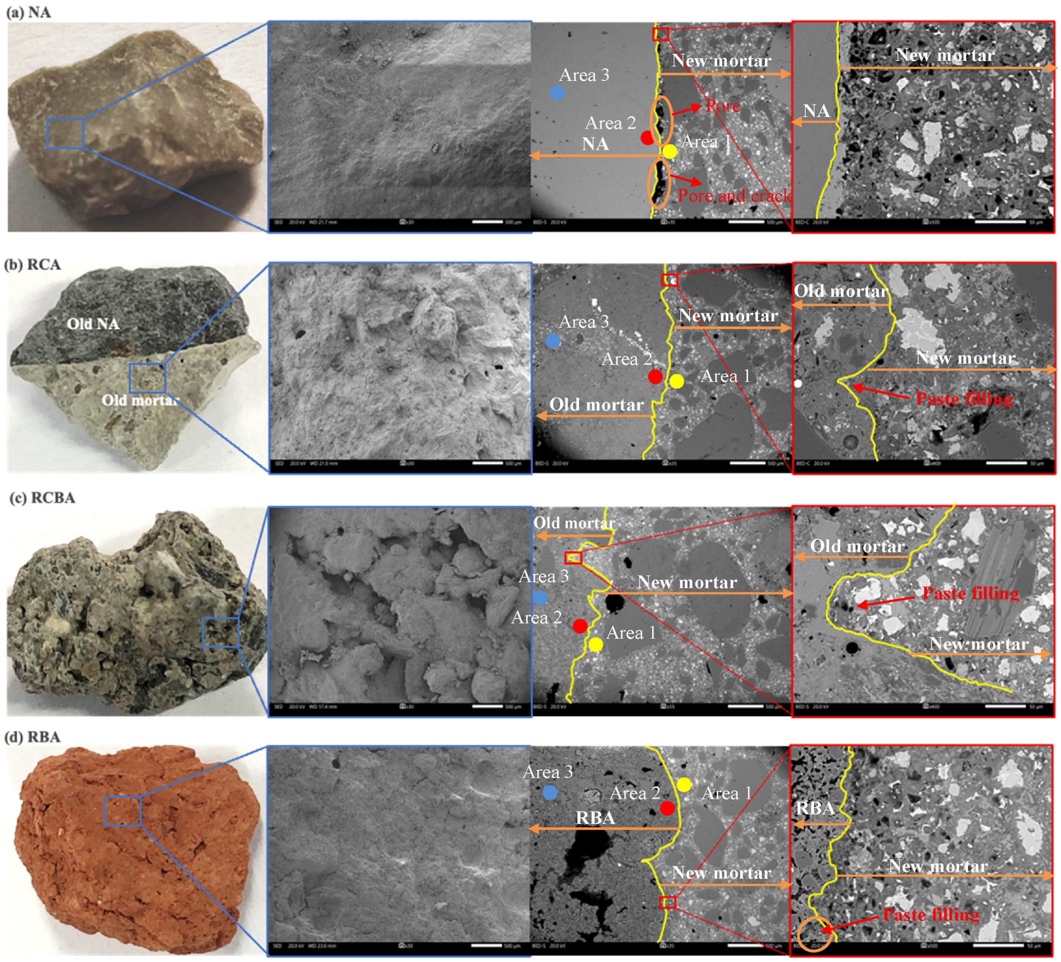


Figure 2.12: Morphology of different types of RAC. Retrieved from [77]

Liu et al. [77] explained that NA concrete exhibited a significant amount of large pores and cracks in between the aggregate particle and the ITZ. What is more, all RA concretes led to denser interface as highlighted by the yellow lines – denoting better compatibility between the old adhered mortars and the new cementitious matrix likely due to the rougher texture of RAs compared to NA. The more porous structure of RAs also allowed the new cement paste within the pores of the aggregates, further enhancing the bond. All these factors contributed to the notably higher tensile bond strength of all RA concretes, including the one with RBA, compared to conventional NA concrete – 5% (RBA) up to 49% (RCA) improvement in this aspect. It was also concluded that the ITZ of all RAC had lower porosity and higher micro-hardness compared to NA concrete, arising from the internal curing of the saturated recycled particles. Zaetang et al. [78] stated that 40% of recycled concrete block aggregate replacement was optimum for lower grade concretes and improved the strength from 13.4MPa (NA concrete) up to 17.0MPa after 28 days. The reported LA abrasion loss value for concrete block aggregates was 52.0%, compared to the 30.2% value of NA.

Additionally, there are several studies which provided more insight of the compressive strength of concretes made with recycled coarse aggregate. Tang et al. [80] recorded a 19% drop in strength for concrete made with RCA. They also noted that fine recycled aggregates had more unfavourable effects compared to the coarse replacement. Moreover, Duen et al.[81] showed that different amounts of adhered mortar to RCA played a significant role to the compressive and tensile splitting strengths. The RA with 60% adhered mortar caused a 12.5 to 20.0% weaker concrete on average compared to NA concrete, depending on the designed strength class. Concrete with RAs containing less attached mortar gave rise to intermediate values in terms of decrease in compressive strength. On the other hand, the concrete comprised to RA with 14 to 24% old mortar presented better tensile splitting strength highly likely due to the rough surface of the RAs and the improved microstructure of ITZ.

2.5. Relation between water absorption and compressive strength

Sharaky et al.[82] investigated the effect of including recycled aggregates to concrete mixes. In their research, they used old concrete specimens, crushed and divided the particles into size groups (coarse, fine, powder) and added each of those groups as a replacement of the natural aggregates in a conventional concrete mix design. The measured water absorption of the coarse recycled (RCA) fraction was reported to be 4.32%, while the fines (fRCA) obtained 13.82% absorption. The compressive strength results of the new concrete specimens showed that concrete with 80% RCA and 20% natural coarse aggregates (and 100% natural fine aggregate) had a 16.7%, 13.2% and 18.3% decrease in strength compared to the control recipe (100% natural fine and coarse aggregate) at 7, 28 and 56 days respectively. Generally, a higher rate of strength development was observed in the time between 7 and 28 days compared to 28 and 56 days for the samples containing RCA as replacement. This effect was explained with the possible higher cement hydration rate in the first 28 days compared to the late days.

When relating the water absorption to the compressive strength of concrete, usually a term known as the "effective water to cement ratio" is used in place of the regular w/c ratio. The latter term describes the ratio between the water content as designed in the mix recipe and the cement present in the mix, while the effective ratio utilizes the total amount of water that reacts with cement. In reality, the presence of aggregates which take up 60 to 80% of the volume causes a certain amount of water to be absorbed and thus the effective w/c ratio is always lower compared to the widely reported w/c ratio. Thus, it is crucial to estimate the effective w/c ratio when describing aggregates with higher than usual water absorption, such as recycled aggregates. A paper [83] provided a way of estimating the effective w/c ratio based on the following formula:

$$\frac{w}{c}(eff) = \frac{w}{c} - \alpha * (\frac{\eta}{c}) \tag{2.2}$$

where α is a value between 0 and 1, η is the absorption capacity of the aggregates in [%]. If $\alpha = 1$, then it is assumed that all water that can be consumed by the aggregates is consumed and thus not available to react with cement. If $\alpha = 0$, then the whole water present in the mix is available to react with the cement (i.e. the result will be the regular w/c ratio).

2.6. Predictive model development

Joseph et al.[71] also suggested that the compressive strength of the concrete is inversely proportional to the water absorption of the aggregates. Several other studies [84, 85, 86] concluded that the strength decreases as the equivalent water absorption increases and this drop could reach 10 up to 25%. The same study [71] reported an equation which could be used to evaluate the compressive strength based on the total water content:

$$f_{c,cube} = K * (\frac{1}{1 + (w + a)/c})^2 \tag{2.3}$$

where $f_{c,cube}$ is the compressive strength (N/mm^2), K is a cement constant, c is the absolute volume of cement, w is the total volume of water and a is the total volume of air.
Another output from this research displayed a linear drop in compressive strength as the water absorption increased as depicted in Fig.2.13. In this study, a total of 5 different recipes were used, each with different water absorption values ranging from 3.85 to 6.95%.

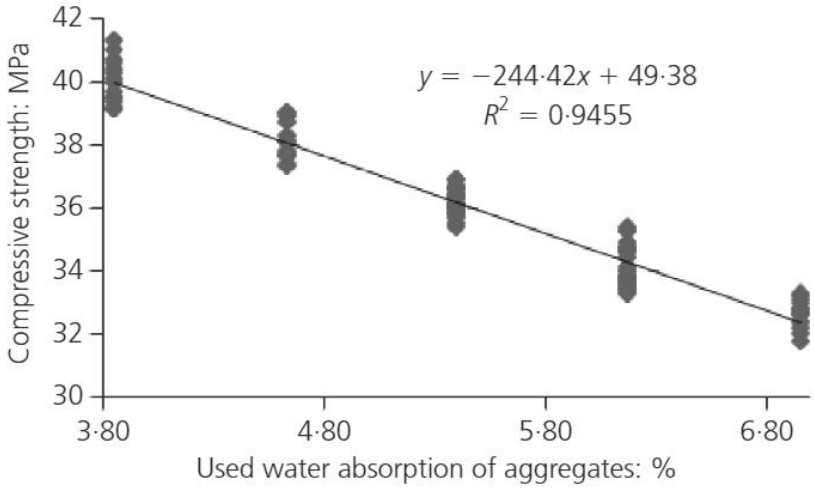


Figure 2.13: Influence of water absorption of aggregates towards the compressive strength. Courtesy of [71].

Xu et al. [87] published a study comparing experimental database, code-based models and empirical relations regarding CRCA. In their paper, they developed a predictive formula taking into account the two major contributors to RAC's mechanical properties according to them: effective w/c and RCA replacement percentage. The relation is depicted in Eq. 2.4:

$$f'_{c,cube} = \frac{28.97 - 4.71r^{1.69}}{\frac{w}{c}(eff)^{0.25}} \tag{2.4}$$

where $f'_{c,cube}$ is the predicted compressive strength of RCA [MPa], r is the RCA replacement ratio [%], $\frac{w}{c}(eff)$ is the effective w/c ratio [-].

2.7. Chapter summary

To conclude, this chapter reviewed a broad range of related project regarding recycled aggregate concrete. The relevant properties of individual materials, such as contaminants and main constitutes were reported and used as reference for further analysis. Overall, it could be said that a similar project with comparable sample set was not found in literature and the results obtained from this research could be of utmost importance towards the sustainability of the construction industry and particularly within concrete production aspect.

3
Methodology

3.1. Introduction

This chapter aims to describe the methodology and procedure of the undertaken laboratory experiments during the project. In Section 3.2 all materials used throughout the study are presented while the following Section 3.3 provides information regarding all practical work carried out.

3.2. Materials

In order to describe all practical work done throughout the project, first all materials used are shown in more detail, followed by the actual experimental processes which require those materials. In this section all materials required for water absorption tests, concrete mix design and concrete compressive strength testing are described. In Section 3.2.1 all concrete contaminants are listed and any preparatory actions performed are outlined. In Section 3.2.3 the concrete mix design is explained, incorporating the contaminants within the base materials.

3.2.1. Contaminants

In this section all materials listed are later referred to as concrete contaminants (or only contaminants). In total 9 different contaminants were used for this research and they include bricks, wood, glass, gypsum, ceramic tiles, plastic (HDPE), EPS (sometimes referred to as foam), mineral fibers, RSC (recycled sand concrete). In the following section, all contaminants are listed and looked in depth.

Brick

Regular brick blocks, widely available in the Netherlands were chosen for this research. The density was assumed to be approximately 1900 kg/m^3 as a mean value representative for multitude of different masonry bricks. The value was later validated as part of the water absorption tests (see Section 3.3.1). A water intake value ("vriiw wateropneming") was prescribed on the label of some of the bricks used and it read 17%. Bricks were used both for water absorption tests and as part of concrete mix design. In order to utilize them for both tests, bricks were firstly crushed into smaller chunks by hand and hammer, then placed into a crushing machine (Fig. 3.1a) until particles of sizes smaller than 20mm in diameter were obtained.

(a) Equipment used to crush bricks into smaller particles

(b) Vibrating tray sieve used for particle separation

Figure 3.1: Equipment used frequently throughout the experiments

Figure 3.2: Brick transition from whole blocks to 4-16mm particles

The next step was to sieve all particles using a vibrating tray sieve (Fig. 3.1b) and separate into groups including particles <4mm, 4-8mm, 8-16mm and >16mm in diameter. Particles smaller than 4mm were of no interest to this study and particles larger than 16mm were placed back into the crushing machine and the following steps were repeated until they fell in the desired size ranges. Fig. 3.2 shows the brick blocks and the transition to desired particle size distribution (8-16mm and 4-8mm, left to right).

Wood

Mixed wood shreds, available in the laboratories of TU Delft, were made use of for the project. The specific type of wood was not required to be known, as long as it had similar characteristics as the timber used for construction purposes. Additionally, mixed wood shreds were desirable for the research since they brought a larger uncertainty and more variation in the practical results as would be the case in reality where different types of wood (hardwood, softwood) could be found in buildings. After processing of the available wood, only the particles with diameter less than 16mm and length between 2 and 10cm were kept (Fig. 3.3). Furthermore, fine particles were also separated by sieving. The length of the sieved wood shreds was not of interest to be kept within 4-16mm since in practice wood is supplied in this state when recycled. Unlike most other contaminants, wood particles were not grouped into the desired size categories (4-8mm; 8-16mm), but were rather left in a single set, namely 4-16mm in diameter and 2-10cm in length.

Figure 3.3: Representative wood particles after final processing

Glass

The glass used for this experiment was taken mostly from shattered windows since it resembles the glass found at the demolished construction site. However, glass originating from bottles was not excluded since after in-depth research on the structural behaviour of the materials, it was concluded that for this study different types of glass will have an insignificant difference in performance. The shattered glass pieces were next reduced in size by using hand tools, then sieved and separated into groups as most other contaminants (4-8mm; 8-16mm). The density of glass was assumed to be 2500 kg/m^3.

Gypsum

Gypsum was available in the form of small blocks in the laboratory of TU Delft. Each block was crushed into smaller chunks, then sieved and divided into the desired size groups identically to most of the contaminants. Fig.3.4 illustrates the initial stage of a gypsum block prior further processing. The density of the gypsum blocks was evaluated to be in the range of 740-760kg/m^3.

Figure 3.4: Raw gypsum blocks ready for crushing and sieving

Ceramic tiles

Another common material found on demolished construction sites is the ceramic tile. The tiles supplied by TU Delft were leftover material used in previous reparatory activities performed in the university and came in different types and sizes, as well as both used and unused state - meaning some tiles had hardened mortar attached to their back sides. Similarly to wood, the broader tile dataset could only enhance the applicability of the results and replicate the reality better. Furthermore, ceramic tiles are categorized by their water absorption by ISO 13006 [53] which is directly linked to this study. However, in reality various types of tiles are recycled together and cannot be separated by type and thus the tiles in this project were used accordingly. The only preparation included crushing into smaller pieces, sieving and dividing into 4-8mm and 8-16mm size groups as most other contaminants (see Fig. 3.5). The density of ceramic tiles was estimated to be 1900kg/m^3.

Figure 3.5: Ceramic tiles, 8 to 16mm in size, after crushing and sieving

Plastic (HDPE)

Plastic as a material comes in many different types and it is spread across numerous fields of application. In the construction industry, there are several types of plastics that are most commonly used, including PVC, HDPE, PE, PET, Polycarbonate as elaborated previously. Although various types have divergent properties, all plastics share comparable behaviour concerning the experiments of this project. For this reason, the easily accessible HDPE plastic, which is delivered to TU Delft directly from a recycling plant in the Netherlands was chosen for further evaluation. However, unlike all previous contaminants, the HDPE came in approximately one size (Fig. 3.6) which was in the magnitude of 4-8mm in diameter. This effectively meant that plastic would only be used in this size range for all experiments.

Figure 3.6: HDPE plastic elements are delivered in state as depicted

EPS foam

Expanded polystyrene foam or simply referred to as foam was obtained in two different states within the boundaries of TU Delft - clean (new) and dirty (previously used). The clean one was extracted from various packaging and usually comes in different shapes and sizes, although common pieces are shown in Fig.3.7. The dirty version was previously used in the laboratories of TU Delft and most often had some hardened mortar attached to it. Both types were utilized for identical rationale as per wood and tiles. The required preparation for foam included reducing the larger blocks/chunks into smaller pieces, 4-16mm in diameter and keeping them in this single size group only.

Figure 3.7: Representative "clean" EPS foam particles

Mineral fibers

The last individual contaminant that could be found at construction site after demolition which was used in this project is mineral wool or also known as mineral fiber. In terms of availability and preparation, mineral fibers resembled plastic - they were delivered in one size (Fig. 3.8) and were used for upcoming tasks directly in their initial state.

Figure 3.8: Mineral fibers used in the project

Recycled coarse concrete aggregates

CRCA (Concrete made from recycled coarse aggregate) differs slightly from RAC (Recycled aggregate concrete). RAC is concrete made from any recycled aggregates (fine and/or coarse) which are substituting the natural aggregate in any desired percentage (0-100%). CRCA on the other hand, is concrete specifically made out of recycled coarse aggregate, which is in partial or full replacement of the coarse natural aggregate of conventional concrete. What is more, a major contribution of the C&DW is old concrete, demolished to coarse particles which contain aggregates and adhered cement-mortar. If these coarse concrete particles are recycled and used to make a new batch of concrete, this is indeed the so-called CRCA, i.e. concrete made from RCA. Therefore, RCA was also used in this study, mainly for comparative purposes. The recycled aggregates used in this research originated from old concrete specimens, which were crushed, sieved and divided into different particle size fractions. As mentioned previously, the coarse aggregate fraction used throughout this project lies between 4 and 16mm diameter size and accordingly only such particles were collected from the crushed concrete. The parent concrete was of the so-called sand concrete (SC) type, consisting only of cement, water and fine aggregates (Fig.3.9).

Figure 3.9: Original SC samples. Left: SC39; Right:SC55

This SC does not feature coarse aggregate and its almost never used in practice (at least for proper construction purposes) due to financial reasons as aggregates are much cheaper than cement. There are three main mix designs used to fabricate the SC specimens, all shown below in Table 3.1.

Table 3.1: Original concrete recipes used for SC/LQ specimens

Label:		SC39	SC55	LQ
Material	Type	Amount [kg/m^3]		
Cement	CEM III/B 42.5 N	516.1	469.9	516.1
Fine aggregate	NA 0-4mm	1548.4	1409.7	-
Fine aggregate	NA 1-2mm	-	-	1548.4
Water	Cold	200.7	258.5	200.7
w/c ratio		0.39	0.55	0.39
c/a ratio		0.33	0.33	0.33
91 day strength [MPa]		57.1	51.3	-

As it can be seen from the table, the three SC types consisted of different parameters. The SC39 mix had a water to cement ratio of 0.39 and standard fine aggregates were used (0 to 4mm). Similarly, SC55 also made use of the 0 to 4mm sand particles, but it had a larger water portion, thus resulting in a higher water to cement ratio of 0.55. The LQ specimens were made following the SC39 recipe identically, with the difference that low quality fine aggregate was used instead. This low quality (LQ) aggregate denoted that only particles with sizes between 1 and 2mm are used - for reference Fig.3.11 provides a detailed view of a single aggregate. For all three parent concretes cement CEM III/B (42.5 N) was used and they all kept the same cement to aggregate (c/a) ratio of 1/3. For the visualization of SC particles, refer to Fig.3.10 and Fig.3.12.

Figure 3.10: Original SC samples. Left: SC39; Right:SC55

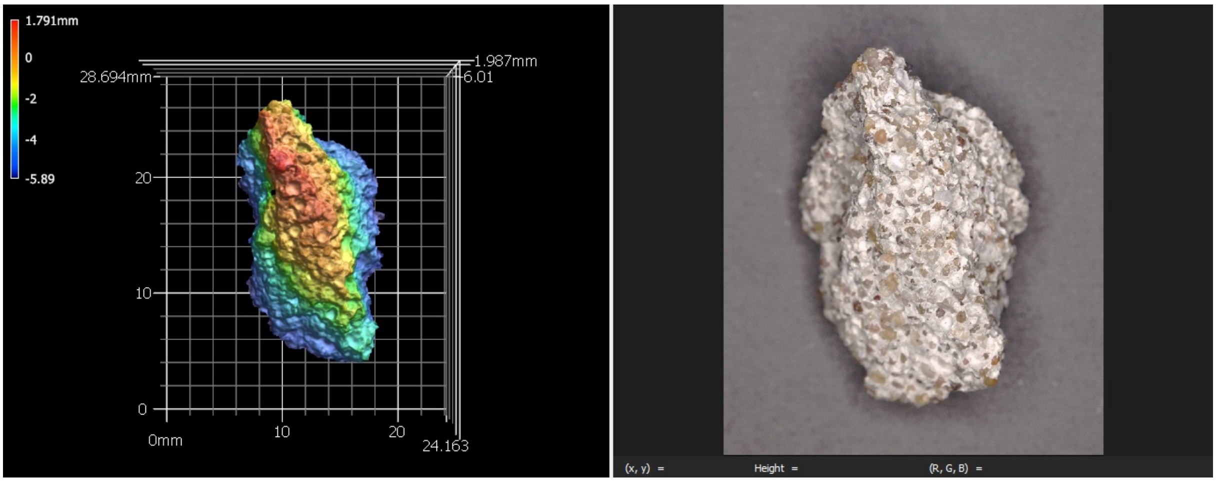


Figure 3.11: Low quality (LQ) aggregate sample

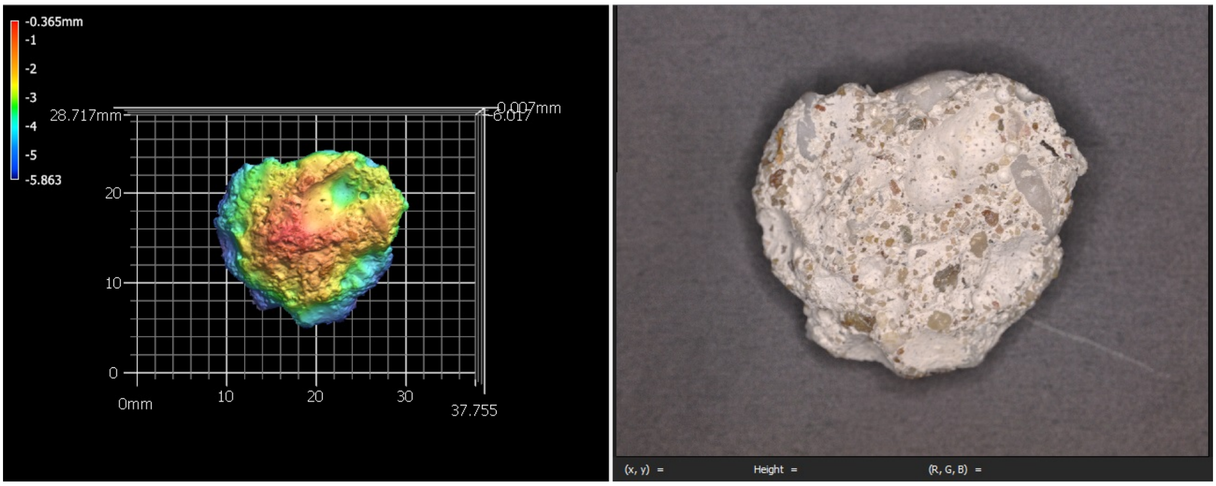


Figure 3.12: Crushed sand concrete (SC) aggregate sample

3.2.2. Air

The last component of the experimental part of the study involved preparing samples which are comparable to all previous results and could also be related to further research projects. Thus, the behaviour of each contaminant had to be equalised to the inclusion of air voids inside the concrete. To simulate the air bubbles, there are several feasible options an air-entraining agent, small hollow spheres made from aluminium or other light metal or individual polystyrene foam particles. As this study focuses also on the volume and mass replacement of NA, it was decided that polystyrene foam is the most suitable choice since it would keep constant volume upon addition within the mix, while air-entraining agents were reported to vary in terms of air bubbles produced under different conditions (humidity, air pressure, temperature). In order to investigate the suitability of the material, 4 different sizes of foam particles were selected in attempt to obtain a larger dataset with possible similarities between all groups. The size groups included individual foam particles, as depicted in Fig. 3.15, measured 3.5mm in diameter (A%), 1mm diameter (B%), 1.5mm diameter (C%) and 4.5mm diameter (D%). For more detailed review of the group sizes, refer to Fig. 3.13 and 3.14.

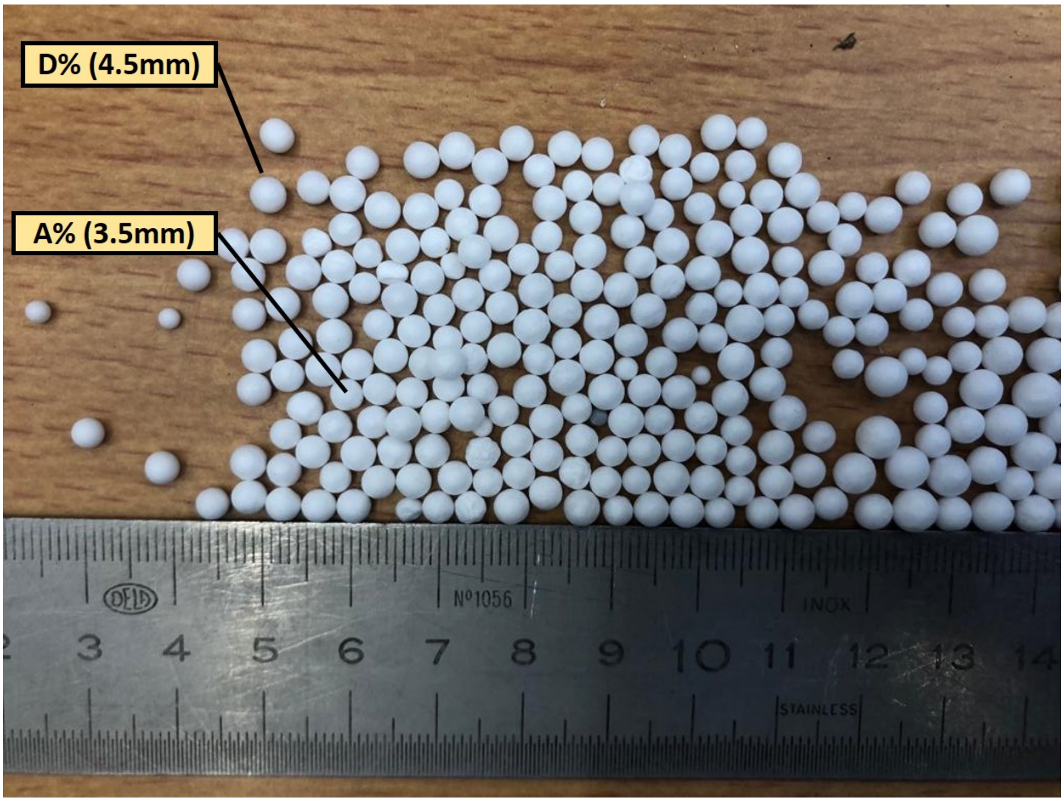


Figure 3.13: Air (foam) groups A% and D%

Figure 3.14: Air (foam) groups B% and C%

Figure 3.15: Individual foam particles used to simulate air voids in this research

3.2.3. Concrete mix design

In order to evaluate one of the main properties of concrete, its compressive strength, first a proper concrete recipe had to be designed. For this project, there were several conditions that were predefined a constant water to cement (w/c) ratio to be kept for all concrete specimens produced, sustained choice of cement and constant air content present in the mix. Additionally, a local Dutch company had provided TU Delft with a mix design for a C30/37 class concrete, which was used as a base and altered throughout the process. The provided recipe featured w/c ratio of 0.45 and air content of 2%, as well as plasticizer equal to 0.4% of the total cement content. Cement Type III A 52.5 R was used for all concrete batches. Another important parameter of the mix design was the arrangement of particles within the coarse aggregate fraction (4-16mm). Initially, several sets of 4-16mm gravel particles were ordered from the laboratory of TU Delft and for each one sieve analysis was performed. The sieve analysis featured the standard IS 16mm, 8mm and 4mm sieves in order to obtain the particle size distribution in terms of percentage between 4-8mm and 8-16mm groups. The mean results of this experiment showed that 4-8mm particles represent 15% of the total, while 8-16mm formed the majority of the aggregates with 85%. From that point on, this 85-15% ratio was used throughout the whole project and in order to always maintain it constant, 4-8mm and 8-16mm particles were ordered and kept separately so that they can be easily added to any given mix in correct proportions. The official mix design provided by the company is shown in Table 3.2:

Table 3.2: Initial concrete recipe for 1m^3 of concrete

Material	Type	Amount
Cement	CEM III B 42.5N	368kg
Fine aggregate	Sand 0-4mm	833kg
Coarse aggregate	Gravel 4-16mm	1000kg
Plasticizer	Normal	1.472kg
Water	Cold	122kg
Air		20l

The resulting concrete is of C30/37 strength class and F4 consistency class (refer to Table 3.5 for more information of concrete workability). The particle size distribution is displayed in Fig.3.16:

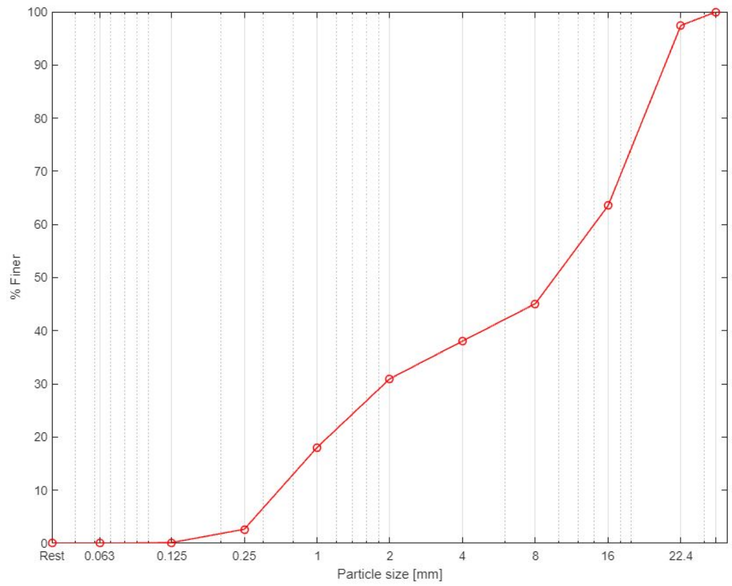


Figure 3.16: Grading curve for C30/37 concrete mix design

Provided that it is not an easy task to replicate the exact grading curve provided from the local company, the particle size distribution for this project was altered for convenience. 4 different test recipes (T1, T2, T3A, T3B) were designed and cast in order to determine the best option for further analysis. Cement type III B was replaced by CEM III A (less clinker content), air content was always kept at 2% of the total volume. The latter was achieved by designing all recipes such that the constituents were only able to fill in 98% of the volume, leaving 2% for air. The overview of each of the four alternative concrete recipes is depicted in Table 3.3:

Table 3.3: Test concrete batches and their respective mix proportions

		T1	T2	T3A	T3B
Material	Type	Amount			
Cement	CEM III A 52.5R	363.80kg	368.00kg	366.70kg	366.70kg
Fine aggregate	Sand 0-4mm	804.90kg	804.70kg	802.30kg	802.30kg
Coarse aggregate	Gravel 4-16mm	1078.20kg	1063.55kg	1063.40kg	1063.40kg
Plasticizer	Normal	0.412kg	1.404kg	1.467kg	1.467kg
Water	Cold	164.60kg	165.00kg	165.00kg	165.00kg
Air		2.00%	2.00%	2.00%	2.00%

Concrete T1 had unintentionally lower plasticizer content, which was fixed for all recipes that followed. Concretes T1, T2 and T3A all utilized coarse aggregate in one group, namely 4-16mm. For T3A, the aggregate contents were ever so slightly altered compared to T2 based on observations during the previous concrete casting. Additionally, the grading of the coarse aggregate group is different at various locations, it was expected that the concrete class would be different compared to the reference mentioned previously. Furthermore, it cannot be certain that each time new concrete is cast in the laboratory of TU Delft, the same grading as last time would be available. In order to determine this, for each new concrete batch a sieve analysis would have to be performed and highly likely aggregate amounts would have to be adjusted to resemble the initial grading. In order to overcome this issue, T3B was created as a simplified version with identical material amounts as T3A (see Fig. 3.17, only making use of the 85-15%

distribution among the coarse aggregate. Thus, for T3B, 85% of the coarse aggregate content resulted in the value for 8 to 16mm particles and 15% for the 4-8mm particles. In other words:

$$CA_{8-16mm} = 0.85 * CA = 0.85 * 1063.4 = 903.89kg \tag{3.1}$$

$$CA_{4-8mm} = 0.15 * CA = 0.15 * 1063.4 = 159.51kg \tag{3.2}$$

Figure 3.17: T3A (back, crushed) and T3B (front) specimens

For each concrete mix, a certain procedure was followed in order to obtain the concrete and its desired properties, to cast it in moulds and to set it to cure afterwards. The procedure can be divided into main steps with sub-steps for each:

1. Preparation of materials
    - Collect desired amount of material according to mix design (cement, coarse and fine aggregate, water, contaminants) (see Fig. 3.18)
    - Always calculate required materials by adding extra allowance for half a specimen in order to account for the losses of material throughout the casting sequence
2. Preparation of moulds
    - Prepare desired amount of moulds on the previous day of casting
    - Each mould has a cubic size, 150x150x150mm^3 dimensions
    - Clean the inside of the moulds using a regular brush
    - Oil the inside of the moulds using oil which prevents concrete from sticking to the surface of the moulds
    - Leave moulds with their open side facing downwards so that all excess oil is removed (Fig. 3.19)

- On the day of casting, make sure that the rubber pin placed on the bottom side of the moulds is in place and start casting

3. Mixing the materials

- Power the concrete mixer and the suction (if available) within the laboratory
- Wet the inside of the mixer with water and let it rotate for around 1-2min
- Pour the water out of the mixer and leave it at a position so that all remaining water could leak out
- When no more water is dripping from the mixer, position it conveniently and put the fine and coarse aggregate inside
- Add about half of the water and start mixing the aggregates for around 1min
- Add the cement and continue mixing for 1-2mins, while slowly adding the remaining water and plasticizer to the mix
- Stop mixing and perform series of workability tests[1] to determine whether the concrete is within desired parameters
- If workability is satisfactory, continue to next step; if not, alter mix design

4. Casting

- Fill up the previously oiled moulds halfway and place them on a vibrating table
- Vibrate for 30sec
- Fill up the samples, allowing concrete to be over the upper side so that after compaction it reduces in height
- Vibrate for another 30sec
- Remove any overflow by using a trowel and smoothen out the top surface of the sample
- Put a label on the top surface and cover specimens with plastic foil to avoid evaporation - Fig. 3.20
- Leave for 24 hours

5. De-moulding

- After the 24 hours have passed, remove plastic foil and rubber pin from the moulds
- By applying air pressure to the opening of the lower side of the mould, de-mould the cube specimens one by one
- Clean the inside and outside of the used moulds and put back the rubber pin
- Clean and debris along the edges of the upper side of the specimens by gently tapping with a hammer or by hand
- Transfer all specimens to a concrete curing room until its time to perform further experiments with them (Fig. 3.21)

[1] The workability tests, part of Step 3 are standard experiments as described by BS EN 12350-2:2019 (Concrete Slump test) [88] and BS EN 12350-5:2019 (Flow table test) [89].

Figure 3.18: Contaminants are kept separately from the aggregates prior to mixing (part of Step 1)

Figure 3.19: Oiled moulds are left upside down to unload all excess oil (part of Step 2)

Figure 3.20: Transparent foil is placed on top of the cast specimens to reduce water loss (part of Step 4)

Figure 3.21: Specimens are moved to the curing room at constant moist environment (part of Step 5)

In the end, concrete T3B was chosen as the fundamental mix design (reference) for this study.

Table 3.4 presents the results of the workability tests for all test concretes:

Table 3.4: Workability of the test concrete mixtures

	T1		T2		T3A		T3B	
	mm	Class	mm	Class	mm	Class	mm	Class
Slump cone	120	S3	130	S3	160	S4	170	S4
Flow table	420	F3	490	F4	515	F4	550	F4

According to NEN 8005 (Dutch codes for concrete workability) [90], each of the tests provides data for the consistency class - the slump cone test prescribes the consistency (S1 to S5) of the plastic and semi plastic mixes (Classes 2 and 3 of old Dutch standards VBT 95 [91]) while the flow table test is preferred for flowable mixtures (Class 4 of Dutch VBT 95). More information on the consistency classes is presented in Table 3.5 below. Green colour denotes the preferred method for a required consistency, while red colour depicts the less desired method.

Table 3.5: Concrete workability classes

VBT'95 Class	Consistency	Class	Degree of compactability [-]	Class	Slump [mm]	Class	Flow table diameter [mm]
	Dry	C0	≥ 1.46				
1	No slump	C1	1.45 – 1.26	S1	<40	F1	≤ 340
2	Semi plastic	C2	1.25 – 1.11	S2	50 – 90	F2	350 – 410
3	Plastic	C3	1.10 – 1.04	S3	100 – 150	F3	420 – 480
4	Very plastic			S4	160 – 210	F4	490 – 550
	Flowable			S5	≥ 220	F5	560 – 620
	Very flowable					F6	≥ 630
	Self compacting					F7	630 – 800

The degree of compactability V indicated in Table 3.5 is calculated as follows:

$$V = \frac{400}{400 - s} \tag{3.3}$$

where s is the mean value, to the nearest millimetre, of the four distances from the surface of the compacted concrete to the upper edges of the compaction container as defined in NEN-EN 12350-4 [92] standard.

Furthermore, in terms of the particle size distribution, there is a distinguished difference in the finer particles content, as it can be seen from the comparative Table 3.6 below:

Table 3.6: Particle size distribution comparison

Concrete mix according to / Percentage of aggregate content	Company	Project (T3B)
0-4mm	45.4%	43.0%
4-8mm	18.1%	8.6%
8-16mm	36.5%	48.4%

3.3. Testing procedures

The following paragraph outlines the two main testing procedures used throughout the whole project. In Section 3.3.1, the water absorption test is described, while Section 3.3.2 provides information about determining the compressive strength of concrete. The results of both test procedures are presented in Sections 4.2.1 and 4.2.2 respectively.

3.3.1. Water absorption

Since one of the aims of the project is to correlate the water absorption of the coarse aggregate to the compressive strength of the resulting concrete, an appropriate method for evaluating the moisture absorption of the materials, including aggregates and contaminants, had to be selected. An already existing standard, NEN/EN 1097-6:2022 [93], was the preferred method of analysis. The standard procedure was mildly altered to accommodate the inclusion of all contaminants as part of the survey:

1. Sample preparation
   - Weight out 1.000kg of the coarse aggregate and always keep the 85-15% ratio of aggregate fractions constant
   - The coarse aggregate can include the natural aggregate (gravel), as well as all other contaminants used in this study
   - All materials should be added according to the 85-15% particle distribution
   - After coarse materials are prepared, they should be sieved through a 4mm sieve so that all finer particles are removed
   - Submerge the remaining materials in a glass vessel and leave for 24 hours until they are fully saturated (Fig. 3.22)
2. Measurements after 24 hours
   - At the end of soaking period remove entrapped air by gentle agitation
   - Overfill the vessel with water, put a lid on top and measure the weight of the assembly (value M_2)
   - Remove all water and dry the particles using absorbent cloths to ensure surface dry conditions
   - Fill in the glass vessel to the top, place the lid and measure the weight of the assembly without the aggregates present (value M_3)
   - After aggregates are surface dry, measure their weight (value M_1)
   - Place the surface dry aggregates in a tray and in an over at 110^oC for another 24 hours (Fig. 3.23)
3. Measurements after 48 hours
   - Take out the samples from the over and cool down the aggregates in an air tight container
   - Measure the weight of the cooled down aggregate (value M_4)

Based on these 4 measurements, the following material properties could be obtained:

$$SG_{rd} = \frac{M_4}{M_1 - (M_2 - M_3)} \tag{3.4}$$

$$\rho_{rd} = SG_{rd} \cdot \rho_w \tag{3.5}$$

$$ASG_{rd} = \frac{M_4}{M_4 - (M_2 - M_3)} \tag{3.6}$$

$$\rho_a = ASG_{rd} \cdot \rho_w \tag{3.7}$$

$$SG_{ssd} = \frac{M_1}{M_1 - (M_2 - M_3)} \tag{3.8}$$

$$\rho_{ssd} = SG_{ssd} \cdot \rho_w \tag{3.9}$$

$$WA_{24h} = \frac{M_1 - M_4}{M_4} \cdot 100\% \tag{3.10}$$

where SG_{rd} is the specific gravity of the over-dried particles [-], ρ_{rd} is the oven-dried particle density [kg/m^3], ρ_w is the density of water at test temperature [kg/m3], ASG_{rd} is the apparent specific gravity of the oven-dried particles [-], ρ_a is the apparent particle density [kg/m^3], SG_{ssd} is the specific gravity of the saturated and surface-dried particles [-], ρ_{ssd} is the saturated and surface-dried particle density [kg/m^3], WA_{24h} is the water absorption after 24h immersion [%].

Figure 3.22: Samples are fully submerged in water and kept for 24 hours. In this example, the samples examine the WA of 100% Brick.

Figure 3.23: Specimens are placed inside an oven at 110°C for 24 hours.

Fig. 3.24 visualizes the different states of an aggregate particle as outlined in the above procedure and equations. The surface moisture in a), b) and c) is negative, meaning the particle can absorb water in such states, while d) has none surface moisture and e) has positive i.e. cannot absorb more water. The total moisture is: a) none; b) less than the absorption capacity drying; c) less than the absorption capacity, absorbing; d) absorption capacity; and e) greater than absorption capacity [74].

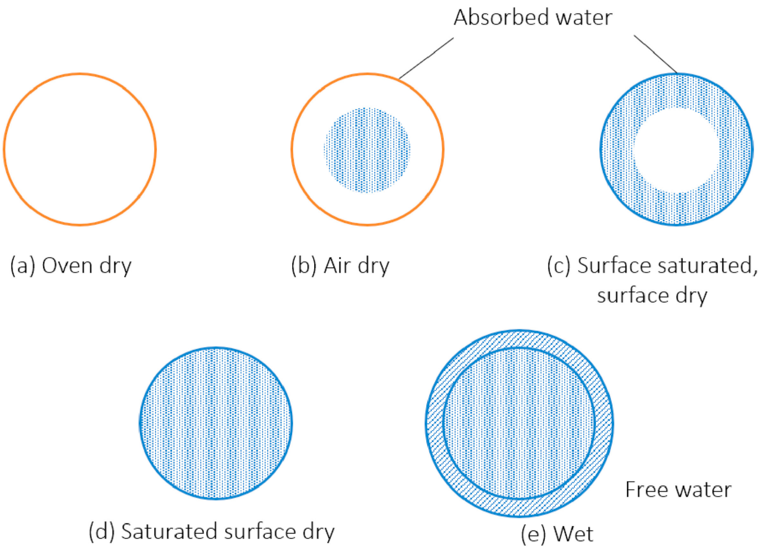


Figure 3.24: Aggregate moisture conditions. Courtesy of [74].

An indication of precise calculations is the following equation:

$$\rho_{ssd} = \rho_{rd} + \rho_w \cdot (\frac{\rho_a - \rho_{rd}}{\rho_a}) \tag{3.11}$$

Based on equation 3.10, the water absorption of a single material could be determined for example natural aggregate, brick, glass. However, the goal of this experiment is to link the water absorption of the coarse aggregate which also includes different contaminants in its composition. In other words, the water absorption values of individual materials are not sufficient to obtain the desired relation. For this reason, several options to derive the combined water absorption of a number of materials were examined. First, it was suggested that the water absorption of two or more materials could be theoretically estimated using the following principle:

$$WA(M+N) = x \cdot WA(N) + y \cdot WA(M) \pm \sqrt{(x \cdot \sigma^2(N)) + (y \cdot \sigma^2(M))} \tag{3.12}$$

where x, y are the mass percentages of each of the corresponding materials N,M [%]; WA(N,M) are the water absorption values of materials N,M [%]; $\sigma^2(N,M)$ are the variances of the WA values for each material [%] and (M+N) denotes the compound containing materials M and N.

In case more than two materials were present in a combination, then the same principle was used with the difference that the standard deviation of any 2 materials was calculated and then added to the third, then the fourth and so on. Examples:

1. Combination of 95% Natural aggregate (NA) and 5% Glass:
   $WA(NA{+}Glass) = 0.95 \cdot WA(NA) + 0.05 \cdot WA(Glass) \pm \sqrt{(0.95 \cdot \sigma^2(NA)) + (0.05 \cdot \sigma^2(Glass))}$
2. Combination of 98.5% NA, 1% Brick and 0.5% Gypsum:
   $WA(NA{+}Brick{+}Gypsum) = 0.985 \cdot WA(NA) + 0.01 \cdot WA(Brick) + 0.005 \cdot WA(Gypsum) \pm \sqrt{(0.985 \cdot \sigma^2(NA)) + (0.01 \cdot \sigma^2(Brick)) + (0.005 \cdot \sigma^2(Gypsum))}$

This method allowed for two different sets of data to be used and compared - one set containing water absorption values for materials based on literature study and one set containing water absorption values entirely based on the experimental procedure of this research. Moreover, the data set with literature study-based values in combination with the principles outlined by equation(s) 3.12 was categorized as purely theoretical, while the experimental value data set in combination with equation(s) 3.12 was classified as semi-empirical.

The next option to evaluate the water absorption of a mix of materials was to experimentally analyse the behaviour of the mixture. In order to do this, once again the procedure outlined by current EU/Dutch standards [93] was followed, utilizing a various number of materials inside the 1.00kg sample, based on desired proportions. This method provided purely experimental results and could be compared with the purely theoretical range and semi-empirical values.

3.3.2. Compressive strength

The main objective of the study was to associate the input variables such as water absorption of the coarse aggregate, cement and water content to the compressive strength of the resulting concrete. In order to have a comparable result in the end, a constant method for obtaining the compressive strength of the concrete had to be chosen. For this purpose, the standard approach defined by NEN/EN 12390-3:2019 [94] was deemed appropriate and thus performed for all samples manufactured throughout the research project.

The testing facilities in the laboratory of TU Delft feature a Instron machine which operates automatically after proper initial setting is applied. The rate of loading was always kept at 13.5kN/s (converts to 0.6MPa/s for the specimen size of 150x150x150mm^3), which is within the defined range of NEN/EN 12390-3:2019 [94], Section 7.2.

The course of action for carrying out the compression testing was as follows:

1. Samples collection and preparation
    - Collect required specimens from curing room at the desired day of testing (7- or 28-days strength)
    - Leave specimens until surface of all sides appears dry
    - Place each cubic specimen on a scale and take its weight
2. Testing
    - Place specimen inside testing machine
    - Select correct settings: Automated Compression, 150x150x150mm^3 specimen size, 13.5kN/s loading rate
    - Start the test and wait until test is done
    - Take notes of the result, remove the failed specimen, clean the chamber of the testing machine and repeat for the remaining specimens

3.4. Chapter summary

To conclude, this chapter provided general information regarding the materials and methods used when carrying out all experimental procedures. All contaminants were described in detail and their relevant properties were mentioned. The preparation prior to using them was also outlined. Special attention was paid to RSC and air due to the slightly different procedures while making the materials ready for further use and their significance to the project. The concrete mix design was followed from initial suggestions to optimisation and choosing the final recipe. The procedure of casting concrete specimens was also featured, together with water absorption tests along with corresponding standards. The description of both tests was principal to obtaining the experimental data elaborated in the next chapter.

4

Results, discussion and comparison

4.1. Introduction

In this chapter, all results obtained based on the experimental procedures described in Section 3 are presented. In addition, these results are further analyzed and compared to literature and used as input for the predictive model buildout. Based on all information, general comments regarding the projects aims and objectives are drawn and any following work is presented.

4.2. Testing procedure results

All results derived from the testing procedures outlined in Section 3.3 are listed and discussed in the following sections. In Section 4.2.1, the water absorption values of all carried out experiments are shown, while in the next Section 4.2.2 the compressive strength of all different concrete mixes after 7 and 28 days is displayed. Based on the results from both experiments and the available information presented in all previous chapters, Section 4.5 overlooks the goal of the project in greater detail and links all components together.

4.2.1. Water absorption

Following the procedure summarized in Section 3.3.1, the water absorption values of most individual contaminants, including natural aggregate itself, were examined. Below in Table 4.1 all experimentally achieved WA values for individual materials are presented. The table manifests the mean water absorption value and the corresponding standard deviation based on the number of tests performed for the given material. The SC entry is based on the mean WA value of all sand concrete aggregates used in this research (SC39, SC55 and LQ) since in reality it wouldn't be possible to tell the origin of a given crushed concrete specimen. It must be mentioned that the number of conducted tests varies from one material to another. The full dataset extracted from all water absorption tests, including values as described in Section 3.3.1 and properties calculated based on equations 3.4 to 3.10 is presented in Annex A.

Table 4.1: Expertimental water absorption of individual materials

Sample	Water Absorption (mean) [%]	Standard deviation [%]
100% Natural aggregate	1.39	0.04
100% Brick	16.56	0.13
100% Glass	1.80	0.02
100% Gypsum	98.84	0.80
100% Ceramic tiles	15.27	0.25
100% SC	10.98	1.05

Contaminants including wood, HDPE plastic, PE foam and mineral fibers were not experimentally inspected for their water absorption. The main reasoning behind this decision was the fact that after a certain number of water absorption tests had been done, it was evident that some materials were not suited for this exact method and their moisture content could not be properly evaluated using the mentioned procedure. Also relying on literature review, it had been reported that this procedure is not appropriate for materials with very different composition to that of aggregates. Furthermore, the available vessels used throughout all water absorption experiments could not contain the required amount of wood, HDPE plastic, PE foam and mineral fibers since 1.00kg of each of those materials takes up larger volume than the capacity of the vessel. Thus, it was decided that their WA values had to be extracted from literature as a starting point and from then on had to be modified accordingly as the experiments were performed, in particular the partial replacement of NA with each of those lighter materials.

Table 4.2 confirms that the testing procedure is valid for materials similar to aggregates. The table illustrates the attempt to examine whether the combination of natural aggregate and any other material results in a linear behaviour in terms of the water absorption of the new compound. As described by equation 3.12, the aim is to see if the complexity of predicting the newly achieved water absorption could be reduced and only explained with a simple linear relation. As it turned out, materials such as bricks, ceramic tiles, gypsum came close to the expected theoretical behaviour, calculated based on equation 3.12. The input for the displayed theoretical range was based on the already obtained water absorption and deviation of the materials (natural aggregate, brick, glass, gypsum, ceramic tiles) or on reported values (wood, HDPE plastic, PE foam, mineral fibers). It is also evident that the latter had a greater scatter in terms of obtained results and this arose the need for more tests to determine the more realistic value.

Table 4.2 contains examples with two or more tests for the same specimen. For such cases, this signifies that the testing procedure was re-done due to a uncertain results in the previous test. Whenever the results from the second tests were within close proximity of the initial one, then a mean value for the specific sample was used further. In the case where the two results were very different, the second value was always taken as the correct one due to the higher precision and care taken during the latter test. This was the case for 1.00% and 5% Glass, 1.50% Wood and 1.00% Mineral fibers as it can also be seen from the table where these values are highlighted by an asterisk.

Table 4.2: Experimental water absorption of combination of natural aggregate and contaminants

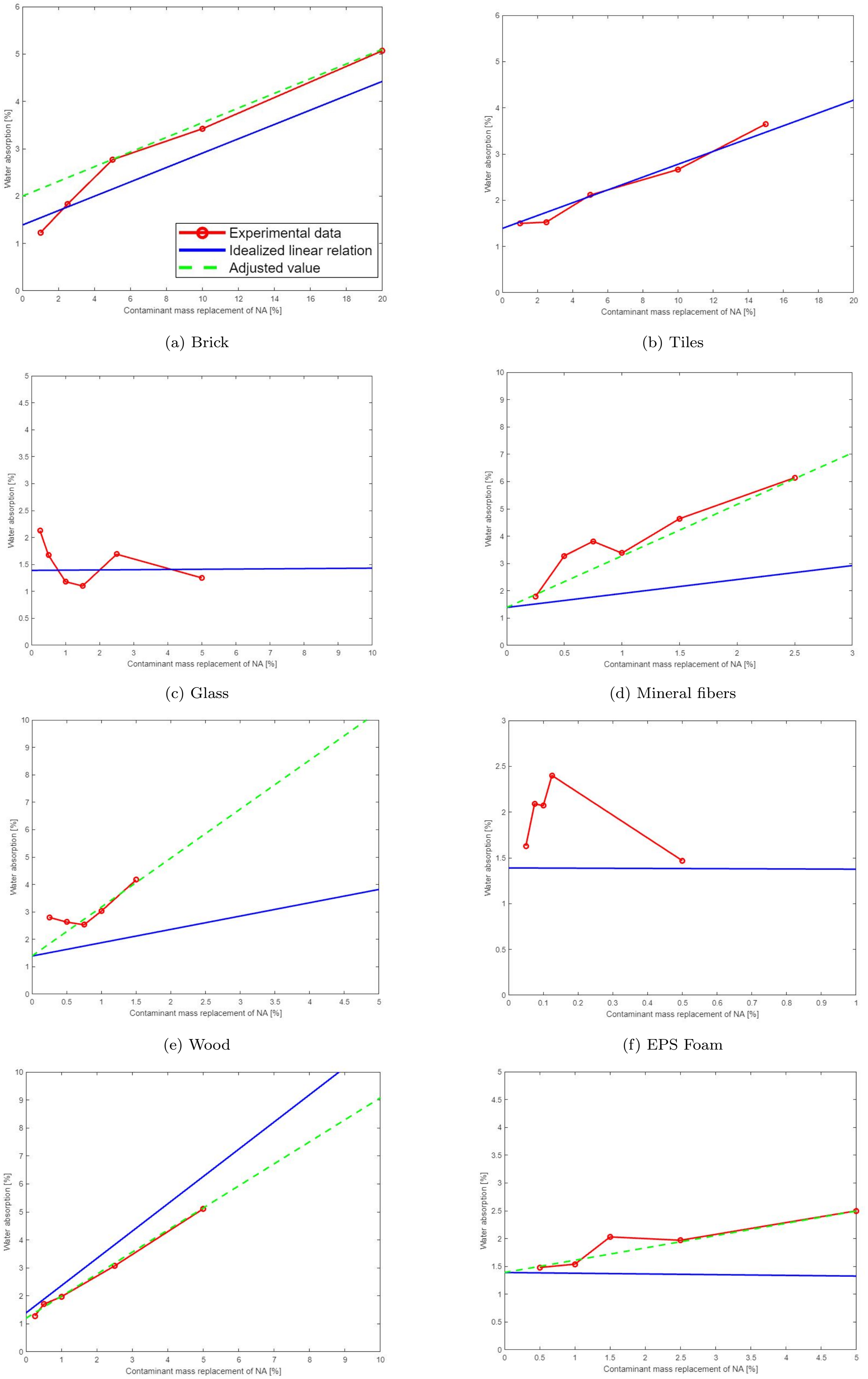
Contaminant mass replacement of NA	Water Absorption [%]	Theoretical range [%]
1.00% Brick	1.11	1.50 – 1.59
1.00% Brick	1.34	1.50 – 1.59
2.50% Brick	1.83	1.73 – 1.81
5.00% Brick	2.94	2.11 – 2.19
5.00% Brick	2.60	2.11 – 2.19
10.00% Brick	3.42	2.87 – 2.95
20.00% Brick	4.97	4.38 – 4.47
20.00% Brick	5.18	4.38 – 4.47
0.25% Glass	2.13	1.35 – 1.44
0.50% Glass	1.31	1.35 – 1.44
0.50% Glass	2.03	1.35 – 1.44
1.00% Glass	2.23	1.36 – 1.44
1.00% Glass	1.18*	1.36 – 1.44
1.50% Glass	1.10	1.36 – 1.44
2.50% Glass	1.90	1.36 – 1.44
2.50% Glass	1.48	1.36 – 1.44
5.00% Glass	2.18	1.37 – 1.45
5.00% Glass	1.25*	1.37 – 1.45
0.25% Wood	2.80	1.47 – 1.56
0.50% Wood	2.63	1.59 – 1.69
0.75% Wood	2.53	1.70 – 1.81
1.00% Wood	3.03	1.81 – 1.94
1.50% Wood	2.40	2.04 – 2.21
1.50% Wood	4.17*	2.04 – 2.21
0.50% HDPE Plastic	1.48	1.34 – 1.43
1.00% HDPE Plastic	1.54	1.34 – 1.42
1.50% HDPE Plastic	1.29	1.33 – 1.42
1.50% HDPE Plastic	2.09	1.33 – 1.42
2.50% HDPE Plastic	1.97	1.32 – 1.40
5.00% HDPE Plastic	2.50	1.29 – 1.37
15.00% HDPE Plastic	3.28	1.16 – 1.24
0.25% Gypsum	1.28	1.52 – 1.61
0.50% Gypsum	1.70	1.69 – 1.78
1.00% Gypsum	1.97	2.04 – 2.12
2.50% Gypsum	3.07	3.06 – 3.15
5.00% Gypsum	5.11	4.77 – 4.88
0.050% PE Foam	1.63	1.35 – 1.43
0.075% PE Foam	2.09	1.35 – 1.43
0.100% PE Foam	2.07	1.35 – 1.43
0.125% PE Foam	2.40	1.35 – 1.34
0.500% PE Foam	1.47	1.34 – 1.43
0.25% Mineral fibers	1.79	1.48 – 1.56
0.50% Mineral fibers	3.28	1.60 – 1.69
0.75% Mineral fibers	3.81	1.73 – 1.82
1.00% Mineral fibers	2.07	1.86 – 1.95
1.00% Mineral fibers	4.69*	1.86 – 1.95
1.50% Mineral fibers	4.07	2.10 – 2.22
1.50% Mineral fibers	5.20	2.10 – 2.22
2.50% Mineral fibers	6.14	2.60 – 2.75
1.00% Ceramic tiles	1.50	1.49 – 1.57
2.50% Ceramic tiles	1.53	1.70 – 1.78
5.00% Ceramic tiles	2.11	2.04 – 2.13
10.00% Ceramic tiles	2.66	2.73 – 2.83
15.00% Ceramic tiles	3.65	3.42 – 3.53
20.00% Ceramic tiles	4.18	4.11 – 4.23

Originating from the data in Tables 4.1 and 4.2, graphs were plotted comparing the theoretical behaviour of mixed aggregate and contaminant with the actual experimental performance. In Fig. 4.1a to 4.1h below, all 8 contaminants, excluding RSC, are featured in a comparative graph. The RSC results are described in detail in Section 4.3 as part of a side study, complementary to this research. On each subfigure, the blue line denotes the idealized linear relation in a mixture of aggregate and contaminant based on the WA of pure materials and Eq.3.12. The contaminant's WA could either be fully experimentally obtained (brick, gypsum, glass, ceramic tiles) or based on literature (wood, mineral fibers, HDPE, EPS). As explained previously in Section 3.3.1, the semi-empirical values feature the aggregate-alike materials, while the rest compose a combination between purely theoretical (based on contaminant's WA) and semi-empirical (based on natural aggregate's WA). The red line on each plot signifies the actual experimental records, while the green dash represents an adjustment where a linear behaviour exists but with different gradient compared to the idealized case. Based on the green line, the so-called adjusted water absorption values of HDPE, mineral fibers, wood and gypsum were evaluated and presented in Table4.3. These adjusted numbers may not correspond to the values in practice, however for this study they were set as fundamental for further analysis.

Table 4.3: Alternative water absorption based on actual behaviour of contaminants

Material	Adjusted water absorption [%]
Brick	17.5
HDPE Plastic	23.5
Gypsum	80.0
Wood	180.0
Mineral fibers	190.0

Looking at Fig.4.2 alongside Fig.3.24, it is relevant to mention why some materials follow the idealized trend better than others. Judging by the results and the literature study, it is only logical that brick, tiles and gypsum follow the depicted states in Fig.3.24 very closely. Similarly, wood, fibers and HDPE follow a linear pattern, which deviates from the initially designed one. Once again referring to the aggregate moisture states, it can be said that the above three materials also abide by set conditions, however the difference in expected versus actual experimental values could be due to the greater shrinkage and/or expansion abilities that they possess. It is important to note that depending on the state a given particle is in, the water to cement ratio could be influenced. For example, if the aggregates are not fully saturated, then they will absorb some of the mixing water of the concrete, taking from the cement hydration water required for strength development. Contrary to this, if the particles have free moisture on their surface, then this water becomes part of the mixing water, increasing the amount necessary for the designed strength and ultimately resulting in weaker and more permeable concrete. To summarize, if the particles contain free water, this moisture will be immediately available for cement hydration together with the mixing water. If the particles are not fully saturated however, they will absorb some of the available water for cement hydration with time, leaving less water than required, which could lead autogeneous shrinkage and crack formation. Therefore, it is of utmost importance to know the state on aggregates prior to mixing so that any adjustments are performed either way. The standard methodology of water absorption on its own is not sufficient to account for this adjustment. The current moisture content of aggregates before mixing has to be evaluated and compared to their WA value – if the moisture content is lower that their WA, then the aggregates will absorb some of the mixing water. Opposite to this, if the moisture content is higher than the WA, then the aggregates will contribute free water to the mix.



(a) Brick

(b) Tiles

(c) Glass

(d) Mineral fibers

(e) Wood

(f) EPS Foam

(g) Gypsum

(h) HDPE Plastic

Figure 4.1: Water absorption of combinations of natural aggregate and contaminants

4.2.2. Compressive strength

The next phase of the project comprised of preparing various concrete mix design samples to be examined. Since the main interest of this research is to investigate the role of the coarse aggregate to the compressive strength of the concrete, contaminants had to be added to the natural coarse aggregate in different amounts and quantities. This on the other hand led to an emerging issue - the 8 available contaminants could all be added in various proportions to the gravel. Furthermore, a different number of contaminants could be included in the coarse portion of the aggregates. To overcome this problem, it was decided that a random sampling method (RSM) in two steps was to be applied in this case. The first step (Phase 2 of the project) filtered a small percentage of the total amount of combinations possible randomly and the second step (Phase 3 of the project) was based upon the results from the first in order to come up with more meaningful samples. As mentioned previously, a parameter of the study is set at maximum of 5% water absorption values of the coarse aggregate, no matter of its composition.

RSM Step 1

The base of the first step of the random sampling method was built upon the possible combinations of the 8 contaminants available for the project, excluding RSC. For RSC, a side study was performed, with parameters as defined in Chapter 3.2.1 and the results were added as supplementary to the main study. This initial step of the filtering of key samples was not as precise and was based on the results of the water absorption tests performed on a combination of NA and a single contaminant. The idea was based upon creating 4 water absorption ranges (Very good (VG), Good (G), Limit (L), Not considered) based on the contaminant percentage mass replacement of NA. Also based on the water absorption of NA (1.39%), the WA ranges were divided as follows: "Very good" for all values <1.50%; "Good" for the range between 1.50-3.00%; "Limit" between 3.00-5.50% and "Not considered" for water absorption above 5.50%. Relying on the results presented in Fig.4.1a to 4.1h, Table 4.4 was produced. In the table, the values depicted correspond to the permissible NA mass percentage replacement of a given contaminant.

Table 4.4: Artificial division of WA ranges per contaminant based on empirical results

WA Range / Contaminant	Very Good	Good	Limit	Not considered
Brick	<2%	2 to 5%	5 to 20%	>20%
Ceramic tiles	<1%	1 to 10%	10 to 25%	>25%
Glass	5 to 10%	0 to 5%	5 to 10%	>10%
Mineral fibers	-	0 to 1%	1 to 1.5%	>1.5%
Wood	-	-	0 to 1.5%	>1.5%
EPS Foam	-	-	0 to 0.5%	>0.5%
Gypsum	<0.5%	0.5 to 2.5%	2.5 to 5%	>5%
HDPE Plastic	-	0 to 5%	5 to 10%	>10%

Based on Table 4.4, for any given number of contaminants present (from 1 to 8), the total number of combinations could be estimated deriving from the WA ranges. In other words, for the case of any 2 contaminants present, there were certain quota of VG-VG; VG-G; VG-L; G-G; G-L; L-L combinations. Out of the mentioned possibilities, some were likely to produce a sample with a water absorption below 5% (VG-VG; VG-G; VG-L; G-G), while the rest were assumed to result in a sample with higher that 5% water absorption (G-L; L-L). Once again, this was not scientifically backed up, it was only a simplification done in order to reduce the number of possible samples. Following the example of 2 contaminants, the same could be done for 3, 4, 5 and more than 6. The prediction of a good resulting sample differed from one case to another and the total number of good samples was evaluated using basic statistics. The extracted output valuable for the initiation of this step is presented below in Table 4.5:

Table 4.5: Preliminary statistical refinement of samples based on the obtained individual WA values of contaminants

Contaminants present	"Good" sample combination	Statistical equation	Number of possible samples
1		$\sum(VG+G+L)$	18
			Total: 18
2	VG-VG	C$\binom{2}{4}$	6
	VG-G	4*6	24
	VG-L	4*8	32
	G-G	6*6	36
			Total: 98
3	VG-VG-VG	C$\binom{3}{4}$	4
	VG-VG-G	6*C$\binom{2}{4}$	36
	VG-VG-L	8*C$\binom{2}{4}$	48
	VG-G-G	4*C$\binom{2}{6}$	60
	G-G-G	C$\binom{3}{6}$	20
			Total: 168
4	VG-VG-VG-VG	C$\binom{4}{4}$	1
	VG-VG-VG-G	C$\binom{3}{4}$*6	24
	VG-VG-G-G	C$\binom{2}{4}$*C$\binom{2}{6}$	90
	VG-G-G-G	4*C$\binom{3}{6}$	80
			Total: 195
5	VG-VG-VG-VG-G	C$\binom{4}{4}$*6	6
	VG-VG-VG-G-G	C$\binom{3}{4}$*C$\binom{2}{6}$	60
			Total: 66
6+	VG-VG-VG-VG-G-G	C$\binom{4}{4}$*C$\binom{2}{6}$	15
			Total: 15

The proportion of each category was then calculated based on the number of combinations for that group divided by the total number of possible samples. The number of samples for each group were afterwards estimated as the nearest whole number of the product of the proportion and the total number of samples chosen for Phase 2. In total, it was decided that 18 samples were to be produced and tested as part of the first step. Below in Table 4.6, the overview of the described calculation is presented:

Table 4.6: Fraction weight of each contaminant group based on statistics

Category	Proportion	Number of samples chosen [actual]
1 contaminant	$18/560 = 3.2\%$	18*3.2% = 1 [6]
2 contaminants	$98/560 = 17.5\%$	18*17.5% = 3 [4]
3 contaminants	$168/560 = 30.0\%$	18*30.0% = 5 [4]
4 contaminants	$195/560 = 34.8\%$	18*34.8% = 6 [3]
5 contaminants	$66/560 = 11.8\%$	18*11.8% = 2 [1]
6+ contaminants	$15/560 = 2.7\%$	18*2.7% = 0 [0]

As it can be seen from the data above, the proportion of the group with 1 contaminant present is significantly lower compared to most others. On the other hand, it was believed that if just 1 contaminant is added to the NA, that could possible carry a greater weigh in terms of obtained results, especially in the initial stages. Thus, it was decided that the numbers presented in Table 4.6 would be adjusted so that they accommodated more samples with only 1 contaminant present – see the "actual" value in square brackets in the table. The chosen samples were denoted with S1 to S18 in the following sections. Each sample was tested for the water absorption of its coarse aggregate, the compressive strength after 7 and 28 days.

An addition to the procedures outlined in Section 3.3 is the alternation of the water content of each sample containing replacements of NA. Upon adding contaminants to the concrete mix, the water absorption of the coarse aggregate changes and in order to keep the same workability throughout all experiments, the water content for each sample was adjusted according to the experimental water absorption value of the sample. The new water content was calculated as given in Eq. 4.1. It should be mentioned that this is not a scientifically backed procedure and it was applied in order to prevent any significant rise in the water content due to the higher absorption of the aggregates, which is known to lead to lower compressive strengths. In this manner, the extra water content could be kept relatively low and thus the effective w/c ratio would also remain intact.

$$w = w_0(1 + (WA(S_n) - WA(NA))) \tag{4.1}$$

where w_0 is the initial water content required for 100% natural aggregate as coarse aggregate (no contaminants) [kg] , $WA(S_n)$ is the water absorption of a given sample S_n and $WA(NA)$ is the water absorption of natural aggregate as measured in Phase 1 [%].

Below the results of all samples comprising Phase 2 are presented in Table 4.7. The third column represents how much coarse aggregate volume do the contaminants of a given sample replace. For example, sample S1 contains glass which is 10% of the mass of NA. However, since glass is slightly lighter than NA, the volume of this amount of glass is higher than the volume of the same mass of NA and thus the volume replacement percentage is higher as well (10.8%vol vs 10.0%wt). Generally, the lighter or less dense a given material is compared to NA, the larger the difference between mass and volume replacement percentages. In Annex B a conversion table showing the relation between CA volume replacement, CA mass replacement and total volume replacement is provided. The testing procedures performed are in correspondence with the outlined methods in Chapter 3 and the addendum explained by Equation 4.1. An additional note regarding the equation is that during casting the first concrete specimens, it was observed that this procedure indeed helped with workability. All samples followed the desired fresh concrete requirements and therefore this equation could be considered as a sort of empirical relation which acted in correspondence with its intended purpose, at least for all specimens cast throughout this project. The mixed NA and contaminants samples are visualized in Fig. 4.3 as part of the procedure to evaluate the WA of the coarse aggregate of the samples in Phase 2. The cubic specimens, tested for compression, are shown in Figures 4.4 and 4.5. The mix designs of all samples are illustrated in Annex C.

Table 4.7: Water absorption of coarse aggregate fraction and compressive strength of Phase 2 samples

Label	Description (repl. %wt of NA)	CA volume replacement [%]	Experimental WA [%]	Theoretical WA range [%]	Mean weight [kg]	7 days strength [MPa]	28 days strength [MPa]	Strength development [%]
REF	Natural aggregate 100%	-	1.39	-	8.04	42.02±0.56	58.34±0.56	72.0
S1	Glass 10%	10.8	1.25	1.24-1.31	7.93	43.37±0.44	55.03±0.44	78.8
S2	Wood 1.5%	5.8	4.17	2.04-2.21	7.79	36.39±0.34	53.72±0.34	67.7
S3	Brick 20%	28.4	4.97	4.38-4.47	7.81	45.19±0.11	59.65±0.11	75.8
S4	Foam 0.5%	63.5	1.47	1.34-1.43	7.27	26.72±1.18	41.40±1.18	64.5
S5	Min.fiber 1%	36.3	2.07	1.86-1.95	7.89	41.51±0.95	59.83±0.95	69.4
S6	Ceramic tiles 15%	21.3	3.65	3.42-3.53	7.87	44.27±0.60	62.58±0.60	70.7
S7	Brick 1% + Gypsum 0.5%	3.2	1.92	1.62-1.70	7.97	41.66±0.74	54.21±0.74	76.9
S8	Foam 0.25% + Min.fiber 0.25%	40.8	1.51	1.47-1.56	7.55	36.19±2.02	48.06±2.02	75.3
S9	Ceramic tiles 5% + Foam 0.25%	38.9	1.94	2.04-2.13	7.47	34.24±1.25	49.92±1.25	68.6
S10	Ceramic tiles 5% + Min.fiber 0.25%	16.2	2.30	2.17-2.26	7.90	43.31±2.22	57.24±2.22	75.7
S11	Brick 1% + HDPE 1% + Gypsum 0.5%	6.1	2.88	1.61-1.69	7.81	38.09±0.82	52.18±0.82	73.0
S12	Glass 2.5% + Brick 1% + HDPE 1%	7.0	2.19	1.46-1.54	7.96	37.71±0.93	51.88±0.93	72.7
S13	Glass 5% + Wood 1% + Gypsum 0.5%	11.0	3.20	1.87-2.00	7.90	36.66±0.23	52.98±0.23	69.2
S14	HDPE 3% + Brick 2% + Wood 1%	15.2	2.06	2.09-2.22	7.69	31.38±0.37	45.67±0.37	68.7
S15	HDPE 1% + Brick 1% + Wood 1% + Gypsum 0.5%	9.9	3.49	2.07-2.20	7.79	35.16±1.64	44.76±1.64	78.6
S16	Glass 5% + Brick 2% + Gypsum 2% + Wood 1%	19.3	5.40	3.76-3.89	7.80	38.48±0.45	49.96±0.45	77.0
S17	HDPE 3% + Brick 2.5% + Glass 2.5% + Wood 1%	22.5	3.17	2.13-2.25	7.63	32.86±1.46	40.70±1.46	80.7
S18	Glass 5% + HDPE 1% + Wood 1% + Brick 1% + Gypsum 0.5%	15.3	3.38	2.10-2.14	7.74	32.99±2.15	50.22±2.15	65.7

In Fig. 4.2, the data presented above in Table 4.7 is illustrated in a way to visualize the effect of water absorption towards the compressive strength. Samples are divided into 4 main group according to the number of contaminants present, as well as the data point which are highly reliable are also marked. The reliability aspect is based on the performance of individual contaminants under WA tests, meaning that samples including bricks, tiles and gypsum only are qualified as authentic. It is clear once again that the water absorption on its own is not sufficient predictor of the compressive strength as emphasized by the figure.

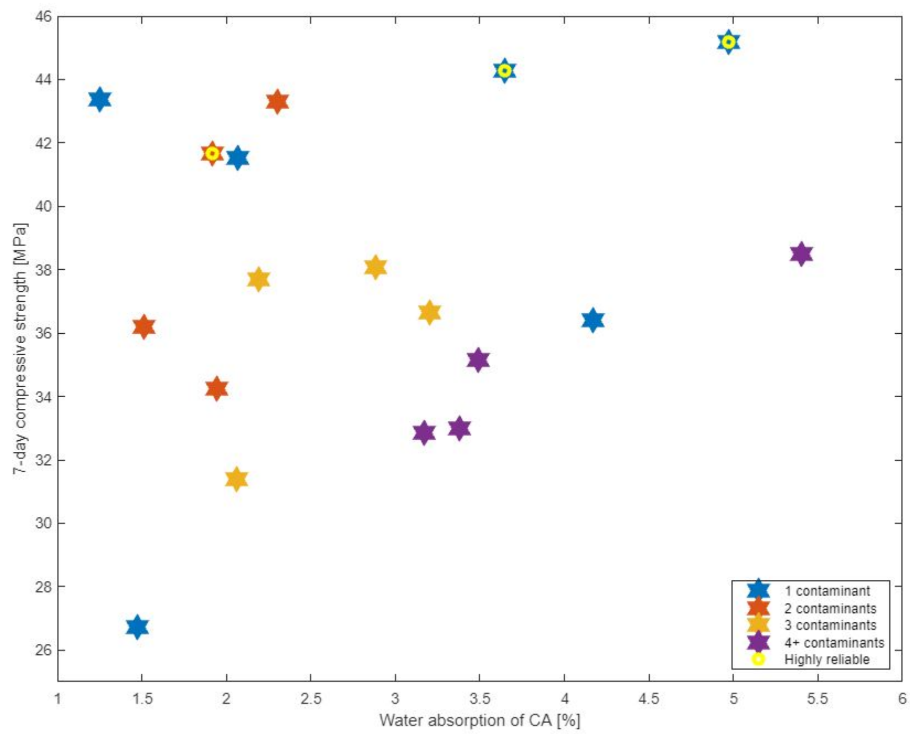


Figure 4.2: Experimental relation between water absorption of coarse aggregate and compressive strength

Figure 4.3: Phase 2 samples evaluated for their WA values as part of the standardized procedure

Figure 4.4: Part of Phase 2 samples after compression tests.

Figure 4.5: Detailed overview on the tested specimens

The expected deliverables after completing Phase 2 included determining whether the theoretical predictions of water absorption of a combination of more than 1 contaminant came close to reality; determining which pattern between the mass and volume replacement of NA and compressive strength exists and how to use that pattern for the development of the predictive model; investigating the effect of the number of contaminants present in the coarse aggregate and the effect of individual contaminants to the compressive strength. The key findings based upon the aforementioned objectives are listed below:

1. Similar or identical water absorption values of different samples do not result in the same compressive strength development;
2. Generally, theoretical predictions for a number of contaminants larger than 2 differ from reality;
3. The larger the number of contaminants present, the greater the deviation in compressive strength results.

Based on these three statements, it was evident that the compressive strength was likely based on the type, number and volume/mass replacement of NA. Furthermore, a predictive model entirely based on the water absorption of coarse aggregate was not feasible due to the variance in the mechanical strength of the concrete given the different composition of the coarse aggregate portion. In order to investigate the mass and volume replacement effect, as well as the correlation to the water absorption, the next phase (Phase 3) featured samples with identical water absorption and:

- Different number of contaminants
- Different volume of contaminants
- Different mass of contaminants

RSM Step 2

The second step of the random sampling method (Phase 3) followed directly from the obtained results in the previous step. As mentioned, this phase featured samples with constant water absorption values and different number, mass or volume of contaminants present. For each of the three types, 4 samples were selected randomly, keeping to the defined parameters of the set. Samples S19 to S22 feature WA levels in the magnitude around 2.50% and number of contaminants varying from 1 to 3. It should be mentioned that S20 had already had its WA estimated from previous experiments and despite the theoretical range difference, it was already known what the actual water absorption was. The rest of the samples produced results in the acceptable range (from 2.13% to 2.77%) which was crucial for the experiment. Samples S23 to S26 aimed at 3.00% water absorption and varying mass replacement of NA from 1% to 10%. Those 4 samples could also be used to enhance the next set of samples, featuring WA of approximately 2.00% and different volume replacement of NA. Similarly to S20, S27 had had a known WA value and was included in the set due to this. However, S28 and S29 produced results which did not meet the expectations of WA close to 2.00% and could not be directly used for the specific purpose initially intended. Nevertheless, those samples enrich the whole dataset and were utilized in the in-depth analysis and development of the predictive model. The full extent of the values is presented in Table 4.8.

Table 4.8: Water absorption of coarse aggregate fraction and compressive strength of Phase 3 samples

Label	Description (repl. %wt of NA)	CA volume replacement [%]	Experimental WA [%]	Theoretical WA range [%]	Mean weight [kg]	7 days strength [MPa]	28 days strength [MPa]	Strength development [%]
S19	Brick 5%	7.1	2.77	2.11-2.19	7.93	39.70±2.78	58.73±2.78	67.6
S20	Wood 0.75%	2.9	2.53	1.70-1.81	7.90	34.82±0.48	54.28±0.34	64.2
S21	Ceramic tiles 4% + Gypsum 1%	9.3	2.19	2.59-2.68	7.84	39.55±1.97	55.12±1.97	71.8
S22	Brick 3% + HDPE 1.5% + Gypsum 1%	12.1	2.13	2.47-2.55	7.68	35.49±1.14	48.47±1.14	73.2
S23	Brick 7.5%	10.7	3.01	2.49-2.57	7.93	40.78±2.34	59.28±2.34	68.8
S24	Wood 1%	3.9	3.03	1.81-1.94	7.91	32.15±1.39	51.38±1.39	62.6
S25	Gypsum 2.5%	9.0	3.07	3.06-3.15	7.77	39.10±1.08	54.95±1.08	71.2
S26	HDPE 5% + Glass 2.5% + Gypsum 2.5%	25.9	3.53	2.98-3.05	7.38	29.40±1.16	39.27±1.16	74.9
S27	HDPE 2.5%	7.1	1.97	1.32-1.40	7.80	35.63±1.46	49.38±1.46	72.1
S28	Brick 2.25% + Gypsum 0.25%	4.1	1.41	1.86-1.95	7.94	41.83±0.55	60.03±0.55	69.7
S29	Glass 1.5% + Min.fiber 0.5% + Wood 0.5%	5.3	2.71	1.82-1.92	7.75	35.42±0.49	53.65±0.49	66.0
S30	Ceramic tiles 1% + HDPE 1% + Gypsum 0.5%	6.1	1.83	1.82-1.90	7.78	36.76±0.99	56.04±0.99	65.6

Based on this set of results, the following findings were noted:

1. Number of contaminants effect - Generally, the higher the number of contaminants, the higher the water absorption. Also, as mentioned previously, the standard deviation in compressive strength increased as the contaminants increased. The compressive strength tended to decrease as the contaminants increased, however the early strength development was quicker compared to samples with less contaminants (including the reference 100% NA).
2. Volume of contaminants effect - This effect was highly dependant on the contaminants which took up the volume - wood in small volumes (<1.5%wt of NA) decreased the compressive strength by approximately 15%. On the other hand, larger quantities of brick (>10%wt of NA) and tiles (7%wt of NA) gave a positive effect on compressive strength compared to the reference. Foam had a negative effect on the compressive strength and even in very small quantities took up a significant portion of the volume of CA (>30%vol).
3. Mass of contaminants effect - Usually the larger the mass replacement of NA, the higher the compressive strength drop. However, this phenomenon was reliant on the nature of the replacing materials, especially HDPE, foam, wood. The latter are very light and even in small quantities take up large volumes which contributed negatively to the performance of the concrete since individually all listed contaminants are weak in compression. On

the other hand, significant mass replacements of brick and tiles (>15%) led to increase in strength compared to reference. Despite the seemingly positive effect, it should be noted that there might be durability problems in long term.

4. Water absorption: theory vs experimental - In the end, it was evident that the water absorption of a mixture of several materials could indeed be predicted, however the greater the materials in the composition, the less precise the theoretical range is. For this reason, an adjustment factor should be introduced when trying to set up the predictive model in order to account for the greater deviation in results.

4.3. SC Side study

The additional topic of crushed concrete aggregates as contaminant was included in this research due to its relevance and the availability of old concrete specimens in the repository of TU Delft. As mentioned previously in Section 3.2.1, the parent concrete was either with w/c of 0.39 (SC39) or 0.55 (SC55) and only sand concrete samples were utilized for this test. A total of 6 additional samples were prepared, again testing their water absorption values and compressive strength at 7 and 28 days. An important note is that for these specimens the volume replacement percentage was of utter most importance and thus it was taken as the base point for replacing the aggregates. The logic is derived from the fact that the lighter SC aggregate (density approximately 1.8 times less than natural aggregate) would take up more volume than NA if replaced by mass and thus the design cement content will not be sufficient for the desired strength. Therefore, for this experiment the mass replacement was altered in such way that the same volume is kept as all previous tests or in other words the mass of the added sand concrete aggregates was less than the initial mass of natural aggregates. The water absorption of all SC types was also evaluated prior to casting the specimens, following the outline procedure in Chapter 3. The results are given in Table 4.9:

Table 4.9: Water absorption of coarse aggregate fraction and compressive strength of SC samples

Label	Description (repl. %vol of NA)	Initial mass equivalent [%]	Experimental WA [%]	Theoretical WA range [%]	Mean weight [kg]	7 days strength [MPa]	28 days strength [MPa]	Strength development [%]
REF	NA 100%	100	1.39	-	8.04	42.02±0.56	58.34±0.56	72.0
R1	100% SC55	55.6	13.17	-	7.49	37.59±0.32	51.04±0.32	73.7
R2	100% SC39	55.6	11.07	-	7.47	38.18±0.63	50.55±0.63	75.5
R3	75% SC39	41.7	8.50	8.39-8.92	7.64	38.57±1.84	52.25±1.84	73.8
R4	50% SC39	27.8	5.68	5.71-6.76	7.79	39.73±0.10	54.47±0.10	72.9
R5	25% SC39	13.9	3.01	3.03-4.60	7.92	40.88±0.26	56.75±0.26	72.0
R6	100% LQ	55.6	8.70	-	7.51	36.48±0.29	50.65±1.39	72.0

In comparison, the predicted strength values based on Eq.2.4 reported in literature overestimate the experimental ones by around 6 to 10%. It should be noted that this equation only predicts the 28-day strength and doesn't take into account the type of cement used but rather the effective w/c ratio only (apart from the replacement ratio). Contrasting to the values in Table4.9, the estimations based on the aforementioned equations are as follows: 63.37MPa (25%repl.), 61.13MPa (50%), 57.94MPa (75%) and 53.91MPa (100%). Furthermore, the quality of the recycled aggregate is also not considered by the disclosed equation, which could contribute towards the occurring variance.

In addition to WA and CS tests for RSCs, crushing value tests were also performed in accordance with IS 2386 (Part 4):1963 [95]. The results are summarized in Table4.10. The crushing value is interpreted as whether a given aggregate is suitable for certain construction type. In other words, it provides insight of the strength potential of the aggregate and the stronger an aggregate is, the lower its crushing value should be. The governing standards limit aggregates with crushing value above 30% of implementing within surface courses. The presented results show that for SC39 and SC55 aggregates, the value was approximately 30%, merely satisfying the base requirements for road application. The significantly higher value of LQ aggregates signified its weak resistance to gradual compression loads. Despite the higher crushing values of all RAs compared to NA, it is evident from Table 4.9 that this property does not affect the compressive strength of the concrete directly.

Table 4.10: Crushing value for RSCs compared to NA

Label	Description (repl. %wt of NA)	Crushing value [%]
REF	100% NA	16.00
R1	100% SC55	33.80
R2	100% SC39	29.98
R6	100% LQ	58.12

4.4. Comparison to Air

The end point of this project included a comparison of all RA concrete made to the inclusion of air voids within conventional concrete. Thus, air entrainment in the foam of individual EPS foam particles (contrasting from the shape of EPS used as a contaminant) was added to the same concrete recipe (T3B). Attention was especially paid upon casting these samples so that the full calculate volume of air (foams) was contained within each cubic specimen. All 4 size groups were tested for 7-day strength, while samples A% were also tested after 28 days. Note that the label of each specimen also contains the volume replacement of NA with air – example A4% denotes the EPS type A, which replaces 4% of the initial NA volume. The next column of Table 4.11 provides the mass replacement percentage and the results of compressive strength tests are also displayed:

Table 4.11: Compressive strength of comparative concrete samples made artificial air voids as replacement of coarse natural aggregate

Label (vol. NA)	Mass replacement [%]	Mean weight [kg]	7 days strength [MPa]	28 days strength [MPa]
A1%	0.017	7.79	42.24	58.02
A2%	0.034	7.73	39.70	54.88
A4%	0.068	7.77	35.16	50.38
A6%	0.101	7.64	33.80	49.32
B1%	0.017	7.87	40.33	-
B2%	0.034	7.79	38.17	-
B4%	0.068	7.68	36.59	-
B6%	0.101	7.55	34.24	-
C1%	0.017	7.91	42.96	-
C2%	0.034	7.85	38.49	-
D1%	0.017	7.78	41.24	-
D2%	0.034	7.76	41.02	-
D4%	0.068	7.73	37.77	-
D6%	0.101	7.56	32.92	-

Based on the above values, the plot in Fig. 4.6 depicts the difference in strength for all size groups of foam.

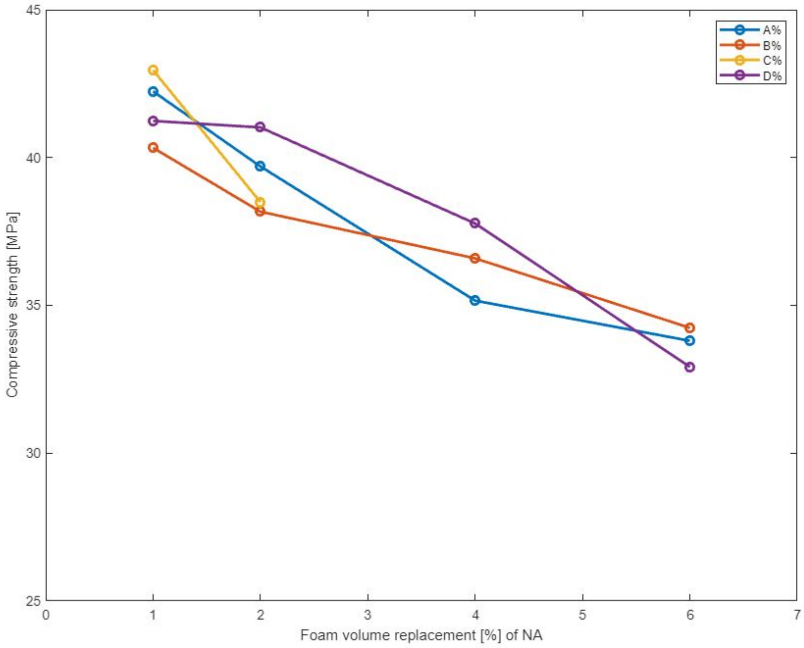


Figure 4.6: 7 days compressive strength of Phase 4 air-concrete samples

4.5. Analysis

Starting from WA results presented in Tables 4.1 and 4.2, it becomes apparent that some contaminants behaved in accordance with the theoretical range estimated previously, while others registered significant divergence compared to the established hypothesis. For example, ceramic tiles complied with theory to such an extent that no adjustment in their actual WA value was required as it can be seen from Fig. 4.1b (green dashed line). Brick and gypsum are the other 2 materials which were within acceptable span of results, however a slight alternation in their measured WA value was made to improve the overall fit. The mean WA values of brick and gypsum were reported to be 16.56% and 98.84% (as measured). These values were adjusted to 17.50% and 80.00% respectively and overall they correspond to what had been quoted from literature when describing bricks nonetheless. This confirms that materials similar to aggregates came close to expected values and could be predicted with greater accuracy compared to others. Gypsum, despite being comparably different to aggregates (including bricks and tiles), also showed a relatively predictable behaviour when in combination with NA. It was expected that the small amounts of gypsum added as replacement to NA would give rise to larger variance due to the fact that gypsum is soluble in water as reported in literature. Nonetheless, it seems that the limited solubility didn't interfere with the WA tests and provided meaningful results. The other contaminant tested for its water absorption, glass, yielded results around the theory, however a greater scatter in those was reached (Fig.4.1c). It was also curious that the literature-reported WA for glass had been in the magnitude of 0.20% on average, yet upon testing a value of 1.80% was achieved. This experimental value fit much better into the comparative model depicted in the figure. Despite the scatter in results, it is clear that the overall trend was not fat from the theory. Additionally, some tests were repeated in order to confirm or distinguish between values with significant differences or new tests for intermediate mass replacement percentages were performed with the same reasoning. The final conclusion when it comes down to the WA behaviour of glass in combination with NA was that it followed the theory with larger deviation. This deviation however is not crucial since the actual WA of glass was within close proximity of the value of NA and thus any glass addition should not make worse or improve the WA of the combination. The rest of the materials (wood, mineral fibers, EPS foam, HDPE plastic) were not tested for WA and rather hypothetical value as reported by literature was assigned to those. As it turned out, these values did not match the experimental behaviour closely and considerable adjustment had to be done. The reason why those 4 contaminants were not tested for absorption as reported previously was that they do not resemble aggregates and the results would not make sense. Furthermore, the required samples would have a significantly larger volume if composed of plastics, fibers or wood, compared to the natural aggregate. The used glass vessels would not be able to accommodate the dimensions of the samples and this would also interfere with some of the constant parameters for this study. Looking at the plots for those materials (Fig. 4.1d, 4.1e, 4.1f, 4.1h), it is obvious that all were added to NA in different amounts. Due to the physical properties of EPS foam, it had to be added in very small mass replacement percentages. As part of the CS tests, all mass replacement values were converted to volume replacement, as it can be seen from Tables 4.7 and 4.8. From there it is evident that 0.5% mass replacement of foam was equivalent to 63.5% volume replacement of CA or 25% replacement of the total volume (sample S4). Even so, the water absorption seemed to stay within admissible limits (below 2.5%) and consequently foam was not considered as important influence on WA of CA. HDPE Plastic on the other hand showed a constant rise in WA with increasing fraction increments which is contrary to what was expected. The adjusted WA value for HDPE plastic turned out to be approximately 23.5%, while the one from literature was closer to 0.10%. This is a noteworthy difference and could perhaps be explained with the applicability of the chosen test procedure. The reported values from literature were based on experiments specifically designed for plastics, however in this project another test was performed trying to estimate the same property. In practice, it is hard to use different tests to evaluate the WA of recycled aggregates and one which is most suitable must be chosen. In this case, the WA test performed to all samples resulted in a unexpectedly high value for the water absorption of plastic, however it is more important that the results mostly followed a linear trend. Despite the high value, it could be assumed that the WA value was predictable based on the adjusted WA value of plastic. Exactly the same applies to wood and mineral fibers. As it can be seen from their subplots, experiments tended to follow a linear relation which was different to theory, notably higher. No matter the suitability of the test, it is of high importance that WA results could be predicted based on some arbitrary values.

To conclude, brick and ceramic tiles were the main contributors towards the WA and since they resemble the natural aggregate the most; limiting values in terms of mass or volume replacement had to be introduced. In order to keep the maximum 5% WA, bricks should replace no more than 20% of the mass of NA, while this value was around 25% for tiles. Wood was also part of this group with maximum of 2% mass replacement if acceptable WA is desired. Gypsum, mineral fibers and HDPE plastic also had a great influence on the WA, however their volume fraction was usually considerably lower compared to bricks and as such were considered secondary contributors towards the WA. Glass and foam either showed improvement of the WA of the mix or kept it within the NA-levels of WA, hence did not contribute towards the overall WA.

In terms of the compressive strength results presented in Section 4.2.2, it is obvious that the WA of CA was not the main contributor to the strength development. Samples with very high

WA such as S3 (Brick 20%) and S6 (Tiles 15%) shaped a concrete with better performance compared to the reference both 7 and 28 days after casting. In addition, samples with very similar absorption (S5, S7, S9, S12, S14, S22, S27 all had WA $\approx 2 \pm 0.1\%$) manufactured concretes with contrasting strengths – ranging from 31.38 up to 41.66MPa after 7 days and 45.67 to 59.83MPa after 28 days. Moreover, the samples chosen for RSM Step 2 (S19 to S30) were set to investigate in more detail the dependency of CS on mass and volume replacement, number and type of contaminants present. Considering those samples, it is clear that the CS was not linearly dependant on the WA of CA and the latter parameters indeed had a greater influence on the resulting strength. In the following paragraphs, each of those parameters is evaluated in terms of the effects it carried on the strength of recycled concrete according to the experimental procedure of this study.

Mass replacement was the initial choice of inclusion of contaminants to the concrete recipes due to the fact that was straightforward to compute and is useful when it concerns real-life application. Since aggregate content is one of the three main components of a concrete mix design (others include cement and water content), it is easy to calculate a given fraction of that and to replace it with another material. Examining Tables 4.7 and 4.8, once again confirms that this was not the most influential criterion affecting the CS. Furthermore, for smaller amounts ($\leq 5\%$), the mass and volume replacement values came in close proximity provided that materials such as EPS foam, HDPE plastic or mineral fibers were not included. The latter are considerably lighter than aggregates and thus take up more space for the same mass. What is more, none of them contributed towards the strength since they possess qualities describing ductile materials. For these reasons, for materials as the ones listed above, volume replacement is a more appropriate gauge as it is the case in the current EU regulations (float contaminants are measured in volume of contaminant per unit mass of aggregate) Once again looking at both replacement percentages, it could be confirmed that generally the larger volume any contaminant replaced, the lower the compression after 7 and 28 days was. The only times this statement did not hold true was when it regarded bricks or ceramic tiles – large quantities (both as mass and volume fractions) of these materials had a seemingly positive effect overall. Combination of contaminants, resulting in relatively high volume replacement (over 15%) principally meant decreased performance anywhere from 10 up to 30% given that the main presence was neither bricks nor ceramic tiles.

The number of present contaminants proved to be a key criterion upon inspection of results in this instance. However, the discussion to follow should not be taken as conclusive or final since this project only looked at a limited number of samples and any general comments are hard to make at this point. Nonetheless, the trends observed should be emphasized in future studies in order to confirm or disprove the role of "number of contaminants" as indicator within RAC design. Looking at the results, all comparable to reference (close or better CS) contained 2 or less contaminants within the mix, in most cases only 1 present. For example, even recipes with low mass/volume replacement, but large number of contaminants (3-4) present such as S11, S15, S22 reduced the strength by 9 to 16% after 7 days and 11 to 23% after 28 days. Generally samples with 4 or more contaminants plummeted the CS by 16-17% on the seventh day and over 20% on the twenty-eighth. What could be taken from this as a conclusion is that in a lot of cases, the recycled concrete is likely to be at least 10 to 20% weaker in compression if more than 2 contaminants are present, independently of their type. If, of course, the recycled aggregates coming from a plant have been previously refined to a certain extent, then the latter statement would not apply, however for most recycled concrete manufactures this might appear as a rule of thumb.

All previous criteria led to one – the type of contaminant present appeared to carry the greatest weight when evaluating the compressive strength of recycled concrete. However, all above parameters were used with comparative functions to tie all components together.

- Commencing with brick, it had already been stated that this material was highly influential on the water absorption of the coarse aggregate portion and improved the compressive strength when added in certain quantities. To expand on this, amounts larger than 10% of mass replacement (equivalent to 14.2% CA volume replacement) tended to bring positive effect on the strength, while smaller contents acted as ideal substitute of natural aggregate i.e. have neutral effect on the CS. This finding confirms what was reported by [29] – equal compressive strength up to 25%vol replacement of NA. Attention should be paid for amounts over 20% mass replacement (28.4% volume replacement) since the WA of the CA went beyond the limit prescribed in the current standards. Despite the improvement of CS for such mixes, it is yet to be seen whether the 91-days strength is comparable or if any durability issue exist in the longer term. This phenomenon could be explained by the altered cement hydration process taking place within the NA-brick samples. It is a well known fact that concrete needs water in order to harden (cure) and whenever there is no more water, it stops getting stronger. The larger moisture content kept within the brick particles was likely helping the constant release of water with time, providing more water for a longer period of time. While this could be beneficial up to a certain moment in time, the precise consequences of the high inner water content could not be predicted accurately and is best to keep within standard-suggested limits. To summarize, brick gravitated around being a very effective substitute of natural aggregate and should be put high in the list of recycled materials to be re-used in building construction.

- Ceramic tiles showed very similar behaviour to bricks. Differences existed and included the slightly weaker effect that tiles had on the water absorption and also the slightly better improvement of CS they brought. Limiting values were set to 25% of mass (35.5% volume) replacement. Overall, based on the results, ceramic tiles performed moderately better compared to bricks and this might had been due to the high breaking strength of ceramic tiles. The results of this research were in accordance with what has been delineated by several studies [54, 55] regarding ceramic tiles – partial replacements from 14 to 30%wt carry positive effect on concrete strength. Similarly to bricks, tiles were likely to bond well with other aggregates and possibly did not interfere with the formation of a proper ITZ.

- Wood is one of the most commonly found residual materials in C&DW. If included in recycled concrete, the wood affected the water absorption of the aggregate significantly, even in small amounts such as 1% mass replacement. For this reason, wood should be kept within limited quantities (up to 2% mass replacement) in order to maintain a desirable WA. In addition to this, such amounts of wood (0.5 to 1.5%) usually resulted in compressive strength drop of 12.5 up to 21.0% compared to reference, with or without any other contaminants present. Moreover, the difference was always greater after 28 days so contrary to bricks and tiles, the high water absorption of wood did not lead to similar results. This noted, wood was considered a secondary contaminant regarding both the WA and CS, affecting both properties in a negative manner.

- Judging by experimental results, mineral fibers evidently resulted in acceptable WA ranges upon addition in equivalent to real-life contents (1.5% of mass replacement). For the same amounts, fibers did not seem to affect the CS negatively – in fact they tended to have neutral or even slightly positive effect. The occurrence of improved strength could very well be explained by the same phenomenon as with bricks and tiles, however this case is more peculiar since fibers possess particularly higher absorption and cannot be classified as well-performing in compression. Nonetheless, sample S5 confirmed that restricted fibers content could have an advantageous use to recycled concrete. More than 2% of mineral fibers however should not be added to the mix design, otherwise the WA levels would not be kept as prescribed.

- On its own, gypsum was inclined to give rise to a slight increase in WA and to insignificant CS drop (6 to 7%). Of course, in order for this statement to be true, gypsum had to be kept up to 2.5% of the NA mass within the mix. This should be relatively easily achievable in practise and thus gypsum was categorized as secondary contaminant towards WA and CS.

- Glass particles did not interfere majorly on the WA of the CA – they brought a larger scatter or deviation when evaluating this property, however most times kept the value well within range. Furthermore, up to 10% mass (10.8% volume) replacement, the CS of the RAC was not affected neither positively nor negatively. This denotes that glass bonded well within the mix design and despite having different structure and physical properties compared to aggregates, the overall trend was to replace gravel efficiently, without visible issues arising from ASR. On the other hand, a study published by Santos et al. (2020) [96] disclosed that up to 20% of reactive aggregate such as recycled aggregates did not affect the expansion behaviour of concrete due to ASR. Additionally, expansion was greatest when the reactive RA entirely replaced the NA and when higher strength cement was used. The latter statement is paramount since throughout this experiment, CEM III 52.5 was used. The implications of the above recitation would be that if CEM III 42.5 was used instead, then the concretes might not have shown similar behaviour to the ones tested. It should be noted once again that in order to observe any visible differences according to [96], the amount of glass replacing the NA should be higher than what was tested in this experiment.

- The plastics used in this experiment (HDPE, EPS) both fetched losses in terms of compressive strength of recycled concrete. While this was somewhat expected, the drops in CS reached values of 30% and above for very low mass replacements (up to 0.5% EPS). On the other hand, as mentioned previously, the better describing parameters for these materials (especially EPS foam) is the volume replacement – and the equivalent of 0.5% mass was over 63.5% volume (EPS foam). HDPE introduced a comparable decline in CS as EPS, however the mass and volume replacement values were close to each other. Both materials were primary contributors to the poor compression of RAC – controlled quantities should not exceed 2.5% of HDPE (in terms of mass) and 0.15% of EPS (equal to $\approx$ 19% of volume) if less than 15% CS drop is to be achieved. Not only did the plastics take up large volumes, they also interfered with the composition of aggregates. Their ability to absorb water is limited, however results showed that there were discrepancies when more contaminants were present. On its own, HDPE increased the absorption of water, however the moisture release afterwards did not resemble the one of bricks or tiles. Revisiting Fig.3.24, it is likely that HDPE contributed towards the free water content without providing any moisture located within the particles. Even though such state is not depicted in the figure, given the nature of these materials and their continuously reported limited water absorption, it would be sensible to consider that the moisture content of the plastic was higher than its capability to absorb water, leading to free water content and similar to oven dry conditions simultaneously.

The addition of RSC as a contaminant in this study was dictated by the fact that currently the C&DW is mostly comprised of this material – old concrete, demolished and crushed into desired particle size range. One of the main ideas behind this study was to establish the relation between the compressive strength of the new recycled concrete based on its composition – however the addition of RSC must not be ignored next to contaminants such as bricks, glass, wood and so on. Therefore, a few samples containing only RSC as a contaminant were evaluated in terms of WA and CS. A visual representation of the information given in Table 4.3 is manifested below in Fig. 4.7 and 4.8.

It can be seen that concrete made entirely out of sand concrete (samples R1, R2, R6) provided a design with strength approximately equal to 85-90% of the strength of concrete made from natural coarse aggregate only. Furthermore, the experimentally evaluated WA values for all coarse aggregate fractions of these samples were far beyond the desired 5%. Despite this, the strength development was comparable to the arbitrary value both after 7 and 28 days, even with low quality (LQ) recycled coarse aggregate fully utilized. Nonetheless, in order to keep the regulations, a maximum replacement value had to be introduced so that the WA of CA was not more that 5%. Once again after WA tests on samples made out of NA and RSC (SC55 only), it was concluded that up to 45-50% of mass (80-90% of CA volume) replacement was the limit of inclusion of RSC.

The figures show interesting and even unexpected trends – firstly, as stated, all types of recycled sand concrete particles produced new concretes with very close strengths (37.59, 38.18, 36.48MPa after 7 days; 51.04, 50.55, 50.65MPa after 28 days), no matter of their origin and quality. What is more, the WA value of all CA fractions was different (13.17 vs 11.07 vs 8.70%) and considerably higher than the reference (1.39%) and allowed by codes of practice (5%). Despite all possible issues, the end results were very promising and definitely should be explored further.

Secondly, Fig. 4.8 had more curious output – it showed that if RSC was added to the NA as a partial replacement, it fabricated a concrete with proportionate strength. According to literature, comparable strengths were expected upon 30%wt replacement and 12-25% drop for full replacements. In this instance, the SC in amounts less than 30%wt led to 3 to 7% reduced compression, while 100% replacement yielded results 11 to 13% weaker than reference. Furthermore, it seemed like there was an insignificant difference between the percentage RSC added – for a 25% increase in mass replacement, the strength linearly reduced but was always in close proximity of the reference. On one hand, this is great for the circularity required in the industry – if indeed 75% old recycled concrete with combination of just 25% new aggregate is a recipe for a concrete with strength drop of around 10%, then this is indeed the path to follow. However, to be entirely sure, these tests should be re-evaluated to see whether they will be confirmed or they only occurred on this occasion. Another problem arises, as is evident from the same figure – the water absorption value of such mix design was above norm by 3.5%. As it stands, such design will not be allowed to be used in any residential or even low-rise buildings. This however should serve as an appeal for further investigation to both the standard applicability to RAC and to mix optimization for concrete made out of old recycled concrete.

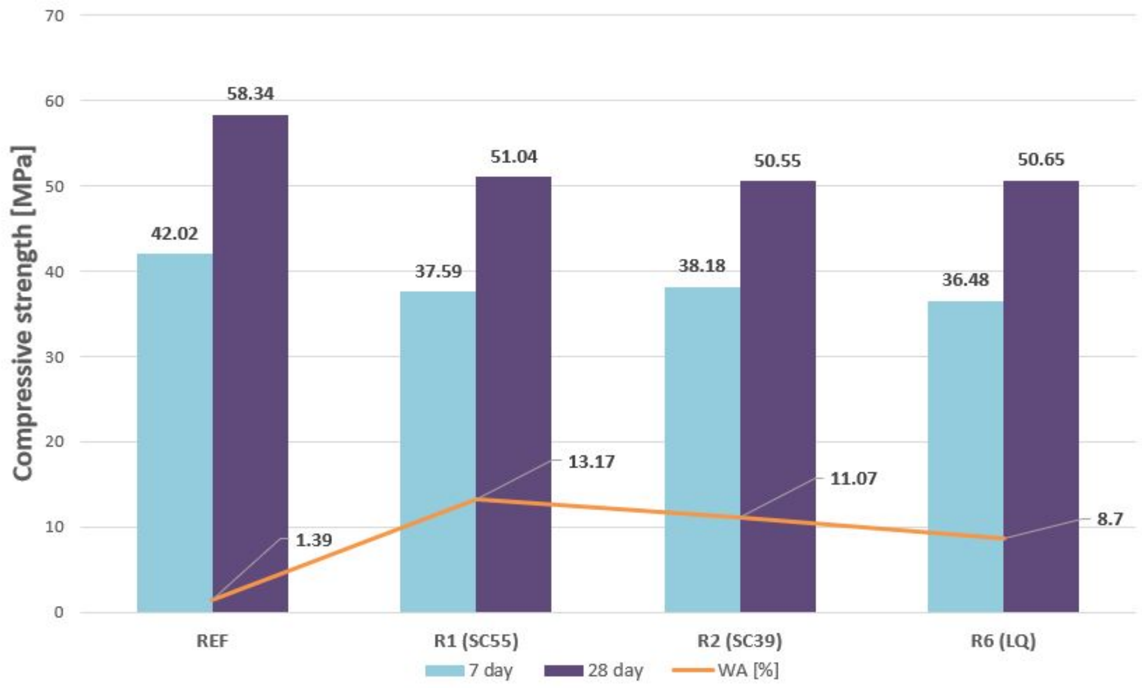


Figure 4.7: Comparison between all types of RSC cast and reference

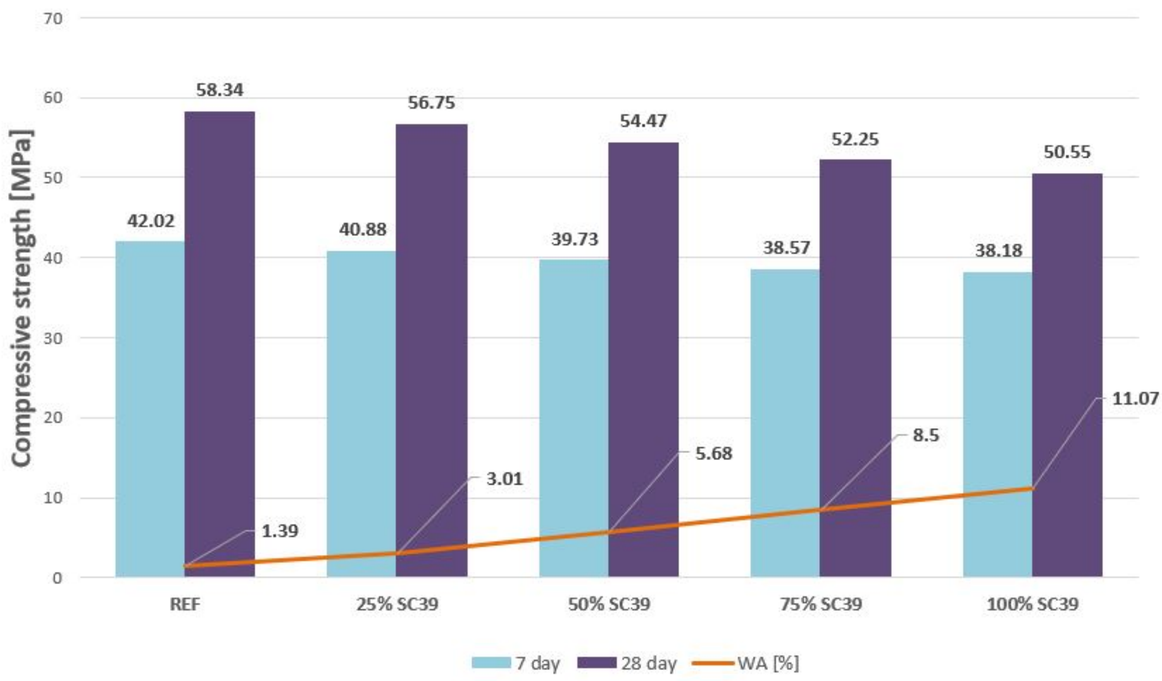


Figure 4.8: Comparison between the RSC made from different fractions of SC39 replacement

The linking component is the final comparison between all RA made concrete samples and the presence of air voids in the mix. In the previous section, the compressive strengths of concretes made with certain amounts of air added to the mix were presented. Below in Fig.4.9 the mean results from each volume replacement fraction are compared with the reference 100% NA sample (which by default includes 2% air as part of its initial design mix). All samples part of Phase 4 followed this design parameter of 2% initial air volume and the foam particles added effectively denote extra air content to the mix (1%, 2%, 4% and 6%).

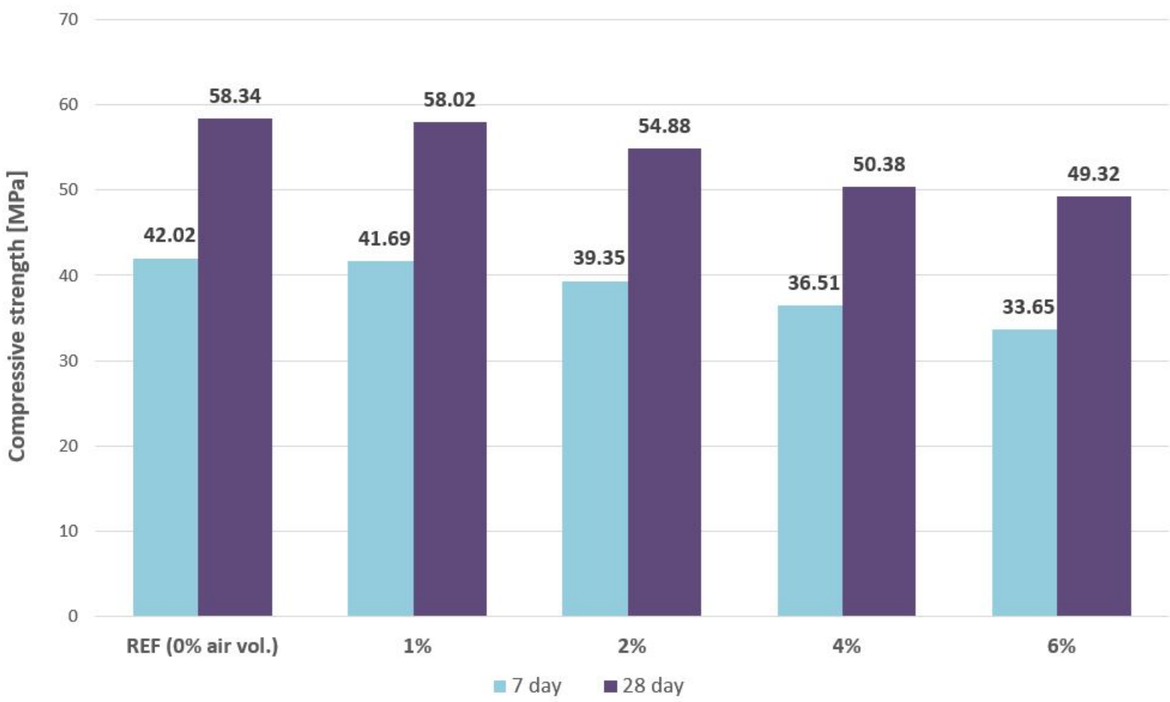


Figure 4.9: Additional air content within the RAC - comparison in terms of compressive strength at 7 and 28 days between values from 0 to 6%

Assessing the results illustrated in the above figure, it could be concluded that the relation between amount of air added and the compressive strength of concrete was practically linear. There was a clear decrease of strength as the air voids increased and the maximum loss of strength was evaluated at 15 to 25% for replacement of 6%. It is also evident that up to 1% of extra air didn't affect the strength and could only be considered as an advantage (lighter overall material). Comparing this data with literature (Zeng et al. (2021) [22]), it was reported that 1% of air leads to 4-6% of reduced strength. In this instance however, 2% of air led to this diminished strength, while 1% only promoted a concrete with comparable strength as stated previously. This slim difference could be explained by the fact that in this experiment air was included in the form of EPS foam particles, which more or less could contribute to the slightly higher strength compared to air in pure form. Despite this difference, it could be confirmed that amounts in the magnitude of 1-2%vol. air yield 5% weaker concrete on average. What is more, up to 4% of air added resulted in a sharper decrease of strength, while the relation from 4 to 6% was more gradual and less significant. However, this could be explained by the limited number of specimens cast for this phase and overall it could be said that 5% of extra air content was the limiting number so that the strength loss was kept up to $\approx$ 20%. As mentioned, the linear relation between air added and compressive strength could be visualized by plotting a trendline based on experimental data. The output is demonstrated in Fig. 4.10 and the linear function is narrated in Eq.4.2:

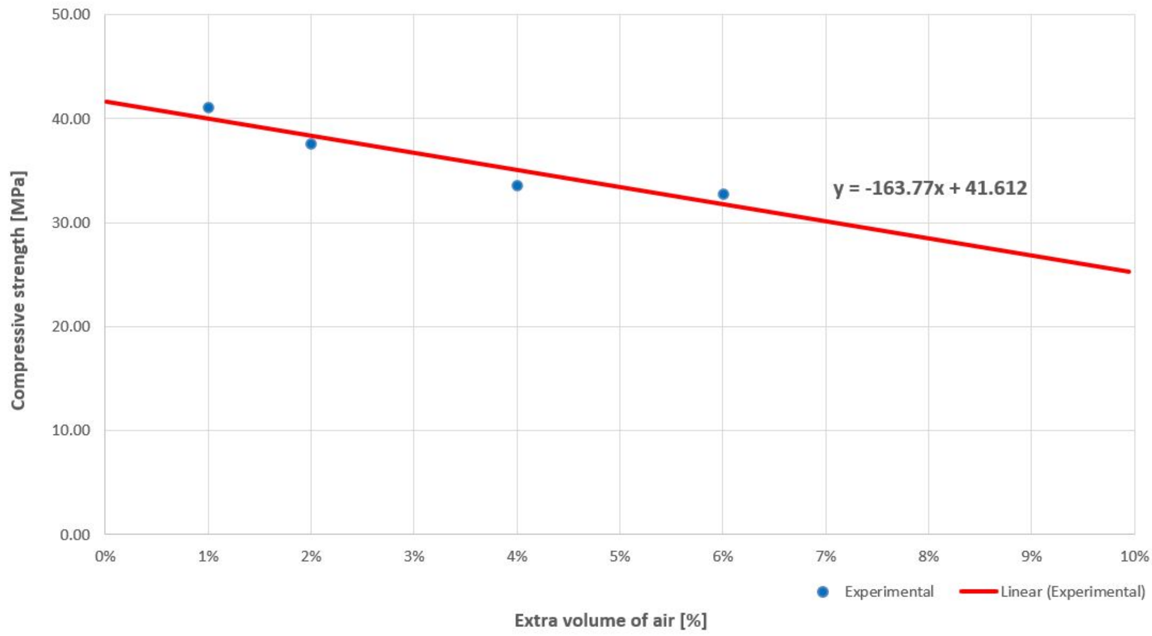


Figure 4.10: Extended relation between air void content [%] and 7-day CS of RAC [MPa]

$$CS(7) = 41.612 - 1.6377 \cdot \delta_{air} \tag{4.2}$$

where $CS(7)$ is the compressive strength of RAC after 7 days [MPa] and δ_{air} is the extra air content added as volume replacement of CA[%].

In Table 4.12 and 4.13 all relevant data reported from literature is summarized in order to compare it to the experimental findings of this research. Following this information, Table 4.14 provides the corresponding values as determined and evaluated during this research. As it can be seen from the tables, there are multiple sources confirming the observed effect of certain contaminants and as expected there are reports which state contradicting data. Especially looking at the recycled aggregate data (Table 4.13), there are numerous research papers which all claim different behaviour. This can be explained by the great variability of the recycled aggregate due to its contents, size distribution, level of contamination, presence of certain materials according to the geographical location an so on. With this in mind, it is adequate that there are sources confirming the data found during this experiment – in this case the water absorption was backed up by at least 3 other papers, while the linear decrease with the increase of RA to NA ratio was in accordance with 3 sources. Water absorption values of bricks and tiles were also in accordance with several research papers, while wood and fibers differed significantly with what has been reported in literature. This once again could be explained by the improper method for these materials chosen in this experiment. In terms of the compressive strength of the resulting concrete, there was positive feedback overall with sources verifying the effect of bricks, tiles, plastics, fibers and recycled aggregates. It was found that PET plastic gave rise to 43.5% CS drop upon 30%wt replacement as reported by [69], while in this research the 60x times lighter EPS replacing 0.5%wt of NA yielded a 34% reduction in strength. Both results are comparable and likely closely related and thus in the table above it is stated that they are in possible accordance with each other.

Table 4.12: Key data relevant to this study as reported in literature

Material	NA replacement	Reported WA	CS effect	Reference
Brick	100%vol 75%vol 50%vol 25%vol	12.85%	70% drop 60% drop 30% drop equal CS	[29]
	100%vol	22-25%	20% drop	[31]
	≤15%vol ≥30%vol	15.81 to 18.91%	equal CS 20% drop	[32]
Wood		20 to 60%		[33]
		53 to 79%		[34]
Glass	33%vol 66%vol 100%vol	0.10%	3.5-5.4% drop 10-13.5% drop 13.5-13.8% drop	[39]
		0.03 to 1.45%		[40]
	50%vol 100%vol of FA		22% drop 17% drop	[41]
	30%vol		comparable CS	[43]
Tiles	20%vol	6.0%	10-15% rise	[54]
	14%wt 20%wt 30%wt	15.76%	5.5% increase 7% increase equal CS	[55]
	25%vol 10 to 50%vol 5 to 20%vol 5 to 20%vol 10 to 50%vol 10 to 40%vol 5 to 10%vol 15%vol 20 to 25%vol		70% drop 6-25% rise up to 25% rise up to 20% drop up to 50% drop comparable CS slight rise equal CS slight drop	[56]
Plastics (PET)	10%wt 20%wt 30%wt 40%wt 50%wt	0.49%	comparable CS 5-16% drop 43.5% drop 62.5% drop 90% drop	[63]
Fibers		100%		[65]
		75%		[66]
	10%wt 20%wt		9% drop 13% drop	[69]
	30%wt		12-27% drop	[67]

Table 4.13: Key data regarding recycled aggregates relevant to this study as reported in literature

RA type	NA replacement	Reported WA	CS effect	Reference
4-20mm RA	20-30%wt	$\leq$ 5%		[70]
8-20mm concrete aggregate		5.4%		[8]
RCA		10%		
		8.74%		[72]
	100%vol		comparable CS	[73]
	$\leq$ 30%wt		comparable CS	
	100%vol		20-25% drop	[76]
	50 to 100%vol		comparable if lower w/c is used	
	50%vol		25% drop	
	15 to 30%vol		18% drop	
	100%vol		comparable; 3-8% rise	[77, 78, 79]
	40%vol		25% rise (low grade concrete)	[78]
	100%vol		19% drop	[80]
RA with 14-24% adh.mortar	100%vol		12-20% drop	[81]
RA with 60% adh.mortar	100%vol		1.5-3% drop	

Table 4.14: Data assessed by this research and comparison with literature

Material	Estimated WA	%wt of NA	%vol of NA	CS effect	In accordance	Contradicting
Brick	16.5 to 17.5%	5 to 7.5%	7 to 10%	3-6% drop	[32] (partially)	
		20%	28.5%	5% rise	[29]; WA: [32]	
Wood	up to 180%	0.75 to 1.50%	3 to 6%	17-25% drop		WA: [33, 34]
Glass	1.80%	10%	11%	3% rise		
Tiles	15.27%	15%	21%	5% rise	[54, 55, 56]; WA: [55]	[56] (partially)
Plastics	N/A	2.5% (HDPE)	8%	15% drop		
		0.5% (EPS)	64%	34% drop	[63]	
Fibers	up to 190%	1%	36%	1% drop	[69] (possibly)	WA: [65, 66]
Gypsum	80 to 98.84%	2.5%	9%	7% drop		
RSC	8.70 to 13.07%	13.9%	25%	3% drop	[73]	[76]
		27.8%	50%	5-7% drop	WA: [8, 70, 72]	[76, 78]
		41.7%	75%	8-10% drop	[76]	
		55.6%	100%	11-13% drop	[81]	[77, 78, 79]

4.6. Chapter summary

In summary, this chapter presented all information as experimentally evaluated based on the testing procedures outlined in the previous chapter. It also provided in-depth analysis of the deliverables, as well as comparison with sources from literature. In the end, key relations were obtained which were crucial for the development of the predictive model and correlating all aspects of the project. Further conclusions were not drawn at this stage, but rather left for the conclusive chapter of the research.

5

Predictive model development

5.1. Introduction

In the following sections, relative information regarding the development of a working predictive model is disclosed. The staring point is depicted in Section 5.2, where the initial scheme of the modelling procedure is explained. Following that, in Section 5.3, the key experimental relations as reported in the previous chapter are used to simplify the modelling procedure. The models, created via external software (Minitab Statistical Software 21.2.0.0) are presented in Section 5.4, while the validation process is given in the next Section, 5.5.

5.2. Draft model propositions

The initial idea behind this project itself was to investigate whether some functional properties of recycled concrete, in particular its compressive strength at given time, could be evaluated as a non-linear function of several main components. In other words:

$$f_{c,cube}(t) = F(WA_{agg}; w/c; c) \tag{5.1}$$

where WA_{agg} is the water absorption of the aggregates [%], w/c is the water to cement ratio [-], c is the cement content [kg/m^3].

Since the w/c ratio and the cement content are key parameters of any concrete design mix, the only variable in the function described by Eq. 5.1 is the water absorption of the aggregates. In conventional concrete, this is also a constant given that the absorption properties of natural aggregates (gravel, sand) are well-known and easily evaluated if required. However, in recycled concrete, there is a very high variance in the composition of the aggregates and this value differs significantly. Thus, it is of high importance to develop a prototype which would be able to predict this value based on the composition of recycled aggregates. The general relation between the WA of the recycled aggregates and their composition might resemble the equation, given below:

$$WA_{agg} = \alpha \cdot WA_{NA} \cdot V_{NA} + \beta_i \cdot WA_{X(i)} \cdot V_{X(i)} \tag{5.2}$$

where α is an adjustment factor [-], WA_{NA} is the water absorption value of natural aggregate [%], V_{NA} is the volume fraction of natural aggregate in the mix [%]; $X(i)$ is any contaminant present in the recycled aggregate, i running from 0 to n and β_i are adjustment factors for all n contaminants.

5.3. Modelling based on experimental results

Relying on the experimental data gathered in the previous phases of the project, some general comments regarding the effect all contaminants pose on the water absorption of aggregates and the compressive strength of the resulting concrete were drawn. Most of these statements were already listed in Chapter 4.5. In the following paragraph only the ones relevant to the development of a model are listed.

It was reported that the main (primary) contributors towards the WA of CA include brick, ceramic tiles and wood, all of which having negative effect. Glass, HDPE, EPS had neutral or slightly positive effect on the WA, however only glass could have any significance towards the WA since the amounts the plastics could be present in the CA were restricted (or must be). Gypsum and mineral fibers affected the WA negatively, nevertheless, in small quantities (as per common C&DW composition) their impact was of minor importance. For these reasons, glass, gypsum and fibers were categorized as secondary contributors towards the WA, while HDPE and foam were treated as tertiary (no influence).

In terms of compressive strength, the major consequences arose from the inclusion of EPS and HDPE. Alongside the plastics, negative effect on the CS also posed gypsum and wood, however their weight was notably lower and thus were classified as secondary. Brick and ceramic tiles also fell into the secondary group, although they tended to increase the strength of recycled concrete. Glass and mineral fibers seemed to have little to no effect on the strength, given their usual volume fractions in C&DW.

Based on the above paragraphs, simplifications in the predictive models were made. These improved the processing time, as well as the accuracy of a potential model. In the coming section, the starting (base) models are described, followed by the simplified versions prompted by the above categorization and analysis.

5.4. Regression Analysis

All models were created with the help of the statistical software Minitab. All models were generated using the "Fit Regression Model" function which takes a number of set predictors (input variables) in order to relate them to a continuous response (output). This model had been used previously in similar projects, linked to concrete and prediction of its properties as already mentioned in Chapter 2.

5.4.1. WA models

As described in Section 5.2, the first step of correlating the water absorption of aggregates and the compressive strength of recycled concrete, was to derive a model evaluating the WA at all times. Based on Eq. 5.2, the first WA model was initiated. The input variables consisted of the contribution of each individual component presented in the CA fraction of the aggregate, including the gravel. The contribution of each material was calculated as the volume fraction of the material in a given sample multiplied by its individual water absorption value as estimated experimentally. The resulting models were three - the first one utilizing an additional "categorical predictor" and no validation method specified for the regression; the second one had no categorical predictor and no specified validation method; the third one also had no categorical predictor, however the validation method as chosen as "test set". The output of all models was the predetermined WA values of all samples included in the models (S1 to S30). The categorical predictor used for the first model was the number of contaminants present in each sample. The results are the presented in the following equations, while the full reports are included in Annex D:

$$WA = X - 25.5 \cdot \gamma_{na} - 1.22 \cdot \gamma_{brick} - 1.51 \cdot \gamma_{tiles} + 0.441 \cdot \gamma_{wood} - 20.7 \cdot \gamma_{glass} - 1.95 \cdot \gamma_{hdpe} - 767 \cdot \gamma_{eps} + 0.439 \cdot \gamma_{gypsum} \pm 0.490 \quad (5.3)$$

$$WA = 60.4 - 42.4 \cdot \gamma_{na} - 2.50 \cdot \gamma_{brick} - 3.02 \cdot \gamma_{tiles} + 0.469 \cdot \gamma_{wood} - 32.3 \cdot \gamma_{glass} - 2.72 \cdot \gamma_{hdpe} - 897 \cdot \gamma_{eps} + 0.208 \cdot \gamma_{gypsum} \pm 0.485 \quad (5.4)$$

$$WA = 79.2 - 56.0 \cdot \gamma_{na} - 3.58 \cdot \gamma_{brick} - 4.17 \cdot \gamma_{tiles} + 0.525 \cdot \gamma_{wood} - 42.5 \cdot \gamma_{glass} - 3.35 \cdot \gamma_{hdpe} - 700 \cdot \gamma_{eps} + 0.063 \cdot \gamma_{gypsum} \pm 0.383 \quad (5.5)$$

where X is a number [%] ranging from 36.8 to 37.6 based on the number of contaminants present; γ_i [%] denotes the contribution of each component i. Eq.5.3 corresponds to the first model as explained above, 5.4 to the second and 5.5 to the third.

The simplified model, presented in Eq. 5.6, was based on assumption listed in the previous section. Primary contributors are entitled with larger adjustment factors ($\alpha_I = 1.2$), while secondary materials had reduced influence ($\alpha_{II} = 0.9$). The rest of the materials were not taken into account while estimating the WA, provided that they were kept within limiting values.

$$WA = 0.46 + 0.64 \cdot \gamma_{na} + 0.98 \cdot \alpha_I \cdot \gamma_{brick} + 0.822 \cdot \alpha_I \cdot \gamma_{tiles} + 0.7985 \cdot \alpha_I \cdot \gamma_{wood} + 1.35 \cdot \alpha_{II} \cdot \gamma_{glass} + 1.16 \cdot \alpha_{II} \cdot \gamma_{gypsum} + 0.455 \cdot \alpha_{II} \cdot \gamma_{fibers} \pm 0.369 \quad (5.6)$$

The final WA model however was selected to simulate the real-life conditions as much as possible. Thus, instead of specifying the design amount [kg/m^3] of each ingredient, relying on the mass portion of each would save time in practice. Furthermore, both SCs were combined into one category since in practice it would be almost impossible to distinguish the exact type of the parent material, LQ aggregate was also added. In the end, the user input is made out of the mass percentage each fraction takes of the total coarse aggregate fraction. The WA is calculated as shown:

$$WA = 1.9 - 0.4 \cdot \psi_{NA} + 1.05 \cdot \psi_{brick} + 0.91 \cdot \psi_{tiles} + 1.16 \cdot \psi_{wood} - 2.2 \cdot \psi_{hdpe} + 0.844 \cdot \psi_{fibers} + 0.977 \cdot \psi_{gypsum} + 0.78 \cdot \psi_{sc} + 0.77 \cdot \psi_{lq} \pm 0.60 \quad (5.7)$$

where ψ_i [%] denotes the mass contribution of each component i.

Reverting to Section 4.5, more specifically to the descriptions of individual contaminants, the aspects mentioned in those paragraphs could be compared to the above equation. In the text is was indicated that recycled aggregates, bricks, tiles, wood, gypsum and fibers tend to increase the WA, as opposed to glass and plastics which had neutral or slightly decreasing overall effect towards WA. Furthermore, recycled aggregates (SC, LQ), bricks and tiles could be incorporated in larger quantities within the concrete mix in contrast with the rest of the materials. Equation 5.6 illustrates a similar trend – glass and EPS are not present due to their neutral effect, HDPE decreases the WA and thus appears with a negative sign (as well as natural aggregates which have lower WA compared to all materials except plastics) and all others increase the WA. In terms of coefficients, upon taking into account that the mass contribution ψ includes the individual WA of materials as constant, it turns out that fibers, gypsum and wood carry greater weight than brick, tiles and RAs. This could be explained by their limited presence within the concrete and it is obvious that for a more conventional RAC design, materials such as bricks will have a more substantial contribution due to their greater volume and mass fraction. Nevertheless, this could turn out as problematic in case larger amounts of these materials are used as the equation would probably yield results which do not replicate the reality.

5.4.2. CS models

The models predicting the compressive strength followed indirectly from the WA models. In other words, the earliest models relying upon input were not correlated with the water absorption of the coarse aggregates as predicted in the developed models. In fact, these models depended on the effective w/c ratio, the content of natural coarse aggregate (gravel) and the content of recycled coarse aggregate. The contents of both fragments were either measured as volume fractions [kg/m^3] or as percentage of volume replacement [%vol] – denoting CS Model 1 and CS Model 2 respectively. Each model had two different validation methods and had the option of the categorical predictor used previously in the WA models. Thus, the resulting versions were 8 in total – 2 main models with 4 submodels (denoted a to d). The equations below describe each one of the models in the order starting from CS Model 1a to CS Model 2d (the full reports are shown in Annex D):

$$CS(7) = A + 97 \cdot w/c + 0.0694 \cdot \beta_{nca} + 0.0904 \cdot \beta_{rsc} \pm 4.02 \tag{5.8}$$

$$CS(7) = B + 17 \cdot w/c + 0.1212 \cdot \beta_{nca} + 0.167 \cdot \beta_{rsc} \pm 3.99 \tag{5.9}$$

$$CS(7) = -25.2 + 76 \cdot w/c + 0.0257 \cdot \beta_{nca} + 0.036 \cdot \beta_{rsc} \pm 4.37 \tag{5.10}$$

$$CS(7) = 14.1 - 247 \cdot w/c + 0.1257 \cdot \gamma_{nca} + 0.170 \cdot \gamma_{rsc} \pm 4.17 \tag{5.11}$$

$$CS(7) = C + 113.2 \cdot w/c - 0.01191 \cdot \beta_{nca} - 0.2118 \cdot \delta_{rsc} \pm 3.62 \tag{5.12}$$

$$CS(7) = D + 122 \cdot w/c - 0.01747 \cdot \beta_{nca} - 0.1751 \cdot \delta_{rsc} \pm 3.89 \tag{5.13}$$

$$CS(7) = 22.2 + 63.0 \cdot w/c - 0.01197 \cdot \beta_{nca} - 0.2033 \cdot \delta_{rsc} \pm 4.03 \tag{5.14}$$

$$CS(7) = 120.1 - 143 \cdot w/c - 0.01601 \cdot \beta_{nca} - 0.1994 \cdot \delta_{rsc} \pm 4.00 \tag{5.15}$$

where A is a number [%] ranging from -87.3 to -75.5;B is a number [%] ranging from -108.0 to -94.4 based on the number of contaminants present; β_i denotes the volume fraction of each NCA or RCA [kg/m^3]; C is a number [%] ranging from -5.7 to +3.8; D is a number [%] ranging from -5.0 to +6.0 based on the number of contaminants present; δ_{rsc} denotes the RSC volume percentage replacement of NCA [%].

As it can be seen from Eq.5.8 to 5.15, the standard deviation for all models was around 4MPa. Based on the experimental results presented in previous chapters, the 7 day compressive strength of the reference sample (100% NA as CA), it was known that the value is 42.02± 0.56MPa. This ultimately meant that all above models had a built-in 10% error when evaluating the CS of another sample. Despite this, all 8 models were used to predict the 7 day strength of the foam-concrete samples, outlined in Section 4.4. The results are shown below in Table 5.1:

Table 5.1: Comparison between foam-concrete CS experimental values and predictions from Models 1 and 2

Model	Prediction for 1% [MPa]	Experimental result 1% (mean) [MPa]	Prediction for 2% [MPa]	Experimental result 2% (mean) [MPa]	Prediction for 4% [MPa]	Experimental result 4% (mean) [MPa]	Prediction for 6% [MPa]	Experimental result 6% (mean) [MPa]
M1a	36.67	41.15	35.63	37.60	34.88	33.59	33.35	32.82
M1b	34.42		33.12		31.82		29.15	
M1c	36.30		36.02		35.75		35.18	
M1d	36.52		35.17		33.82		31.05	
M2a	38.29		38.23		37.98		37.89	
M2b	36.18		36.21		36.09		36.19	
M2c	37.65		37.60		37.37		37.29	
M2d	38.59		38.58		38.40		38.42	

Observing Table 5.1, it is evident that Model 1d (Eq.5.11) had the best-fit, at least when it came down to those specific results. Models 1a and 1b also resembled the overall trend of decrease in strength with increased volume replacement whereas all Model 2 version displayed little to no movement for various volume replacements and thus needed more setting up compared to Model 1 designs. By using the key points mentioned in Section 5.3, the results from Models 1 and 2 and a new tactic based on different input fields, Model 3 was developed:

$$CS(7) = 40.15 - 0.062 \cdot WA + 0.0234 \cdot \beta_{brick} + 0.0308 \cdot \beta_{tiles} - 0.335 \cdot \beta_{wood} - 0.1472 \cdot \beta_{hdpe} - 2.379 \cdot \beta_{eps} - 0.0532 \cdot \beta_{gypsum} - 0.0021 \cdot \beta_{sc55} + 0.00237 \cdot \beta_{sc39} - 0.00362 \cdot \beta_{lq} \pm 2.34 \quad (5.16)$$

where β_i denotes the volume fraction of each contaminant [kg/m^3] including SC39, SC55 and LQ recycled aggregates and WA is in [%].

Based on experimental results and Model 3, several graphs were plotted for a more detailed analysis of the results:

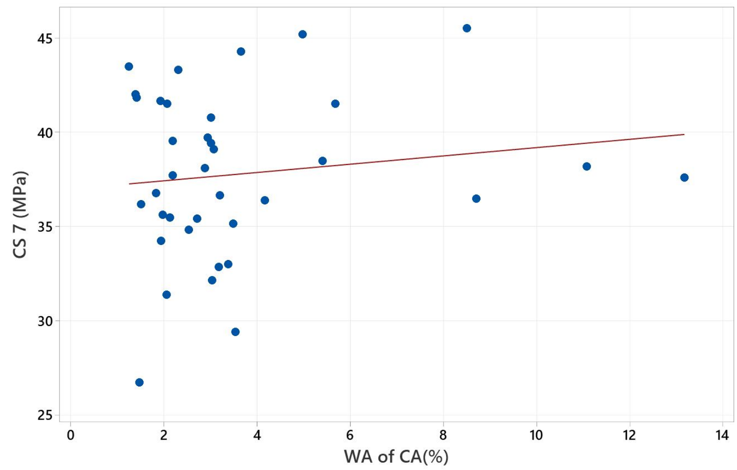


Figure 5.1: Model 3 relation between compressive strength [MPa] and WA[%]

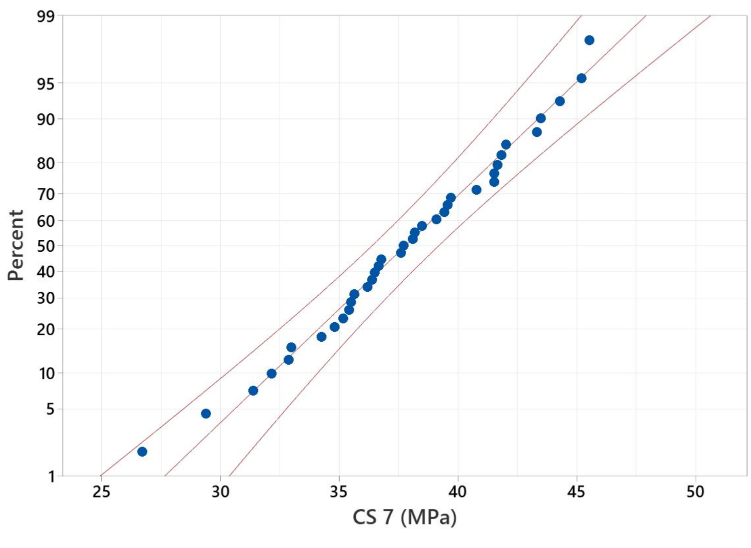
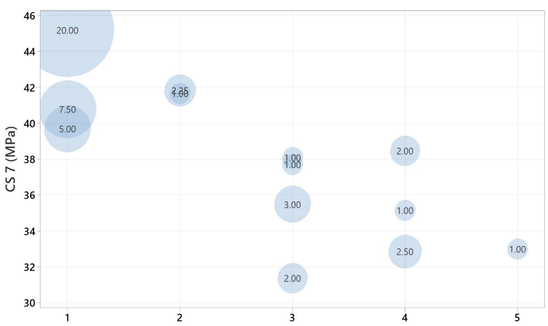
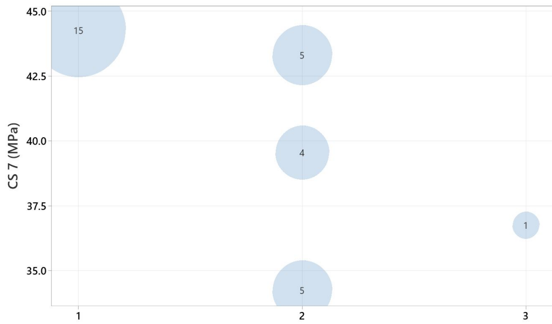


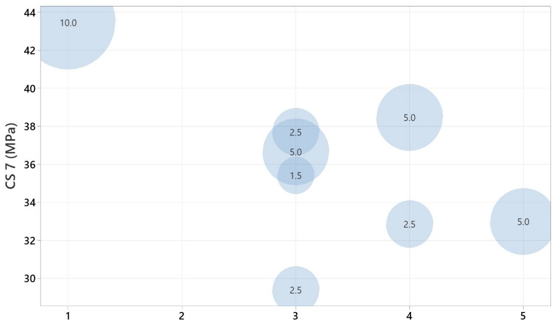
Figure 5.2: Probability plot of 7-day CS. Mean = 37.77MPa; StDev = 4.36MPa; P-Value = 0.94; AD = 0.163



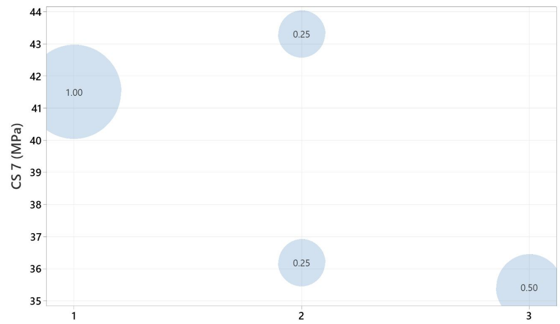
(a) Brick



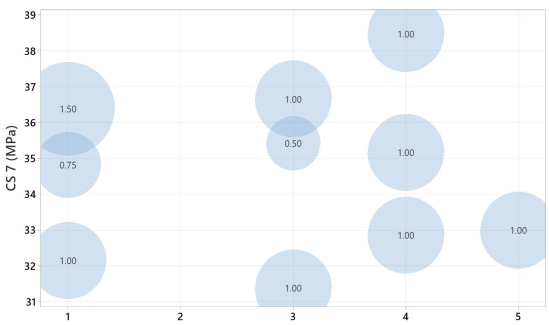
(b) Tiles



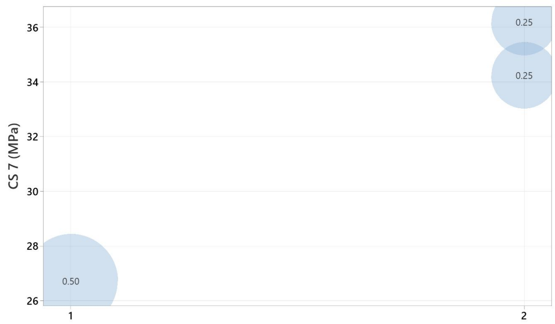
(c) Glass



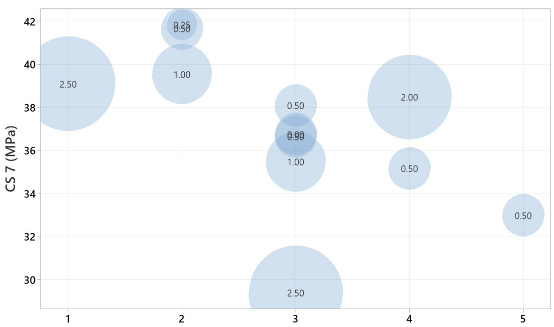
(d) Mineral fibers



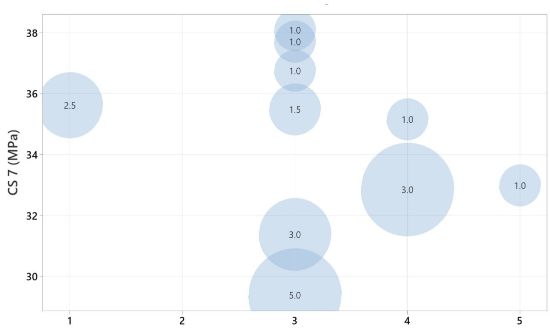
(e) Wood



(f) EPS Foam

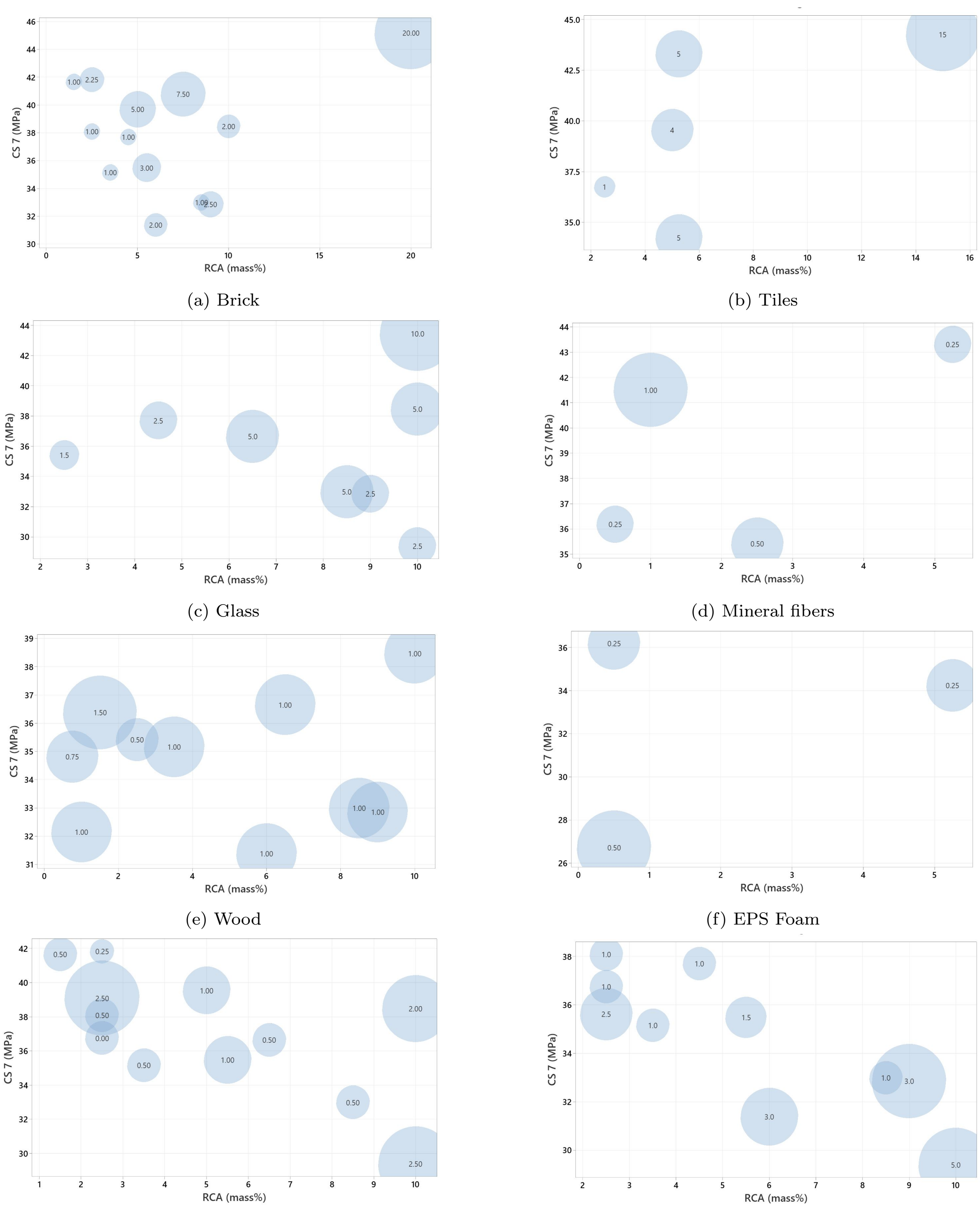


(g) Gypsum



(h) HDPE Plastic

Figure 5.3: Relation between the 7-day strength and the inclusion of a particular contaminant in the recipe alone or in combination with more contaminants



(a) Brick (b) Tiles (c) Glass (d) Mineral fibers (e) Wood (f) EPS Foam (g) Gypsum (h) HDPE Plastic

Figure 5.4: Relation between the 7-day strength and the inclusion of a particular contaminant in the recipe as a mass replacement of NA

The bubbleplots in Fig. 5.3a to 5.3h display how each contaminant affected the CS of concrete when alone or with other contaminants in the mix. The size of each bubble corresponds to the fraction replacement of NA relative to all fractions used in the research. For example brick, even in larger quantities (up to 20%) resulted in high CS when was the only contaminant.

Upon including more contaminants, even lower amounts of brick (2.5%) manufactured concrete with less strength than reference. However, this came to prove that the brick as an individual contaminant only aided the development of early CS and the addition of other contaminants made the concrete weaker. A very similar trend was observed within the ceramic tiles dataset and it was very clear that for constant fraction of tiles (5%) and one more contaminant present (n=2), the difference in CS was notable, ranging from 34.42 to 43.31MPa 7 days after casting. This difference emerged only due to the type of the other contaminant – EPS foam contributed to the lower limit while mineral fibers improved the strength of the sample. Glass also resembled bricks and tiles and it was obvious that this material was not one of the main reasons for poor RAC at least when talking about its compressive strength. EPS foam was the opposite of all three materials mentioned above – as the only contaminant present it directly affected the CS in a very negative way, while lower amounts even in presence of more contaminates resulted in better CS. The rest of the materials did not provide trends as conclusive and obvious as the ones described above and their influence was more complicated and less straightforward as the rest.

The next figure focuses on the relation between the 7-day CS and the NA mass replacement of each contaminant. The y axis depicts the overall mass percentage replaced by all contaminants present in the mix, while the bubble size denotes the individual contribution of a given contaminant to this percent. This set of plots only serves as further proof of all reported so far, only accounting for the actual contents each contaminant takes rather than the number only.

The final CS model was derived entirely based on CS Model 3 and the changed input of the latest WA model. The logical operations follow CS Model 3 identically, only difference came from the additional/changed terms as part of the user input of the model. The CS is estimated as depicted below:

$$\begin{aligned} CS(7) = &-245 - 0.793 \cdot WA + 206.20 \cdot \psi_{NA} + 18.49 \cdot \psi_{brick} + 21.25 \cdot \psi_{tiles} \\ &- 1.19 \cdot \psi_{wood} + 80.00 \cdot \psi_{hdpe} + 4.22 \cdot \psi_{fibers} + 3.73 \cdot \psi_{gypsum} + \\ &+179.80 \cdot \psi_{glass} - 22577 \cdot \psi_{eps} + 24.30 \cdot \psi_{sc} + 33.20 \cdot \psi_{lq} \pm 2.2MPa \end{aligned} \quad (5.17)$$

where ψ_i [%] denotes the mass contribution of each component i, WA is in [%].

Once again returning to previous discussions in Section 4.5, it was communicated that plastics and wood had a detrimental effect towards strength, while most other contaminants had neutral or even carried slightly beneficial upshots. Examining Eq.5.17, it is clear that wood and EPS are reflected as expected with EPS being the worst possible ingredient in a design. The positive contribution of HDPE comes as a surprise, however due to the restricted addition of plastics, its overall effect would not be very significant. Despite this limitation, it is odd that HDPE is disclosed with a positive sign and it is obvious that large amounts will lead to discrepancies between practice and model. All other materials are registered to carry similar positives towards the strength with fibers being the only outlier. The higher weight sustained by the fibers could be embraced by their limited availability, however in case more fibers are used, then the results will be similar to the aforementioned issues with HDPE. Nevertheless, for expected quantities as prescribed in this paper, the model should work fine. Additionally, the statement that the number of contaminants might be a key factor as derived from experiments turned out to be less important in the modelling phase. In the end, none of the equations utilize this as an input variable. In order to properly describe it, a wider database has to be obtained before any clear difference could be distinguished and accurately exhibited in the model. At this stage, it was proven more efficient to keep this factor out of the model until more information becomes available.

The information conveyed in this chapter, accompanied by Eq.4.2, completed the full dataset required for all desired outputs of the model. In the end, the user was able to provide the content of all present contaminants in various units and the model was able to predict the WA of the coarse aggregates, the compressive strength after 7 and 28 days and how does this RAC compared to conventional concrete with raised content of air voids. A layout of the initial interface, linking all input parameters with the desired outcome is presented in Fig. 5.5. Please note that this version was yet to be validated and possibly altered so that it accommodated larger set of samples. Moreover, this model was not a general model, i.e. it was only suitable for recycled concretes with w/c equal to 0.45 and cement CEM III/A 52.5R. The Matlab scripts for the GUI (graphical user interface) and calculation file are presented in Annex E. In the figure, a random non-existing sample was chosen as input with purely visual purposes.

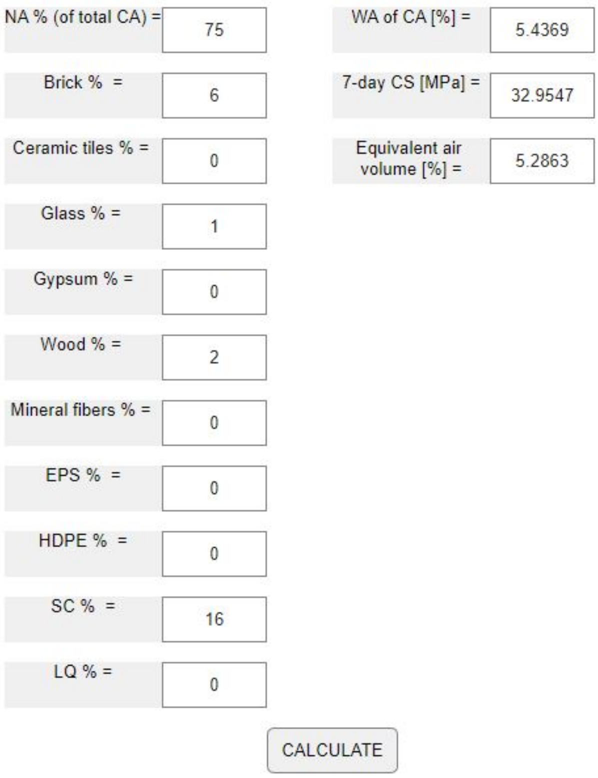


Figure 5.5: Interface of the final model prior to validation. No limits or restrictions are applied, the user has to take care when estimating the correct amounts of each material.

Based on all information communicated in this chapter, the logical next step was to put all models to test with new samples, examining both the WA and CS aspects. The next section deals with choosing suitable samples, presents the results and compares those with all predictions derived from the developed models.

5.5. Validation

In total 9 samples were prepared and tested for their water absorption properties in identical manner as previously in the research. The samples were tailored based on the availability of certain materials in the laboratory and the amounts added were randomized, only aiming at differing WA predictions. Furthermore, those samples also featured SC and LQ aggregates in combination with other contaminants unlike previous experiments. The aim of this was to expand the model's boundaries and to enhance its performance. In Table 5.2 below all validation samples are outlines, together with the model predictions and the actual experimental values:

Table 5.2: Comparison between model prediction and experimental WA values for validation samples V1 to V9

Label	Description	Model [%]	Actual [%]	Linear diff. [%]
V1	NA 80% + Brick 13% + Glass 7%	3.84	2.72	1.14
V2	NA 85% + Gypsum 6% + HDPE 5% + Brick 4%	6.46	5.96	0.50
V3	NA 90% + Glass 7.3% + Brick 2.7%	1.64	1.02	0.62
V4	NA 82% + Glass 10% + Wood 4.5% + HDPE 3.5%	5.05	4.23	0.82
V5	NA 97.8% + Brick 1.4% + Wood 0.8%	2.73	1.62	1.11
V6	NA 80% + LQ 20%	2.80	2.56	0.24
V7	NA 60% + SC55 40%	5.35	4.73	0.62
V8	SC55 64% + NA 35% + Wood 1%	8.45	8.37	0.08
V9	Brick 66% + Glass 29% + HDPE 5%	13.92	11.98	1.94

Prior to any analysis, it should be mentioned that the initial accuracy of the model was defined as ±0.6% as illustrated by Eq.5.6. Based on this and the fact that this project is mainly targeting WA below 5%, it was assumed that the model accuracy could be adjusted as described in Table 5.3:

Table 5.3: Quality of predictions based on standard deviation of model and prediction values

Prediction range	Successful if	Good if	Unsatisfactory if
Up to 5%	$\leq 1\sigma$	1-2σ	$>2\sigma$
5 to 10%	$\leq 2\sigma$	2-3σ	$>3\sigma$
Above 10%	$\leq 3\sigma$	3-4σ	$>4\sigma$

Relying on the information above, it is evident that only sample V1 falls in the unsatisfactory predictions category. Samples V2, V6, V7 and V8 all provide successful predictions, while the rest of the specimens (V3, V4, V5, V9) correspond to good predictions, most cases providing very close values to the successful prediction limit. It is also very important to note that the model did well in predicting values for non-standard samples such as V9 which is mainly comprised of bricks and glass, rather than NA. Despite the difference of almost 2%, it is key that the model properly distinguished the categorical WA of above 10%. In addition, samples with notable amounts of recycled aggregates (SC, LQ) such as V6, V7 and V8 were very accurately forecast despite the lack of similar samples in previous tests. Overall, the WA segment of the model was deemed satisfactory given that the arising differences for most samples were insignificant compared to practical purposes and green light was given to the CS component.

Parallel to the WA validation and prior to CS tests, additional tests were performed on the role of cement type. The purpose of this experiment was to diversify the model by including several cement types to the research. Below in Table 5.4, the compressive strength of concretes utilizing three cement types are compared to the control concrete made with CEM III 52.5 R:

Table 5.4: Effect of cement type on compressive strength of concrete

Label	Description	7 days strength [MPa]	Ratio /REF
C-REF	CEM III 52.5	42.02	1.000
C1	CEM III 42.5	40.25	0.958
C2	CEM I 52.5	46.57	1.108
C3	CEM I 42.5	30.01	0.714

According to the results presented above, the relation between the three additional cements and CEM III 52.5 was estimated in the form of coefficients (last column of Table 5.4). These coefficients were then used to broaden the model. In addition, strength was also measured after 28 days for the above-mentioned specimens and the relations to reference were confirmed.

In summary, 13 extra samples were designed and evaluated for their compressive strength after 7 days. 7 samples featured combination of contaminants in random amounts and numbers without the inclusion of RCS, while the other 6 samples included crushed sand concrete. Table 5.5 describes all aforementioned samples along with their expected and actual strengths.

Table 5.5: Comparison between model prediction and experimental CS values for validation samples V10 to V22

Label	Description	Model [MPa]	Actual [MPa]	Diff. [MPa/%]
V10	NA 97.5% + Brick 2% + Wood 0.5%	38.59	36.42	2.17/+5.62
V11	NA 89% + Brick 10% + Glass 1%	41.45	40.54	0.91/+2.20
V12	NA 98% + Wood 1% + HDPE 1%	34.36	33.75	0.61/+1.78
V13	NA 88% + Brick 10% + Glass 1% + HDPE 1%	39.40	41.16	1.76/-4.47
V14	NA 97% + Gypsum 1% + Wood 1% + HDPE 1%	33.85	26.19	7.66/+22.63
V15	NA 88.8% + Brick 5.5% + Glass 3.6% + HDPE 2.1%	37.85	36.90	0.95/+2.51
V16	NA 95.6% + Brick 2.1% + Gypsum 1.2% + Wood 1.1%	35.50	34.76	0.74/+2.08
V17	SC 100%	38.30	37.42	0.88/+2.31
V18	NA 60% + SC 40%	39.31	39.22	0.09/+0.23
V19	NA 59.9% + SC 40% + Wood 0.1%	38.92	37.30	1.62/+4.16
V20	SC 60% + NA 39.9% + Wood 0.1%	38.91	36.90	2.01/+5.17
V21	SC 60% + NA 37.9% + Brick 2% + Wood 0.1%	39.01	40.32	1.31/-3.36
V22	NA 59% + SC 30% + Brick 10% + Glass 1%	41.44	42.10	0.66/-1.60

Judging by the results, the model predicted most results reasonably well. In the last column of the table above the difference between the prediction and actual strength could be seen, indicating that with the exception of sample V14, the rest of the projections come in very close proximity of the reality. Another important aspect is the standard deviation of the prediction, which is 2.2MPa as stated previously. If this deviation is taken into account, it is evident that all samples except V14 fall within the predefined boundaries of the model. This denotes a very successful validation of the predictive model and proves that such model could indeed be implemented within the construction industry. Looking at the problematic sample, V14, which utilizes a relatively small amount of contaminants – 1% of wood, gypsum and HDPE (each), the prediction is off by 7.66MPa from the achieved strength after 7 days. Despite the seemingly large difference, it was believed that if more specimens of the same samples are cast, then both values would converge. Furthermore, wood as one of the main contributor towards the poorer compressive strength of recycled concrete has a significant role in the mix design. This said, the actual strength of RAC is very sensitive to the amount of wood present in the mix and thus even the smallest difference between the design and the actual amount of material present in the concrete could make a notable variance.

What is more, a clear trend of overestimation of the results is observed, with only V13, V21 and V22 providing contrasting numbers. This is the less preferred option compared to underestimation for obvious reasons, however it could easily be remedied by introducing a safety factor within the model's description. It is evident that in most cases, the overestimation is between 2 to 5%, so a 3% strength reduction rate (average) could be applied to all predictions. The underestimation observed in 3 of the samples was always under 4.5% which translated to below 1.8MPa difference in this target range – meaning that no further changes had to be done to incorporate this variation. The reduction due to the overestimation was done prior to releasing the final model and could be seen in the conclusive chapter of this research. Introducing this strength reduction will not affect the underestimated values in a negative way since the differences are not that significant in the first place and also any variance due to the contamination of RAC would be taken into account.

Based on the information stated in the previous paragraph, the new equation describing the compressive strength at 7 days would take the following shape:

$$\begin{aligned} CS(7) = 0.97\cdot\alpha_{cem}(&206.2\cdot\psi_{NA} + 18.5\cdot\psi_{brick} + 21.3\cdot\psi_{tiles} - 1.2\cdot\psi_{wood} + 80.0\cdot\psi_{hdpe} + 4.2\cdot\psi_{fibers} \\ &+ 3.7\cdot\psi_{gypsum} + 179.8\cdot\psi_{glass} - 22577.0\cdot\psi_{eps} + 24.3\cdot\psi_{sc} + 33.2\cdot\psi_{lq} - 0.78\cdot WA - 245.0) \\ &\pm 2.2MPa \end{aligned} \tag{5.18}$$

where ψ_i [%] denotes the mass contribution of each component i, WA is in [%], α_{cem} is the correction factor taking into account the cement type used.

Reverting to Fig.4.2, the strength of the samples in question could be evaluated using the aforementioned equation. The model values were imposed over the original experimental data presented in the figure and the results are evident in Fig. 5.6. On the plot, the green markers depict the model predictions and these values are connected to the experimental ones with black vertical lines. The lines illustrate the difference between the predictions and actual measured strength. It is clear that the model underestimated the strength of this set of samples (S1 to S18) in the majority of the cases. Furthermore, it is also apparent that trends such as the increasing strength with increasing WA of CA (as displayed by the yellow markers on the graph) could not be properly matched. Nonetheless, the model delivered a very good prediction in terms of range when taking into account the predefined deviation. In addition to this, the fact that most specimens develop a higher strength than the predicted number was also a positive aspect conveyed by the model. Moreover, it is suggested that there are at least 3x times more data points than coefficients in a statistical equation upon fitting experimental data. In this case there are 36 base data points and 11 coefficients as outlined by Eq. 5.18 which satisfied the rule of thumb. Overall, the equation didn't emphasize certain categories or materials better than others; there was a constant trend of underestimation observed predominantly indifferent of the number or type of contaminants present. An important feature however would be the fact that below 3-3.5% WA, there were a number of very close predictions, 3% or less in terms of accuracy ($\leq 1MPa$). Actually, almost 43% of the samples which fell in this WA range had their strength properly predicted by the model. None of the ones above 3.5% WA had similar results. This could prove useful since many standards limit the WA around these values, so any discrepancies coming from samples with larger WA carry less importance.

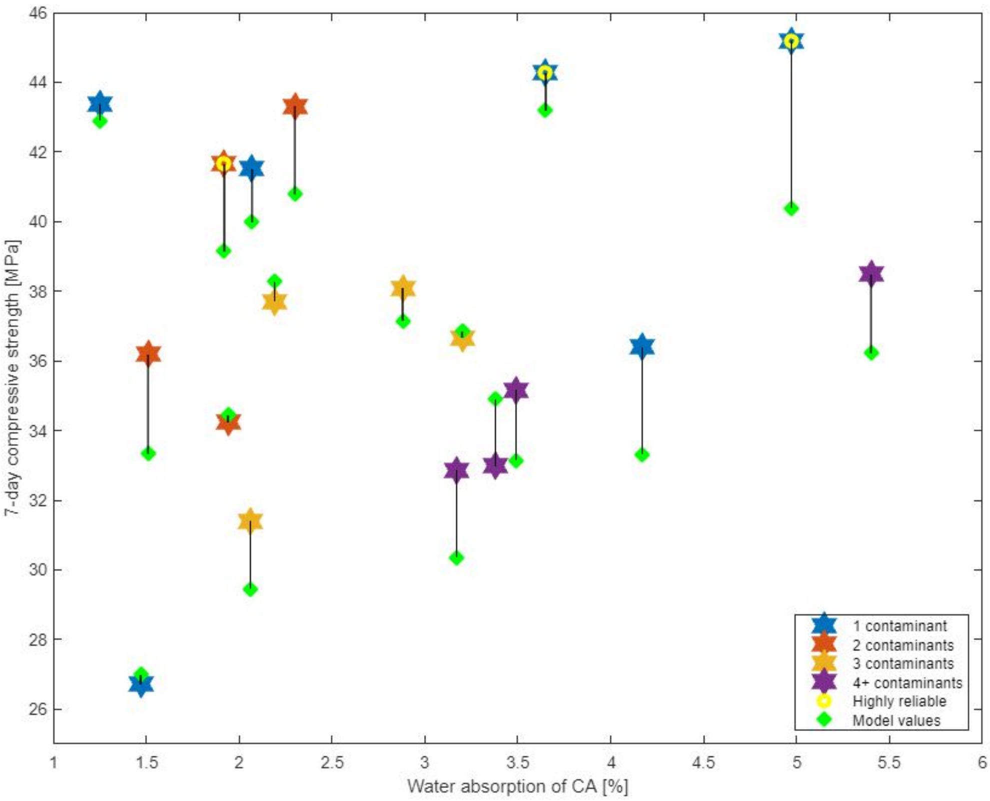


Figure 5.6: Comparison of model predictions to experimental values for samples S1 to S18

However, in attempt to further optimize and simplify the relation, it was decided that some materials could be combined due to their similar behaviour. Judging by previous comments and results, bricks and tiles (br/ti) were the obvious choices, as well as sand concrete and low quality aggregates (ra). The effort to merge these descriptors is arrayed in the equations below. Note that there are two sets of equations, each set describing the 7-day or 28-day strength using two approaches. The first viewpoint makes use of the new parameters, which are two less than the initial equation, all in linear form. The second method utilizes the squared term of the combined value of bricks and tiles in order to investigate if this would better describe certain samples. The equations are listed below:

$$CS(7) = 0.97 \cdot \alpha_{cem,7} \cdot (239.7 \cdot \psi_{NA} + 22.2 \cdot \psi_{br/ti} + 30.0\psi_{ra} - 3.6 \cdot \psi_{wood} + 123.1 \cdot \psi_{hdpe} + 4.2 \cdot \psi_{fibers} + 3.3 \cdot \psi_{gypsum} + 206.7 \cdot \psi_{glass} - 21644.0 \cdot \psi_{eps} + 0.18 \cdot WA - 293.0) \pm 1.9MPa \tag{5.19}$$

$$CS(7) = 0.97 \cdot \alpha_{cem,7} \cdot (244.0 \cdot \psi_{NA} + 22.0 \cdot \psi_{br/ti} + 0.23 \cdot \psi^2_{br/ti} + 30.5 \cdot \psi_{ra} - 3.6 \cdot \psi_{wood} + 128.8 \cdot \psi_{hdpe} + 4.2 \cdot \psi_{fibers} + 3.3 \cdot \psi_{gypsum} + 210.5 \cdot \psi_{glass} - 21720.0 \cdot \psi_{eps} - 0.17 \cdot WA - 299.0) \pm 1.9MPa \tag{5.20}$$

$$CS(28) = 0.97 \cdot \alpha_{cem,28} \cdot (144.0 - 62.5 \cdot \psi_{NA} - 3.8 \cdot \psi_{br/ti} - 8.2 \cdot \psi_{ra} - 6.6 \cdot \psi_{wood} - 354.0 \cdot \psi_{hdpe} + 0.9 \cdot \psi_{fibers} - 2.8 \cdot \psi_{gypsum} - 53.6 \cdot \psi_{glass} - 32561.0 \cdot \psi_{eps} - 0.22 \cdot WA) \pm 2.0MPa \tag{5.21}$$

$$CS(28) = 0.97 \cdot \alpha_{cem,28} \cdot (151 - 68.1 \cdot \psi_{NA} - 3.7 \cdot \psi_{br/ti} - 0.21 \cdot \psi_{br/ti}^2 - 8.9 \cdot \psi_{ra} - 6.7 \cdot \psi_{wood} - 361.0 \cdot \psi_{hdpe} + 1.0 \cdot \psi_{fibers} - 2.9 \cdot \psi_{gypsum} - 57.6 \cdot \psi_{glass} - 32533.0 \cdot \psi_{eps} - 0.21 \cdot WA) \pm 2.0MPa \quad (5.22)$$

where ψ_i [%] denotes the mass contribution of each component i, WA is in [%], $\alpha_{cem,i}$ is the correction factor (7 or 28 days) taking into account the cement type used.

Despite the enhanced ratio of data points to coefficients, Eq. 5.19 and 5.20 provided worse results than the already established relations. On the other hand, Eq. 5.21 and 5.22 supplied almost identical values to the previously suggested rule that approximately 72% of the strength is achieved at the seventh day compared to the twenty-eighth. Nevertheless, in attempt to diminish any discordance between all three equations estimating the strength after 28 days, it was decided that the mean value of all should be taken as the prediction. Thus, this is the value shown in the model illustrated in Fig. 5.7. In terms of the 7-day equations and the effect of combined terms, no clear advantage was observed in either of the versions, both providing significant errors for all tested specimens. Therefore, Eq. 5.18 was kept as the working relation, also used in the model. Regardless, these equations should be recorded with the purpose of aiding any future studies in the field.

All in all, the 22 samples part of the validation phase of the project reinforced the predictive model and proved that such a model could be introduced. Another positive feature of such type of model is that it will get better and better the more samples are used establish and validate it. In other words, if such project is implemented in the industry, its accuracy is going to improve with time which is great news. Further optimization and globalization aspects could be added to the model at later stages, yet the current version portrays the foundation of a very significant line of work for the near future.

After the model was successfully validated (WA and CS) and the cement tests were performed, the interface and final functionality of the design were altered and the latest version is depicted in Fig. 5.7:

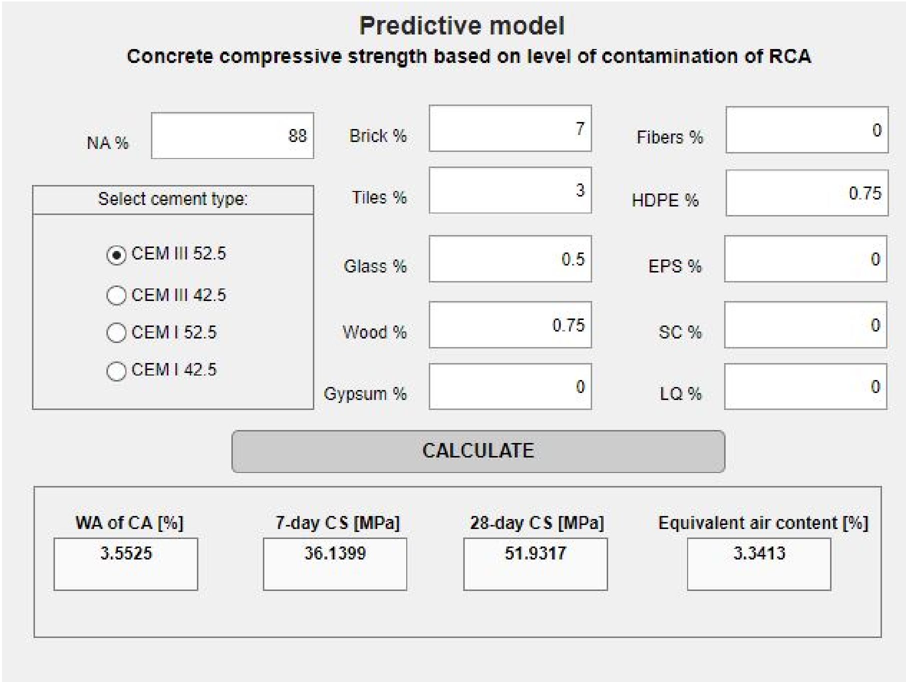


Figure 5.7: Interface of the final version of the predictive model. Matlab script could be found in Annex E.

5.6. Chapter summary

This chapter focused on one of the main deliverables of this project – the predictive model which ties all experimental components of the study together. It was shown how the model was initiated, designed and optimized and in the end validated by another set of experimental data. Overall, the development of the model was deemed successful which is encouraging for the advancement of the sustainable practices in the construction industry.

6 Conclusions and recommendations

In this conclusive chapter of the study all major findings are presented in a systematic and organized manner. The opening section backtracks to the core of the project – the aims, objectives and the research questions which finally receive answers. Following is the summary in the form of tables, equations and conclusive remarks which represents the key facts extracted from the bulk of information. In the end, recommendations for future work based on the aspects observed throughout this study are listed and their origin is retraced to its initial source.

6.1. Reverting to the project's idea frame

Going back to the aims and objectives of the research, it can be seen that all points were met during the project's execution. In total, 112 samples were prepared and tested for their water absorption potential. The specimens included individual materials such as natural aggregate, bricks, glass and so on, as well as combinations of two or more materials. Through random sampling method and critical evaluation at certain stages, a total of 69 samples were designed and over 250 specimens were cast, cured and crushed in order to evaluate their compressive strength capacity. All achieved results were compared with reported values from literature and collected together in order to build a predictive model relating the constituents of the coarse aggregate portion of a concrete mix design with the expected water absorption of the fraction in question, along with the strength of the design. The model was validated and optimized with more tests – 22 samples already accounted for in the above totals. Along the duration of the project, it was deduced that the water absorption of the coarse aggregates was not the major contributor towards the strength development of the recycled concrete as it was believed initially, but rather the type and amount of contaminants present in the mix played the key role when it came down to the most important mechanical property of concrete.

Examining the research questions set in the commencing phase of the project, in this paragraph are the answers to each one as deduced with the help of all data obtained throughout the study. It was concluded that the water absorption of recycled aggregate was not a linear function of the content of relevant constituents within the fraction. Generally, this relation was linear only when a single contaminant was present alongside the natural aggregate, which does not properly describe the recycled aggregate in reality. For the contaminants chosen in this research, it was proven that brick, ceramic tiles, gypsum, wood, HDPE plastic and mineral fibers follow a linear pattern in terms of WA of samples containing natural aggregate and the contaminant in question, while glass and EPS foam resulted in more complex behaviour compared to other materials. Upon looking at mixes with more than one contaminant present, it was seen that usually the predefined linear range was not sufficient in providing a close prediction. In fact, the theoretical range often yielded values lower than reality or in other words it underestimated the water absorption of recycled aggregate. This statements held true for all WA values scrutinized in the study and were not limited to values below or equal to 5%. It was also confirmed that recycled aggregates with identical water absorption did not lead to concrete design with comparable compressive strength. There was a multitude of examples where samples with very close experimentally evaluated water absorption values delivered significantly different strength after 7 and 28 days. This only proved that the water absorption of coarse aggregate is not the main contributor towards the compressive strength and by itself is not sufficient to describe this property of concrete. Furthermore, after the modelling phase, it was demonstrated that water absorption could be accounted for based on the composition of a given sample. The deviation from the prediction and the actual value was also implemented in the model which ultimately made the model's core mechanics a linear function of all constituents' properties. Looking beyond the water absorption of coarse aggregate portion, it was manifested that the type of contaminant present within the recycled aggregate made the most significant difference when it came down to mechanical strength of recycled concrete. Additionally, the volume that the contaminants took up from the natural aggregate affected the strength as well, along with the number of different materials present in the mix design. Overall, only samples with up to two contaminants resulted in comparable strength as conventional concrete, while the larger number of ingredients led to notable differences in most cases. As stated, the type of contaminant had the greatest influence of the strength and it was shown that wood and plastics brought the largest losses, while bricks, tiles and glass governed neutral to even slightly positive performance of concrete after 7 and 28 days. For this reason, it was indicated that if natural aggregate is replaced partially by recycled concrete aggregates, it could be beneficial to the strength of concrete, however more experiments have to be performed on this aspect in order to fully prove this point.

6.2. Major discoveries and breakthroughs

Generally, the most important findings of this study could be collected and arranged into a few concise segments. Starting with Table 6.1, all contaminants part of the research were divided into several main groups and their overall effects on the water absorption of CA, compressive strength of the resulting concrete and any long term effects that are likely to occur given the obtained evidence were recorded. This table could also be used as a check point in further research and could be expanded for additional contaminants.

Table 6.1: Summary table with main effects of contaminants towards recycled concrete

Group	Contaminants	Effect on WA	Effect on CS	Long term effect
Aggregate-like materials	Bricks, tiles, RSC	Increase WA significantly and should be generally kept under 20-30% mass (30-35%vol) replacement of NA in order to fulfill current standard requirements; 40-45%wt (70-80%vol) for recycled sand concrete aggregates	Neutral to slightly positive overall if kept within the WA limiting concentrations	Durability might be an issue; overall lighter concrete which is beneficial in terms of transportation and pollution; higher water absorption could improve hydration process; linear drop in strenght upon increase of RSC to NA ratio
Plastics	HDPE, EPS	Insignificant contribution towards the WA of recycled concrete; however larger volumes could interfere with the rest of the constituents' ability to absorb any water	Highly negative effect; volume replacement of NA should be limited from 8 (denser) to 16% (lighter plastics) if CS drops of 15% or less are expected	Lighter material; the inability of plastics to absorb any water could prevent the proper cement hydration and could lead to less strength development after 28 days
Glass	Soda-lime glass, recycled window glass	Lead to larger deviation in WA without actually affecting it positively or negatively	Up to 10% of NA mass replacement has zero effect towards the CS, larger amounts are not desired	If used within prescribed amounts, all upsides of lighter concrete will be utilized; tendency to bond well, however the water release with time could be limited due to the low individual absorption
Fibrous inorganic materials	Mineral fibers	Worsen the WA of the mix and for this reason should be kept below 1.5% of NA mass	For the acceptable WA range amounts, fibers tend to provide beneficial results	Similarly to ceramics, the higher absorption could improve the cement hydration, however durability could be a problem
Timber	Hardwood, softwood	Elevates the WA and acceptable values are achieved up to 2% NA mass (7.5%vol) replacement	Negative effect on the strength and amounts should be further limited to 1% mass replacement if CS drops of less than 15% are desired	Results of samples containing wood worsen with time which should indicate that after 90 days there might be a sharp descend in strength; lighter end material

From previously disclosed data and analysis it was evident that some materials such as bricks, ceramic tiles, glass and possibly mineral fibers had a positive overall effect on the compressive strength of concrete upon replacing a portion of the natural aggregate. While most of the materials listed above had been tested for a range of values, fibers were only included in limited amounts according to C&DW composition in reality. In other words, in order to prove whether their effect is positive overall, a greater range of samples has to be investigated. As it stands, fibers in acceptable amounts indeed led to increase in strength and were not found to bring issues in short term. Consequently, for these materials it is not possible to state a replacement amount which is comparable with inclusion of air within the mix since air bubbles lead to lower strengths. Therefore, in Tables 6.2 and 6.3 these contaminants are emitted and only the ones which bring strength reduction to recycled concrete are equated to the corresponding air inclusion percentages. Both tables contain the same information, with the difference that 6.2 presents the mass replacement data, while 6.3 outlines the volume replacement equivalents.

Table 6.2: Equivalent air content in concrete related to mass inclusion of certain contaminants

Air in concrete	Equivalent mass replacement of NA				
	Wood	Gypsum	HDPE	EPS	RSC
1.5%		0.5%	0.1%		28-42%
2.0%	0.25%	2.0%	0.5%		
2.5%	0.5%	3.7%	0.9%		55.6%
3.0%		5.4%	1.3%	0.1%	
3.5%		7.0%	1.8%		
4.0%	1.0%	8.7%	2.2%		
4.5%		10.4%	2.5%	0.2%	
5.0%	1.5%	12.1%	3.0%		

Table 6.3: Equivalent air content in concrete related to volume inclusion of certain contaminants

Air in concrete	Equivalent volume replacement of NA				
	Wood	Gypsum	HDPE	EPS	RSC
1.5%		1.8%	0.3%		50-75%
2.0%	1.0%	7.2%	1.4%		
2.5%	1.9%	13.2%	2.6%		100%
3.0%		19.3%	3.7%	12.7%	
3.5%		25.1%	5.1%		
4.0%	3.9%	31.1%	6.3%		
4.5%		37.2%	7.1%	25.4%	
5.0%	5.8%	43.3%	8.6%		

To summarize the key discoveries, below the three core equations governing the predictive model are listed:

$$WA = 1.9 - 0.4 \cdot \psi_{NA} + 1.05 \cdot \psi_{brick} + 0.91 \cdot \psi_{tiles} + 1.17 \cdot \psi_{wood} - 2.2 \cdot \psi_{hdpe} + 0.84 \cdot \psi_{fibers} + 0.98 \cdot \psi_{gypsum} + 0.78 \cdot \psi_{sc} + 0.77 \cdot \psi_{lq} \pm 0.4\% \tag{6.1}$$

$$CS(7) = 0.97 \cdot \alpha_{cem}(206.2 \cdot \psi_{NA} + 18.5 \cdot \psi_{brick} + 21.3 \cdot \psi_{tiles} - 1.2 \cdot \psi_{wood} + 80 \cdot \psi_{hdpe} + 4.2 \cdot \psi_{fibers} + 3.7 \cdot \psi_{gypsum} + 179.8 \cdot \psi_{glass} - 22577 \cdot \psi_{eps} + 24.3 \cdot \psi_{sc} + 33.2 \cdot \psi_{lq} - 0.79 \cdot WA - 245) \pm 2.2MPa \quad (6.2)$$

$$Air\% = \frac{41.612 - CS}{1.6377} \quad (6.3)$$

where ψ_i [%] denotes the mass contribution of each component i, WA is in [%], α_{cem} is the adjustment factor [-] for various cement types as prescribed in Table 5.4, $Air\%$ is the equivalent extra air content based on a given compressive strength $(CS, [MPa])$.

The mass contribution of a component is calculated as follows:

$$\psi_i = WA_i * m_i \quad (6.4)$$

where $_i$ is the individual water absorption of material i [%] and m_i is the mass portion this material takes from the coarse aggregate fraction [%].

To recap, the above equations were the main outcome of the modelling phase, in addition to the 28-day strength prediction method which utilized Eq. 5.21 and 5.22, along with the finding that 72% of the 28-day strength was achieved after 7 days. In conclusion, the data points used to develop the equations were 36 and the resulting coefficients were always less than one third of this number, fulfilling the requirement governing statistical equations upon fitting experimental data. Moreover, the model was able to predict values in the vicinity of the actual strengths, abiding by the allowable deviation included within the equations. In addition, the model's accuracy was even better when samples with WA of around or less than 3.5% were assessed, compared to samples with higher WA. Overall, the trends observed during the experimental part of this project were channeled to the model as anticipated with some coefficients slightly deviating from the expected norm. This on one hand could also be problematic in case certain contaminants are used in quantities larger than the ones defined in this study. Lastly, not all of the observed experimental tendencies were properly perceived by the model - a vivid example was the increasing strength upon higher WA of CA which could not be replicated. However, since the WA did not prove to be one of the major factors affecting the strength, such trends could be possible, but also completely contrasting movements were as achievable. In the end, a prototype of a simplified model was also suggested, combining some of the similar contaminants, however further optimization of such model is required before reaching the accuracy and reliability of the validated model.

6.3. Recommendations for future work

Based on the progress and findings of the project, there were several aspects which could not be further investigated during the timeframe of this study and thus are mentioned in this paragraph as the starting points of any consequential work on the topic of recycled concrete. Firstly, the recycled concrete aggregates should be more thoroughly investigated for their influence on the newly made recycled concrete and variations such as sand concretes, conventional recycled concrete, low and high quality recycled aggregates should be used and compared accordingly. Furthermore, in order to generalize the predictive model even better, more cement types and different water to cement ratios should be implemented by performing similar tests as in this research and also putting the predictions utilizing all cements and ratios to the test. Possibly, more different plastics could also be evaluated so that all plastics could be grouped together as one type of contaminant and not having to separate each one. Similarly, more materials from the ceramics and bricks group could be examined such as roof tiles, calcium silicate bricks and many others. Following the topic of data expansion and model optimization, the more samples included in the model validation, the more accurate it is going to become. However, even more importantly, the model has to be assessed in real conditions and adjusted if necessary. After all, this project was aimed at proving a practical solution for the current trends in the construction industry, so it would be only suitable if indeed the model is implemented in a local factory to see what results it would yield. Finally, if the model proves to be successful in practice, then applying the sample differentiation aspect via any of the previously mentioned techniques would conclude one finished and ready to use product.

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A

Water absorption experimental data

Table A.1: Experimental values of all water absorption tests performed according to predefined procedure

Sample group	%replacement of NA	A	B	C	D	Specific Gravity [-]	Apparent specific gravity [-]	Water Absorption
NA - Reference	100%	1885.10	1267.60	1014.80	1001.00	2.52	2.61	1.38%
	100%	1710.40	1105.90	1013.50	999.60	2.44	2.53	1.39%
	100%	1946.40	1332.80	1014.30	999.80	2.50	2.59	1.45%
	100%	2039.90	1383.40	1013.40	999.20	2.80	2.92	1.42%
	100%	1890.20	1250.40	1017.30	1004.00	2.66	2.76	1.32%
Brick	1%	1885.80	1244.70	1020.80	1009.60	2.66	2.74	1.11%
	1%	1997.70	1356.70	1012.90	999.50	2.69	2.79	1.34%
	2.50%	1936.30	1284.60	1026.00	1007.60	2.69	2.83	1.83%
	5%	1908.50	1248.50	1029.20	999.80	2.71	2.94	2.94%
	5%	1993.80	1369.20	1023.50	997.60	2.50	2.67	2.60%
	10%	1701.90	1101.80	1036.50	1002.20	2.30	2.49	3.42%
	20%	1970.00	1341.80	1056.10	1006.10	2.35	2.66	4.97%
	20%	2378.80	1790.50	1050.50	998.80	2.16	2.43	5.18%
	100%	1700.60	1383.90	579.50	496.60	1.89	2.76	16.69%
	100%	1545.80	1224.60	579.70	497.90	1.93	2.82	16.43%
Glass	0.25%	1965.30	1315.70	1021.30	1000.00	2.69	2.85	2.13%
	0.50%	2083.60	1450.80	1009.50	996.40	2.65	2.74	1.31%
	0.50%	1977.60	1349.50	1021.00	1000.70	2.55	2.69	2.03%
	1%	1686.50	1068.20	1021.50	999.20	2.48	2.62	2.23%
	1%	1712.70	1094.90	1016.40	1004.50	2.52	2.60	1.18%
	1.50%	2094.60	1450.80	989.30	978.50	2.83	2.92	1.10%
	2.50%	1890.70	1254.00	1017.50	998.50	2.62	2.76	1.90%
	2.50%	2033.50	1411.10	1013.00	998.20	2.56	2.66	1.48%
	5%	2387.60	1741.70	1018.80	997.10	2.67	2.84	2.18%
	5%	2230.60	1614.40	1012.00	999.50	2.53	2.61	1.25%
	100%	2060.80	1444.60	1017.50	999.50	2.49	2.61	1.80%
Wood	0.25%	1669.70	1047.50	1023.50	995.60	2.48	2.67	2.80%
	0.50%	1933.50	1297.60	1027.40	1001.10	2.56	2.74	2.63%
	0.75%	1877.20	1223.60	1024.00	998.70	2.70	2.89	2.53%
	1%	1986.10	1302.20	1030.80	1000.50	2.88	3.16	3.03%
	1.50%	2112.80	1494.00	1020.60	996.70	2.48	2.64	2.40%
	1.50%	2643.00	1931.90	1037.60	996.10	3.05	3.50	4.17%
HDPE Plastic	0.50%	1995.00	1335.30	1016.30	1001.50	2.81	2.93	1.48%
	1%	1866.90	1241.60	1015.40	1000.00	2.56	2.67	1.54%
	1.50%	2081.70	1494.00	1012.10	999.20	2.35	2.43	1.29%
	1.50%	1712.30	1080.80	1023.40	1002.40	2.56	2.70	2.09%
	2.50%	2017.20	1404.10	1015.90	996.30	2.47	2.60	1.97%
	5%	2139.20	1610.50	1020.00	995.10	2.03	2.13	2.50%
	15%	2305.30	1807.70	1030.90	998.20	1.87	1.99	3.28%

Sample group	%replacement of NA	A	B	C	D	Specific Gravity [-]	Apparent specific gravity [-]	Water Absorption
Gypsum	0.25%	2003.70	1386.00	1011.20	998.40	2.54	2.62	1.28%
	0.50%	1909.80	1269.10	1016.00	999.00	2.66	2.79	1.70%
	1%	1980.10	1349.70	1015.50	995.90	2.59	2.72	1.97%
	2.50%	1714.40	1070.20	1023.20	992.70	2.62	2.85	3.07%
	5%	2199.40	1548.10	1036.10	985.70	2.56	2.95	5.11%
	100%	1816.70	1570.60	772.30	388.40	0.74	2.73	98.84%
EPS Foam	0.050%	1983.10	1391.20	1012.50	996.30	2.37	2.46	1.63%
	0.075%	1830.70	1256.90	1015.30	994.50	2.25	2.36	2.09%
	0.100%	1936.90	1339.30	1017.80	997.20	2.37	2.50	2.07%
	0.125%	2233.70	1635.00	1023.40	999.40	2.35	2.49	2.40%
Mineral fibers	0.25%	2009.60	1401.50	1007.00	989.30	2.48	2.60	1.79%
	0.50%	1853.60	1259.20	1032.20	999.40	2.28	2.47	3.28%
	0.75%	2019.70	1410.30	1040.60	1002.40	2.32	2.55	3.81%
	1.00%	1702.90	1103.30	1047.40	1000.50	2.23	2.50	4.69%
	1.50%	2058.20	1450.80	1036.10	995.60	2.32	2.56	4.07%
	1.50%	2196.10	1585.60	1051.30	999.30	2.27	2.57	5.20%
	2.50%	2059.30	1450.80	1056.10	995.00	2.22	2.57	6.14%
Ceramic tiles	1%	2036.10	1365.80	1015.80	1000.80	2.90	3.03	1.50%
	2.50%	1740.50	1117.50	1011.90	996.70	2.56	2.67	1.53%
	5%	1918.10	1290.40	1025.20	1004.00	2.53	2.67	2.11%
	10%	2038.90	1375.40	1025.20	998.60	2.76	2.98	2.66%
	20%	2219.70	1614.20	1041.20	999.40	2.29	2.54	4.18%
	100%	2602.50	2030.50	1161.20	1004.30	1.70	2.32	15.62%
	100%	1693.20	1374.70	571.00	496.10	1.96	2.79	15.10%
	100%	1400.20	1085.40	571.00	496.20	1.94	2.74	15.07%
SC39/55	100%	1874.00	1450.80	1060.30	954.60	1.50	1.80	11.07%
	100%	1894.00	1450.80	1057.30	934.30	1.52	1.90	13.16%

Table A.2: Experimental values of water absorption tests performed on Phases 2 and 3 specimens

Sample	A	B	C	D	Specific Gravity [-]	Apparent specific gravity [-]	Water Absorption
Wood 0.75%	1877.20	1223.60	1024.00	998.70	2.70	2.89	2.53%
Wood 1%	1986.10	1302.20	1030.80	1000.50	2.88	3.16	3.03%
Wood 1.5%	2643.00	1931.90	1037.60	996.10	3.05	3.50	4.17%
Brick 5%	1908.50	1248.50	1029.20	999.80	2.71	2.94	2.94%
Brick 20%	1970.00	1341.80	1056.10	1006.10	2.35	2.66	4.97%
Gypsum 2.5%	1714.40	1070.20	1023.20	992.70	2.62	2.85	3.07%
EPS Foam 0.5%	2031.30	1450.80	1014.20	999.50	2.30	2.39	1.47%
Fibers 1%	2039.60	1450.80	1018.70	998.00	2.32	2.44	2.07%
Tiles 15%	2102.90	1450.80	1033.90	997.50	2.61	2.89	3.65%
Plastic 2.5%	2017.20	1404.10	1015.90	996.30	2.47	2.60	1.97%
Gypsum 0.5% + Brick 1%	1721.50	1093.30	1015.90	996.80	2.57	2.70	1.92%
EPS Foam 0.25% + Fibers 0.25%	2022.80	1450.80	1016.40	1001.30	2.25	2.33	1.51%
EPS Foam 0.25% + Tiles 5%	2169.20	1546.00	1017.90	998.50	2.53	2.66	1.94%
Tiles 5% + Fibers 0.25%	2213.30	1546.00	1023.50	1000.50	2.81	3.00	2.30%
Brick 2.25% + Gypsum 0.25%	2098.50	1450.80	1010.60	996.55	2.75	2.86	1.41%
Tiles 4% + Gypsum 1%	2097.20	1450.80	1015.40	993.65	2.69	2.86	2.19%
Tiles 1% +Plastic 1% + Gypsum 0.5%	2085.40	1450.80	1011.40	993.25	2.64	2.77	1.83%
Brick 1% + Gypsum 0.5% + Plastic 1%	2088.00	1450.80	1023.90	995.20	2.57	2.78	2.88%
Glass 2.5% +Brick 1% + Plastic 1%	2089.30	1450.80	1018.20	996.40	2.62	2.78	2.19%
Gypsum 0.5% + Wood 1% + Glass 5%	1959.30	1352.70	1043.20	1010.90	2.32	2.50	3.20%
Wood 1% + Brick 2% + Plastic 3%	1882.50	1265.50	1034.10	1013.20	2.43	2.56	2.06%
Glass 2.5% + Gypsum 2.5% + Plastic 5%	2081.10	1494.00	1053.40	1017.50	2.18	2.36	3.53%
Fibers 0.5% + Wood 0.5% + Glass 1.5%	2177.40	1554.00	1025.40	998.35	2.48	2.66	2.71%
Plastic 1.5% + Brick 3% + Gypsum 1%	2100.50	1494.00	1026.10	1004.70	2.39	2.52	2.13%
Wood 1% + Brick 1% + Gypsum 0.5% +Plastic 1%	2041.70	1450.80	1029.40	994.70	2.27	2.46	3.49%
Gypsum 2% + Brick 2% + Glass 5% + Wood 1%	2000.00	1365.80	1046.50	992.90	2.41	2.77	5.40%
Glass 2.5% + Wood 1% + Brick 2.5% + Plastic 3%	1964.00	1371.60	1025.70	994.20	2.29	2.47	3.17%
Glass 5% + Wood 1% + Brick 1% + Gypsum 0.5% +Plastic 1%	1982.30	1371.60	1027.10	993.50	2.39	2.60	3.38%

B Conversion - replacement units

Table B.1: Conversion table for translating volume to mass replacement units and vice versa

Material	Total vol.%	CA vol.%	CA mass %
Brick	1	2.54	1.79
Tiles	1	2.54	1.79
Glass	1	2.54	2.35
Fibers	1	2.54	0.07
Wood	1	2.54	0.66
EPS	1	2.54	0.02
Gypsum	1	2.54	0.71
HDPE	1	2.54	0.89
SC/LQ	1	2.54	1.41
Brick	0.39	1	0.70
Tiles	0.39	1	0.70
Glass	0.39	1	0.93
Fibers	0.39	1	0.03
Wood	0.39	1	0.26
EPS	0.39	1	0.01
Gypsum	0.39	1	0.28
HDPE	0.39	1	0.35
SC/LQ	0.39	1	0.56
Brick	0.56	1.42	1
Tiles	0.56	1.42	1
Glass	0.43	1.08	1
Fibers	14.29	36.29	1
Wood	1.52	3.85	1
EPS	50.00	127.00	1
Gypsum	1.41	3.58	1
HDPE	1.12	2.85	1
SC/LQ	0.71	1.80	1

C

Concrete mix designs

Table C.1: Materials required for 1 concrete specimen, 150x150x150mm^3

Sample	Experimental WA[%]	Glass [kg]	Wood [kg]	Brick [kg]	Gypsum [kg]	HDPE [kg]	EPS [kg]	Fibers [kg]	Tiles [kg]	Sand 0-4mm [kg]	CA 4-8mm [kg]	CA 8-16mm [kg]	CEM 3A [kg]	Plasticizer [g]	Water [kg]	Effective w/c
Brick 5%	2.77%	0.000	0.000	0.179	0.000	0.000	0.000	0.000	0.000	2.708	0.511	2.898	1.238	5.000	0.565	0.456
Wood 0.75%	2.53%	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.000	2.708	0.534	3.028	1.238	5.000	0.563	0.455
Fibers 1%	2.07%	0.000	0.000	0.000	0.000	0.000	0.000	0.036	0.000	2.708	0.533	3.020	1.238	5.000	0.561	0.453
Tiles 15%	3.65%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.444	2.708	0.472	2.674	1.238	5.000	0.613	0.496
Brick 7.5%	3.01%	0.000	0.000	0.269	0.000	0.000	0.000	0.000	0.000	2.708	0.498	2.822	1.238	5.000	0.566	0.457
Wood 1%	3.03%	0.000	0.036	0.000	0.000	0.000	0.000	0.000	0.000	2.708	0.533	3.020	1.238	5.000	0.566	0.457
Gypsum 2.5%	3.07%	0.000	0.000	0.000	0.090	0.000	0.000	0.000	0.000	2.708	0.525	2.974	1.238	5.000	0.566	0.458
Plastic 2.5%	1.97%	0.000	0.000	0.000	0.000	0.090	0.000	0.000	0.000	2.708	0.525	2.974	1.238	5.000	0.560	0.453
Foam 0.5%	1.47%	0.000	0.000	0.000	0.000	0.000	0.018	0.000	0.000	2.708	0.536	3.035	1.238	5.000	0.557	0.450
Glass 10%	1.25%	0.359	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.708	0.485	2.747	1.238	5.000	0.556	0.449
Wood 1.5%	4.17%	0.000	0.054	0.000	0.000	0.000	0.000	0.000	0.000	2.708	0.531	3.007	1.238	5.000	0.572	0.463
Brick 20%	4.97%	0.000	0.000	0.718	0.000	0.000	0.000	0.000	0.000	2.708	0.431	2.442	1.238	5.000	0.577	0.466
Foam 1%vol repl (all samples)	1.39%	0.000	0.000	0.000	0.000	0.000	0.0006	0.000	0.000	2.708	0.537	3.011	1.238	0.000	0.557	0.450
Foam 2%vol repl (all samples)	1.39%	0.000	0.000	0.000	0.000	0.000	0.0012	0.000	0.000	2.708	0.557	2.973	1.238	0.000	0.557	0.450
Foam 4%vol repl (all samples)	1.39%	0.000	0.000	0.000	0.000	0.000	0.0024	0.000	0.000	2.708	0.557	2.897	1.238	0.000	0.557	0.450
Foam 6%vol repl (all samples)	1.39%	0.000	0.000	0.000	0.000	0.000	0.0036	0.000	0.000	2.708	0.557	2.821	1.238	0.000	0.557	0.450
Brick 2.25% + Gypsum 0.25%	1.41%	0.000	0.000	0.081	0.009	0.000	0.000	0.000	0.000	2.708	0.525	2.974	1.238	5.000	0.557	0.450
Foam 0.25% + Fibers 0.25%	1.51%	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.000	2.708	0.536	3.035	1.238	5.000	0.558	0.451
Foam 0.25% + Tiles 5%	1.94%	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.179	2.708	0.510	2.890	1.238	5.000	0.560	0.452
Tiles 5% + Fibers 0.25%	2.30%	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.179	2.708	0.510	2.890	1.238	5.000	0.562	0.454
Tiles 4% + Gypsum 1%	2.19%	0.000	0.000	0.000	0.036	0.000	0.000	0.000	0.144	2.708	0.511	2.898	1.238	5.000	0.561	0.454
Brick 1% + Gypsum 0.5%	1.92%	0.000	0.000	0.036	0.018	0.000	0.000	0.000	0.000	2.708	0.531	3.007	1.238	5.000	0.560	0.452
Tiles 1% + Plastic 1% + Gypsum 0.5%	1.83%	0.000	0.000	0.000	0.018	0.036	0.000	0.000	0.036	2.708	0.525	2.974	1.238	5.000	0.559	0.452
Plastic 1.5% + Brick 3% + Gypsum 1%	2.13%	0.000	0.000	0.108	0.036	0.054	0.000	0.000	0.000	2.708	0.509	2.883	1.238	5.000	0.561	0.453
Glass 2.5% + Gypsum 2.5% + Plastic 5%	3.53%	0.090	0.000	0.000	0.090	0.179	0.000	0.000	0.000	2.708	0.485	2.746	1.238	5.000	0.569	0.460
Fibers 0.5% + Wood 0.5% + Glass 1.5%	2.71%	0.054	0.018	0.000	0.000	0.000	0.000	0.018	0.000	2.708	0.525	2.974	1.238	5.000	0.564	0.456
Brick 1% + Gypsum 0.5% + Plastic 1%	2.88%	0.000	0.000	0.036	0.018	0.036	0.000	0.000	0.000	2.708	0.525	2.976	1.238	5.000	0.565	0.457
Glass 2.5% +Brick 1% + Plastic 1%	2.19%	0.090	0.000	0.036	0.000	0.036	0.000	0.000	0.000	2.708	0.514	2.915	1.238	5.000	0.561	0.454
Glass 5% + Wood 1% + Gypsum 0.5%	3.20%	0.179	0.036	0.000	0.018	0.000	0.000	0.000	0.000	2.708	0.504	2.854	1.238	5.000	0.567	0.458
Wood 1% + Brick 2% + Plastic 3%	2.06%	0.000	0.036	0.072	0.000	0.108	0.000	0.000	0.000	2.708	0.506	2.869	1.238	5.000	0.561	0.453
Wood 1% + Brick 1% + Gypsum 0.5% +Plastic 1%	3.49%	0.000	0.036	0.036	0.018	0.036	0.000	0.000	0.000	2.708	0.520	2.946	1.238	5.000	0.569	0.459
Gypsum 2% + Brick 2% + Glass 5% + Wood 1%	5.40%	0.179	0.036	0.072	0.072	0.000	0.000	0.000	0.000	2.708	0.485	2.747	1.238	5.000	0.579	0.468
Glass 2.5% + Wood 1% + Brick 2.5% + Plastic 3%	3.17%	0.090	0.036	0.090	0.000	0.179	0.000	0.000	0.000	2.708	0.479	2.717	1.238	5.000	0.567	0.458
Glass 5% + Wood 1% + Brick 1% + Gypsum 0.5% +Plastic 1%	3.38%	0.179	0.036	0.036	0.018	0.036	0.000	0.000	0.000	2.708	0.493	2.793	1.238	5.000	0.568	0.459

D

Regression model reports extracted from Minitab

CS Model 1a

Regression Equation

Cont present			
0	CS 7 (MPa)	=	-75.5 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)
1	CS 7 (MPa)	=	-81.0 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)
2	CS 7 (MPa)	=	-79.0 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)
3	CS 7 (MPa)	=	-84.0 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)
4	CS 7 (MPa)	=	-84.8 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)
5	CS 7 (MPa)	=	-87.3 + 97 w/c + 0.0694 NCA (kg/m3) + 0.0904 RCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-75.5	60.5	-1.25	0.223	
w/c	97	111	0.87	0.390	1.83
NCA (kg/m3)	0.0694	0.0700	0.99	0.330	1068.39
RCA (kg/m3)	0.0904	0.0872	1.04	0.309	1053.59
Cont present					
1	-5.54	4.28	-1.29	0.207	10.48
2	-3.51	4.38	-0.80	0.429	5.95
3	-8.53	4.34	-1.97	0.059	7.29
4	-9.33	4.82	-1.94	0.063	3.96
5	-11.78	5.84	-2.02	0.053	2.05

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.02186	33.67%	14.72%	*

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	229.94	28.74	1.78	0.124
w/c	1	12.33	12.33	0.76	0.390
NCA (kg/m3)	1	15.89	15.89	0.98	0.330
RCA (kg/m3)	1	17.38	17.38	1.07	0.309
Cont present	5	177.53	35.51	2.20	0.083
Error	28	452.91	16.18		
Total	36	682.85			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
1	42.02	42.02	0.00	*		X
13	32.99	32.99	0.00	*		X
14	26.71	36.63	-9.91	-2.64	R	
16	44.27	44.25	0.02	0.01		X

CS Model 1b

Regression Equation

Cont present			
0	CS 7 (MPa)	=	-94.4 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)
1	CS 7 (MPa)	=	-102 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)
2	CS 7 (MPa)	=	-99 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)
3	CS 7 (MPa)	=	-104 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)
4	CS 7 (MPa)	=	-103 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)
5	CS 7 (MPa)	=	-108 + 17 w/c + 0.1212 NCA (kg/m3) + 0.167 RCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-94.4	99.5	-0.95	0.356	
w/c	17	271	0.06	0.952	2.17
NCA (kg/m3)	0.1212	0.0861	1.41	0.177	438.85
RCA (kg/m3)	0.167	0.107	1.57	0.136	428.74
Cont present					
1	-7.20	4.43	-1.63	0.122	8.00
2	-4.79	4.44	-1.08	0.295	4.99
3	-9.22	4.63	-1.99	0.063	5.43
4	-8.73	6.08	-1.44	0.169	2.22
5	-13.35	6.06	-2.20	0.042	2.21

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
3.99370	49.56%	25.83%	*	7.08547	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	266.447	33.3059	2.09	0.096
w/c	1	0.060	0.0601	0.00	0.952
NCA (kg/m3)	1	31.583	31.5829	1.98	0.177
RCA (kg/m3)	1	39.137	39.1369	2.45	0.136
Cont present	5	110.725	22.1450	1.39	0.278
Error	17	271.144	15.9496		
Total	25	537.591			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
11	38.48	38.49	-0.02	-0.00		X
12	32.86	37.84	-4.98	-0.85		X
16	44.27	42.94	1.33	0.13		X
32	38.18	51.02	-12.84	-2.21	R	X
33	37.59	46.84	-9.25	-1.57		X
37	36.48	50.60	-14.12	-2.45	R	X

CS Model 1c

Regression Equation

CS 7 (MPa) = -25.2 + 76 w/c + 0.0257 NCA (kg/m3) + 0.0360 RCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-25.2	63.0	-0.40	0.691	
w/c	76	115	0.67	0.510	1.64
NCA (kg/m3)	0.0257	0.0737	0.35	0.730	1001.28
RCA (kg/m3)	0.0360	0.0919	0.39	0.698	991.81

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.37083	7.68%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	52.417	17.472	0.91	0.445
w/c	1	8.493	8.493	0.44	0.510
NCA (kg/m3)	1	2.317	2.317	0.12	0.730
RCA (kg/m3)	1	2.937	2.937	0.15	0.698
Error	33	630.436	19.104		
Total	36	682.853			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
4	45.19	39.85	5.33	1.52		X
14	26.71	36.50	-9.79	-2.31	R	
16	44.27	41.56	2.71	1.23		X
27	29.40	38.26	-8.87	-2.10	R	
33	37.59	39.48	-1.89	-0.54		X

CS Model 1d

Regression Equation

CS 7 (MPa) = 14.1 - 247 w/c + 0.1257 NCA (kg/m3) + 0.170 RCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	14.1	93.1	0.15	0.881	
w/c	-247	247	-1.00	0.327	1.65
NCA (kg/m3)	0.1257	0.0864	1.45	0.160	406.11
RCA (kg/m3)	0.170	0.107	1.58	0.128	398.65

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
4.16625	28.97%	19.28%	0.00%	7.81839	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	155.72	51.91	2.99	0.053
w/c	1	17.46	17.46	1.01	0.327
NCA (kg/m3)	1	36.69	36.69	2.11	0.160
RCA (kg/m3)	1	43.39	43.39	2.50	0.128
Error	22	381.87	17.36		
Total	25	537.59			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
16	44.27	32.18	12.09	1.23		X
32	38.18	50.09	-11.91	-1.98		X
33	37.59	45.84	-8.25	-1.36		X
37	36.48	49.66	-13.18	-2.21	R	X

CS Model 2a

Regression Equation

Cont present			
0	CS 7 (MPa)	=	3.8 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)
1	CS 7 (MPa)	=	0.2 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)
2	CS 7 (MPa)	=	2.2 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)
3	CS 7 (MPa)	=	-3.1 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)
4	CS 7 (MPa)	=	-3.3 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)
5	CS 7 (MPa)	=	-5.7 + 113.2 w/c - 0.2118 RCA (vol%repl) - 0.01191 NCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.8	38.0	0.10	0.922	
w/c	113.2	83.5	1.36	0.186	1.27
RCA (vol%repl)	-0.2118	0.0757	-2.80	0.009	4.07
NCA (kg/m3)	-0.01191	0.00385	-3.09	0.004	3.98
Cont present					
1	-3.60	3.89	-0.93	0.363	10.67
2	-1.56	3.95	-0.39	0.697	5.99
3	-6.90	3.89	-1.77	0.087	7.23
4	-7.02	4.35	-1.62	0.117	3.97
5	-9.48	5.21	-1.82	0.079	2.01

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.62316	46.17%	30.79%	*

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	315.29	39.41	3.00	0.015
w/c	1	24.14	24.14	1.84	0.186
RCA (vol%repl)	1	102.72	102.72	7.83	0.009
NCA (kg/m3)	1	125.73	125.73	9.58	0.004
Cont present	5	167.69	33.54	2.55	0.050
Error	28	367.56	13.13		
Total	36	682.85			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
1	42.02	42.02	-0.00	*		X
13	32.99	32.99	0.00	*		X
16	44.27	44.02	0.25	0.16		X
25	32.15	39.06	-6.91	-2.01	R	
34	39.42	32.68	6.74	2.27	R	

CS Model 2b

Regression Equation

Cont present			
0	CS 7 (MPa)	=	6 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)
1	CS 7 (MPa)	=	0 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)
2	CS 7 (MPa)	=	3 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)
3	CS 7 (MPa)	=	-2 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)
4	CS 7 (MPa)	=	-2 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)
5	CS 7 (MPa)	=	-5 + 122 w/c - 0.1751 RCA (vol%repl) - 0.01747 NCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	6	102	0.05	0.957	
w/c	122	227	0.54	0.597	1.61
RCA (vol%repl)	-0.1751	0.0935	-1.87	0.078	1.66
NCA (kg/m3)	-0.01747	0.00502	-3.48	0.003	1.57
Cont present					
1	-5.14	4.45	-1.16	0.264	8.52
2	-2.40	4.42	-0.54	0.594	5.21
3	-7.39	4.61	-1.60	0.127	5.66
4	-7.80	5.98	-1.30	0.209	2.27
5	-10.35	6.00	-1.72	0.103	2.29

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
3.88954	52.16%	29.65%	*	4.99974	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	280.406	35.051	2.32	0.069
w/c	1	4.387	4.387	0.29	0.597
RCA (vol%repl)	1	53.096	53.096	3.51	0.078
NCA (kg/m3)	1	183.064	183.064	12.10	0.003
Cont present	5	94.460	18.892	1.25	0.330
Error	17	257.185	15.129		
Total	25	537.591			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	CS 7 (MPa)	Fit	Resid	Std Resid	
11	38.48	36.49	1.98	0.33	X
12	32.86	35.10	-2.24	-0.41	X
16	44.27	44.03	0.24	0.02	X
32	38.18	45.34	-7.16	-1.21	X
33	37.59	45.63	-8.04	-1.37	X
37	36.48	45.60	-9.12	-1.55	X

CS Model 2c

Regression Equation

CS 7 (MPa) = 22.2 + 63.0 w/c - 0.2033 RCA (vol%repl) - 0.01197 NCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.2	39.8	0.56	0.580	
w/c	63.0	85.8	0.73	0.468	1.08
RCA (vol%repl)	-0.2033	0.0827	-2.46	0.019	3.93
NCA (kg/m3)	-0.01197	0.00418	-2.86	0.007	3.80

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.02738	21.62%	14.49%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	147.599	49.200	3.03	0.043
w/c	1	8.755	8.755	0.54	0.468
RCA (vol%repl)	1	98.119	98.119	6.05	0.019
NCA (kg/m3)	1	132.923	132.923	8.20	0.007
Error	33	535.254	16.220		
Total	36	682.853			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
16	44.27	41.25	3.02	1.42		X
27	29.40	37.67	-8.28	-2.09	R	
34	39.42	32.53	6.89	2.06	R	
36	45.52	44.54	0.98	0.32		X

CS Model 2d

Regression Equation

CS 7 (MPa) = 120.1 - 143 w/c - 0.1994 RCA (vol%repl) - 0.01601 NCA (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	120.1	90.9	1.32	0.200	
w/c	-143	200	-0.72	0.480	1.18
RCA (vol%repl)	-0.1994	0.0929	-2.15	0.043	1.55
NCA (kg/m3)	-0.01601	0.00490	-3.27	0.004	1.42

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
3.99798	34.59%	25.67%	0.00%	5.91133	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	185.946	61.982	3.88	0.023
w/c	1	8.253	8.253	0.52	0.480
RCA (vol%repl)	1	73.613	73.613	4.61	0.043
NCA (kg/m3)	1	170.505	170.505	10.67	0.004
Error	22	351.645	15.984		
Total	25	537.591			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	CS 7 (MPa)	Fit	Resid	Std Resid	
11	38.48	35.65	2.83	0.58	X
16	44.27	33.19	11.08	1.22	X
32	38.18	44.05	-5.87	-0.98	X
33	37.59	44.39	-6.80	-1.15	X
37	36.48	44.35	-7.87	-1.33	X

CS Model 3

Regression Equation

CS 7 (MPa) = 40.15 - 0.062 WA of CA(%) + 0.0234 Brick (kg/m3) + 0.0308 Tiles (kg/m3)
- 0.335 Wood (kg/m3) - 0.1472 HDPE (kg/m3) - 2.379 Foam (kg/m3)
- 0.0532 Gypsum (kg/m3) - 0.0021 SC55 (kg/m3) + 0.00237 SC39 (kg/m3)
- 0.00362 LQ (kg/m3)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	40.15	1.46	27.55	0.000	
WA of CA(%)	-0.062	0.832	-0.07	0.942	32.77
Brick (kg/m3)	0.0234	0.0177	1.32	0.197	2.89
Tiles (kg/m3)	0.0308	0.0204	1.51	0.144	1.72
Wood (kg/m3)	-0.335	0.147	-2.28	0.031	3.32
HDPE (kg/m3)	-0.1472	0.0311	-4.73	0.000	1.18

Foam (kg/m3)	-2.379	0.399	-5.96	0.000	1.14
Gypsum (kg/m3)	-0.0532	0.0842	-0.63	0.533	2.34
SC55 (kg/m3)	-0.0021	0.0119	-0.17	0.863	17.79
SC39 (kg/m3)	0.00237	0.00887	0.27	0.792	19.36
LQ (kg/m3)	-0.00362	0.00749	-0.48	0.633	7.44

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	10-fold S	10-fold R-sq
2.34188	79.12%	71.09%	*	*	*

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	540.259	54.026	9.85	0.000
WA of CA(%)	1	0.030	0.030	0.01	0.942
Brick (kg/m3)	1	9.600	9.600	1.75	0.197
Tiles (kg/m3)	1	12.459	12.459	2.27	0.144
Wood (kg/m3)	1	28.548	28.548	5.21	0.031
HDPE (kg/m3)	1	122.864	122.864	22.40	0.000
Foam (kg/m3)	1	194.970	194.970	35.55	0.000
Gypsum (kg/m3)	1	2.192	2.192	0.40	0.533
SC55 (kg/m3)	1	0.167	0.167	0.03	0.863
SC39 (kg/m3)	1	0.391	0.391	0.07	0.792
LQ (kg/m3)	1	1.282	1.282	0.23	0.633
Error	26	142.594	5.484		
Total	36	682.853			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
12	32.86	29.19	3.66	2.12	R	
32	38.18	41.52	-3.34	-2.16	R	
33	37.59	37.59	0.00	*		X
36	45.52	41.21	4.31	2.20	R	
37	36.48	36.48	0.00	*		X

WA Model 1

Regression Equation

cont present			
0	WA of CA (%)	=	36.8 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr
1	WA of CA (%)	=	37.3 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr
2	WA of CA (%)	=	36.7 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr
3	WA of CA (%)	=	37.2 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr
4	WA of CA (%)	=	37.6 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr
5	WA of CA (%)	=	37.3 - 25.5 NA contr - 1.22 Brick contr - 1.51 Tiles contr + 0.441 Wood contr - 20.7 Glass contr - 1.95 HDPE contr - 767 Foam contr + 0.439 Gypsum contr

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	36.8	48.4	0.76	0.457	
NA contr	-25.5	34.8	-0.73	0.474	603.20
Brick contr	-1.22	2.86	-0.43	0.676	409.42
Tiles contr	-1.51	3.13	-0.48	0.635	249.99
Wood contr	0.441	0.259	1.70	0.107	6.33
Glass contr	-20.7	26.4	-0.78	0.445	149.70
HDPE contr	-1.95	1.99	-0.98	0.340	39.82
Foam contr	-767	969	-0.79	0.440	1.34
Gypsum contr	0.439	0.578	0.76	0.458	13.70
cont present					
1	0.455	0.556	0.82	0.425	9.48
2	-0.082	0.555	-0.15	0.884	6.20
3	0.418	0.592	0.71	0.490	8.68
4	0.801	0.720	1.11	0.282	5.85
5	0.533	0.833	0.64	0.531	2.80

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.489761	86.80%	76.70%	*

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	13	26.8064	2.06203	8.60	0.000
NA contr	1	0.1284	0.12844	0.54	0.474
Brick contr	1	0.0434	0.04342	0.18	0.676
Tiles contr	1	0.0562	0.05617	0.23	0.635

Wood contr	1	0.6953	0.69527	2.90	0.107
Glass contr	1	0.1467	0.14675	0.61	0.445
HDPE contr	1	0.2308	0.23085	0.96	0.340
Foam contr	1	0.1502	0.15018	0.63	0.440
Gypsum contr	1	0.1385	0.13850	0.58	0.458
cont present	5	1.1065	0.22129	0.92	0.490
Error	17	4.0777	0.23987		
Total	30	30.8841			

Fits and Diagnostics for Unusual Observations

bs	WA of CA (%)	Fit	Resid	Std Resid	
1	1.390	1.390	0.000	*	X
9	2.060	2.944	-0.884	-2.29 R	
13	3.380	3.380	0.000	*	X
27	3.530	3.002	0.528	2.10 R	

WA Model 2

Regression Equation

WA of CA (%) = 60.4 - 42.4 NA contr - 2.50 Brick contr - 3.02 Tiles contr + 0.469 Wood contr - 32.3 Glass contr - 2.72 HDPE contr - 897 Foam contr + 0.208 Gypsum contr

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	60.4	44.9	1.35	0.192	
NA contr	-42.4	32.4	-1.31	0.204	530.37
Brick contr	-2.50	2.67	-0.94	0.359	363.32
Tiles contr	-3.02	2.91	-1.04	0.311	220.53
Wood contr	0.469	0.248	1.89	0.072	5.90
Glass contr	-32.3	24.8	-1.30	0.207	134.29
HDPE contr	-2.72	1.90	-1.43	0.167	36.96
Foam contr	-897	932	-0.96	0.346	1.26
Gypsum contr	0.208	0.548	0.38	0.708	12.54

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.485432	83.21%	77.11%	62.81%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	25.6999	3.21249	13.63	0.000
NA contr	1	0.4045	0.40446	1.72	0.204
Brick contr	1	0.2066	0.20664	0.88	0.359
Tiles contr	1	0.2534	0.25342	1.08	0.311
Wood contr	1	0.8429	0.84294	3.58	0.072
Glass contr	1	0.3983	0.39828	1.69	0.207
HDPE contr	1	0.4803	0.48034	2.04	0.167
Foam contr	1	0.2185	0.21849	0.93	0.346
Gypsum contr	1	0.0340	0.03397	0.14	0.708
Error	22	5.1842	0.23564		
Total	30	30.8841			

Fits and Diagnostics for Unusual Observations

Obs	WA of CA (%)	Fit	Resid	Std Resid
9	2.060	3.151	-1.091	-2.63 R

WA Model 3

Regression Equation

WA of CA (%) = 79.2 - 56.0 NA contr - 3.58 Brick contr - 4.17 Tiles contr + 0.525 Wood contr - 42.5 Glass contr - 3.35 HDPE contr - 700 Foam contr + 0.063 Gypsum contr

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	79.2	38.4	2.06	0.060	
NA contr	-56.0	27.7	-2.02	0.064	577.45
Brick contr	-3.58	2.29	-1.56	0.143	382.35
Tiles contr	-4.17	2.49	-1.68	0.118	248.43
Wood contr	0.525	0.213	2.47	0.028	4.99
Glass contr	-42.5	21.2	-2.01	0.066	118.61
HDPE contr	-3.35	1.65	-2.03	0.063	32.18
Foam contr	-700	762	-0.92	0.375	1.30
Gypsum contr	0.063	0.494	0.13	0.900	10.38

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
0.383038	93.17%	88.96%	63.88%	0.660132	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	26.0019	3.25023	22.15	0.000
NA contr	1	0.5989	0.59889	4.08	0.064
Brick contr	1	0.3561	0.35612	2.43	0.143
Tiles contr	1	0.4120	0.41200	2.81	0.118
Wood contr	1	0.8933	0.89333	6.09	0.028
Glass contr	1	0.5909	0.59085	4.03	0.066
HDPE contr	1	0.6068	0.60683	4.14	0.063
Foam contr	1	0.1239	0.12388	0.84	0.375
Gypsum contr	1	0.0024	0.00242	0.02	0.900
Error	13	1.9073	0.14672		
Total	21	27.9092			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	WA of CA (%)	Fit	Resid	Std Resid	
6	2.880	1.933	0.947	2.28 R	
9	2.060	3.410	-1.350	-2.84 R	
26	3.070	3.415	-0.345	-0.63	X

WA Model 4

Regression Equation

WA of CA (%) = 0.46 + 0.64 NA contr + 0.980 Brick contr + 0.822 Tiles contr + 0.7985 Wood contr + 1.35 Glass contr + 1.160 Gypsum contr + 0.455 Fibers contr

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.46	8.06	0.06	0.955	
NA contr	0.64	5.82	0.11	0.914	27.38
Brick contr	0.980	0.412	2.38	0.032	19.12
Tiles contr	0.822	0.445	1.85	0.086	12.32
Wood contr	0.7985	0.0890	8.98	0.000	1.35
Glass contr	1.35	5.46	0.25	0.808	6.88
Gypsum contr	1.160	0.278	4.17	0.001	2.87
Fibers contr	0.455	0.213	2.13	0.051	1.17

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
0.369304	93.16%	89.74%	66.79%	0.658334	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	25.9998	3.7143	27.23	0.000
NA contr	1	0.0017	0.0017	0.01	0.914
Brick contr	1	0.7709	0.7709	5.65	0.032
Tiles contr	1	0.4655	0.4655	3.41	0.086
Wood contr	1	10.9882	10.9882	80.57	0.000
Glass contr	1	0.0083	0.0083	0.06	0.808
Gypsum contr	1	2.3700	2.3700	17.38	0.001
Fibers contr	1	0.6202	0.6202	4.55	0.051
Error	14	1.9094	0.1364		
Total	21	27.9092			

Fits and Diagnostics for Unusual Observations

Test Set

Obs	WA of CA (%)	Fit	Resid	Std Resid	
6	2.880	1.942	0.938	2.39 R	
9	2.060	3.413	-1.353	-2.96 R	
26	3.070	3.418	-0.348	-0.66	X

Combined model 7d_v1

Regression Equation

CS 7 (MPa) = -299 + 244.0 NA + 21.99 Br+Tl + 0.233 Br + Tl ^2 + 30.5 RA - 3.58 Wood + 210.5 Glass + 128.8 HDPE - 21720 EPS + 3.33 Gypsum + 4.16 Fibers + 0.166 WA of CA(%)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-299	111	-2.69	0.011	
NA	244.0	80.3	3.04	0.004	14803.19
Br+Tl	21.99	6.98	3.15	0.003	291.77
Br + Tl ^2	0.233	0.443	0.53	0.601	7.65
RA	30.5	10.2	3.00	0.005	16450.52
Wood	-3.58	2.12	-1.69	0.099	4.36
Glass	210.5	63.4	3.32	0.002	40.01
HDPE	128.8	97.8	1.32	0.196	17.17
EPS	-21720	3537	-6.14	0.000	1.22
Gypsum	3.33	1.70	1.96	0.057	9.34
Fibers	4.16	2.09	1.99	0.054	1.56
WA of CA(%)	0.166	0.442	0.38	0.709	18.78

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	10-fold S	10-fold R-sq
1.90593	83.27%	78.43%	71.22%	2.39954	65.11%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	11	686.987	62.453	17.19	0.000
NA	1	33.574	33.574	9.24	0.004
Br+Tl	1	36.004	36.004	9.91	0.003
Br + Tl ^2	1	1.008	1.008	0.28	0.601
RA	1	32.687	32.687	9.00	0.005
Wood	1	10.410	10.410	2.87	0.099
Glass	1	40.038	40.038	11.02	0.002
HDPE	1	6.298	6.298	1.73	0.196
EPS	1	137.011	137.011	37.72	0.000
Gypsum	1	13.952	13.952	3.84	0.057
Fibers	1	14.356	14.356	3.95	0.054
WA of CA(%)	1	0.512	0.512	0.14	0.709
Error	38	138.037	3.633		
Total	49	825.024			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid		
3	36.38	32.28	4.11	2.55	R	
4	45.19	45.27	-0.09	-0.11		X
12	32.86	32.45	0.41	0.51		X
15	41.51	41.01	0.50	0.51		X
42	26.19	31.99	-5.80	-3.29	R	

Combined model 7d_v2

Regression Equation

CS 7 (MPa) = -293 + 239.7 NA + 22.19 Br+Tl + 30.0 RA - 3.59 Wood + 206.7 Glass + 123.1 HDPE - 21644 EPS + 3.27 Gypsum + 4.21 Fibers + 0.181 WA of CA(%)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-293	110	-2.67	0.011	
NA	239.7	79.1	3.03	0.004	14652.37
Br+Tl	22.19	6.91	3.21	0.003	290.94
RA	30.0	10.0	2.99	0.005	16283.77
Wood	-3.59	2.10	-1.71	0.095	4.36
Glass	206.7	62.4	3.31	0.002	39.50
HDPE	123.1	96.3	1.28	0.209	16.96
EPS	-21644	3501	-6.18	0.000	1.22
Gypsum	3.27	1.68	1.94	0.059	9.29
Fibers	4.21	2.07	2.04	0.049	1.56
WA of CA(%)	0.181	0.437	0.41	0.682	18.71

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	10-fold S	10-fold R-sq
1.88819	83.15%	78.83%	71.75%	2.36065	66.23%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	685.978	68.598	19.24	0.000
NA	1	32.743	32.743	9.18	0.004
Br+Tl	1	36.753	36.753	10.31	0.003
RA	1	31.864	31.864	8.94	0.005
Wood	1	10.435	10.435	2.93	0.095
Glass	1	39.117	39.117	10.97	0.002
HDPE	1	5.826	5.826	1.63	0.209
EPS	1	136.281	136.281	38.22	0.000
Gypsum	1	13.483	13.483	3.78	0.059
Fibers	1	14.782	14.782	4.15	0.049
WA of CA(%)	1	0.609	0.609	0.17	0.682
Error	39	139.046	3.565		
Total	49	825.024			

Fits and Diagnostics for Unusual Observations

Obs	CS 7 (MPa)	Fit	Resid	Std Resid	
3	36.38	32.26	4.12	2.58 R	
12	32.86	32.46	0.40	0.50	X
14	26.71	27.51	-0.80	-0.74	X
15	41.51	40.99	0.51	0.53	X
42	26.19	31.94	-5.75	-3.29 R	

Combined model 28d_v1

Regression Equation

CS 28 (MPa) = 151 - 68.1 NA - 3.68 Br+Tl - 0.208 Br + Tl ^2 - 8.9 RA - 6.71 Wood - 57.6 Glass - 361 HDPE - 32533 EPS - 2.91 Gypsum + 0.95 Fibers - 0.206 WA of CA(%)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	151	125	1.22	0.235	
NA	-68.1	89.7	-0.76	0.455	11468.13
Br+Tl	-3.68	7.68	-0.48	0.636	231.99
Br + Tl ^2	-0.208	0.568	-0.37	0.718	10.01
RA	-8.9	11.3	-0.79	0.438	12580.81
Wood	-6.71	2.45	-2.73	0.011	3.95
Glass	-57.6	70.7	-0.82	0.423	38.75
HDPE	-361	108	-3.33	0.003	16.98
EPS	-32533	3823	-8.51	0.000	1.24
Gypsum	-2.91	1.91	-1.52	0.141	9.14
Fibers	0.95	2.27	0.42	0.679	1.59
WA of CA(%)	-0.206	0.503	-0.41	0.685	15.98

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	10-fold S	10-fold R-sq
2.02639	90.55%	86.39%	59.49%	3.58347	56.27%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	11	983.82	89.438	21.78	0.000
NA	1	2.37	2.366	0.58	0.455
Br+Tl	1	0.94	0.944	0.23	0.636
Br + Tl ^2	1	0.55	0.550	0.13	0.718
RA	1	2.55	2.554	0.62	0.438
Wood	1	30.72	30.716	7.48	0.011
Glass	1	2.73	2.728	0.66	0.423
HDPE	1	45.58	45.576	11.10	0.003
EPS	1	297.42	297.417	72.43	0.000
Gypsum	1	9.50	9.500	2.31	0.141
Fibers	1	0.72	0.721	0.18	0.679
WA of CA(%)	1	0.69	0.690	0.17	0.685
Error	25	102.66	4.106		
Total	36	1086.48			

Fits and Diagnostics for Unusual Observations

Obs	CS 28 (MPa)	Fit	Resid	Std Resid
10	44.76	49.09	-4.33	-2.63 R
12	40.70	38.54	2.16	2.63 R

Combined model 28d_v2

Regression Equation

CS 28 (MPa) = 144 - 62.5 NA - 3.76 Br+Tl - 8.2 RA - 6.64 Wood - 53.6 Glass - 354 HDPE - 32561 EPS - 2.80 Gypsum + 0.93 Fibers - 0.220 WA of CA(%)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	144	121	1.19	0.244	
NA	-62.5	86.9	-0.72	0.479	11134.03
Br+Tl	-3.76	7.55	-0.50	0.623	231.83
RA	-8.2	11.0	-0.75	0.460	12215.51
Wood	-6.64	2.40	-2.76	0.010	3.93
Glass	-53.6	68.7	-0.78	0.442	37.81
HDPE	-354	105	-3.37	0.002	16.47
EPS	-32561	3758	-8.67	0.000	1.24
Gypsum	-2.80	1.86	-1.51	0.144	8.93
Fibers	0.93	2.23	0.42	0.680	1.59
WA of CA(%)	-0.220	0.493	-0.45	0.659	15.89

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)	10-fold S	10-fold R-sq
1.99235	90.50%	86.85%	63.74%	3.38023	61.09%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	983.27	98.327	24.77	0.000
NA	1	2.05	2.052	0.52	0.479
Br+Tl	1	0.98	0.983	0.25	0.623
RA	1	2.23	2.231	0.56	0.460
Wood	1	30.25	30.253	7.62	0.010
Glass	1	2.42	2.418	0.61	0.442
HDPE	1	45.21	45.214	11.39	0.002
EPS	1	298.05	298.051	75.09	0.000
Gypsum	1	9.02	9.024	2.27	0.144
Fibers	1	0.69	0.690	0.17	0.680
WA of CA(%)	1	0.79	0.790	0.20	0.659
Error	26	103.21	3.969		
Total	36	1086.48			

Fits and Diagnostics for Unusual Observations

Obs	CS 28 (MPa)	Fit	Resid	Std Resid
10	44.76	49.14	-4.38	-2.70 R
12	40.70	38.51	2.19	2.70 R

E

Matlab scripts for visualization of the complete model

GUI File

```
%initialization
clc
clear
format short g
format compact
close all

%Main configuration
mainfig = figure('Position',[100,100,1000,1000]);

%User input
%NA content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,700,120,35],'String','
    NA content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,700,80,35],'tag','in1'
    )

%Brick content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,650,120,35],'String','
    Brick content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,650,80,35],'Tag','in2'
    )

%Tiles content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,600,120,35],'String','
    Ceramic tiles content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,600,80,35],'Tag','in3'
    )

%Glass content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,550,120,35],'String','
    Glass content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,550,80,35],'Tag','in4'
    )

%Gypsum content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,500,120,35],'String','
    Gypsum content (kg/m3) =')
```

```
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,500,80,35],'Tag','in5'
    )

%Wood content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,450,120,35],'String','
    Wood content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,450,80,35],'Tag','in6'
    )

%Fibers content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,400,120,35],'String','
    Mineral fibers content (kg/m3) = ')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,400,80,35],'Tag','in7'
    )

%EPS content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,350,120,35],'String','
    EPS content (kg/m3) =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,350,80,35],'Tag','in8'
    )

%HDPE content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,300,120,35],'String','
    HDPE content (kg/m3) =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,300,80,35],'Tag','in9'
    )

%SC55 content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,250,120,35],'String','
    SC55 content (kg/m3) =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,250,80,35],'Tag','in10
    ')

%SC39 content
uicontrol('Parent',mainfig,'Style','Text','Position',[100,200,120,35],'String','
    SC39 content (kg/m3) =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[220,200,80,35],'Tag','in11
    ')

%Push button for execution of script
uicontrol('Parent',mainfig,'tag','run','Style','pushbutton',...
 'Position',[300,150,100,35],'string','CALCULATE',...
 'callback','model')

%User output
%WA
uicontrol('Parent',mainfig,'Style','Text','Position',[350,700,120,35],'String','
    WA of CA [%] =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[470,700,80,35],'Tag','out1
    ')
%CS
uicontrol('Parent',mainfig,'Style','Text','Position',[350,650,120,35],'String','
    7-day CS [MPa] =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[470,650,80,35],'Tag','out2
    ')
%Air
uicontrol('Parent',mainfig,'Style','Text','Position',[350,600,120,35],'String','
    Equivalent air volume [%] =')
uicontrol('Parent',mainfig,'Style','Edit','Position',[470,600,80,35],'Tag','out3
    ')
```

Main File

```
clc
clear
format compact
format short g

NA = str2num(get(findobj('tag','in1'),'String'));
BR = str2num(get(findobj('Tag','in2'),'String'));
TI = str2num(get(findobj('Tag','in3'),'String'));
GL= str2num(get(findobj('Tag','in4'),'String'));
GY = str2num(get(findobj('Tag','in5'),'String'));
WO = str2num(get(findobj('Tag','in6'),'String'));
MF =str2num(get(findobj('Tag','in7'),'String'));
EPS = str2num(get(findobj('Tag','in8'),'String'));
HDPE = str2num(get(findobj('Tag','in9'),'String'));
SC = str2num(get(findobj('Tag','in10'),'String'));
LQ = str2num(get(findobj('Tag','in11'),'String'));

NA1 = 1.39*NA/100;
BR1 = 16.56*BR/100;
TI1 = 15.27*TI/100;
GL1 = 1.8*GL/100;
GY1 = 80*GY/100;
WO1 = 60*WO/100;
MF1 = 100*MF/100;
EPS1 = 0.1*EPS/100;
HDPE1 = 1*HDPE/100;
SC1 = 12.12*SC/100;
LQ1 = 8.7*LQ/100;

WA = 1.9 - 0.4*NA1 + 1.05*BR1 + 0.91*TI1 + 2.33*0.5*WO1 + + 0.977*GY1 + 0.844*
    MF1 + 0.78*SC1 + 0.77*LQ1 - 2.2*HDPE1;
CS = -245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1 -1.19*WO1 + 3.73*GY1 + 4.22*MF1 +
    24.3*SC1 + 33.2*LQ1 + 179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA;
Air = (41.612 - CS)/1.6377;

set(findobj('Tag','out1'),'String',num2str(WA));
set(findobj('Tag','out2'),'String',num2str(CS));
set(findobj('Tag','out3'),'String',num2str(Air));
```

Final version

```
classdef app1 < matlab.apps.AppBase

    classdef app1 < matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)
        UIFigure                      matlab.ui.Figure
        Label                         matlab.ui.control.Label
        PredictivemodelLabel          matlab.ui.control.Label
        CALCULATEButton               matlab.ui.control.Button
        Panel                         matlab.ui.container.Panel
        EquivalentaircontentTextArea  matlab.ui.control.TextArea
        EquivalentaircontentTextAreaLabel  matlab.ui.control.Label
        dayCSXMPaTextArea             matlab.ui.control.TextArea
        dayCSMPaTextArea_2Label       matlab.ui.control.Label
        dayCSMPaTextArea              matlab.ui.control.TextArea
        dayCSMPaTextAreaLabel         matlab.ui.control.Label
        WAofCATextArea                matlab.ui.control.TextArea
```

```
        WAofCATextAreaLabel            matlab.ui.control.Label
        SelectcementtypeButtonGroup    matlab.ui.container.ButtonGroup
        CEMI425Button                  matlab.ui.control.RadioButton
        CEMI525Button                  matlab.ui.control.RadioButton
        CEMIII425Button                matlab.ui.control.RadioButton
        CEMIII525Button                matlab.ui.control.RadioButton
        LQEditField                    matlab.ui.control.NumericEditField
        LQEditFieldLabel               matlab.ui.control.Label
        SCEditField                    matlab.ui.control.NumericEditField
        SCEditFieldLabel               matlab.ui.control.Label
        EPSEditField                   matlab.ui.control.NumericEditField
        EPSEditFieldLabel              matlab.ui.control.Label
        HDPEEditField                  matlab.ui.control.NumericEditField
        HDPEEditFieldLabel             matlab.ui.control.Label
        FibersEditField                matlab.ui.control.NumericEditField
        FibersEditFieldLabel           matlab.ui.control.Label
        GypsumEditField                matlab.ui.control.NumericEditField
        GypsumEditFieldLabel           matlab.ui.control.Label
        WoodEditField                  matlab.ui.control.NumericEditField
        WoodEditFieldLabel             matlab.ui.control.Label
        GlassEditField                 matlab.ui.control.NumericEditField
        GlassEditFieldLabel            matlab.ui.control.Label
        TilesEditField                 matlab.ui.control.NumericEditField
        TilesEditFieldLabel            matlab.ui.control.Label
        BrickEditField                 matlab.ui.control.NumericEditField
        BrickEditFieldLabel            matlab.ui.control.Label
        NAEditField                    matlab.ui.control.NumericEditField
        NAEditFieldLabel               matlab.ui.control.Label
    end

    % Callbacks that handle component events
    methods (Access = private)

        % Value changed function: NAEditField
        function NAEditFieldValueChanged(app, event)
            value = app.NAEditField.Value;
        end

        % Value changed function: BrickEditField
        function BrickEditFieldValueChanged(app, event)
            value = app.BrickEditField.Value;
        end

        % Value changed function: TilesEditField
        function TilesEditFieldValueChanged(app, event)
            value = app.TilesEditField.Value;
        end

        % Value changed function: GlassEditField
        function GlassEditFieldValueChanged(app, event)
            value = app.GlassEditField.Value;
        end

        % Value changed function: WoodEditField
        function WoodEditFieldValueChanged(app, event)
            value = app.WoodEditField.Value;
        end

        % Value changed function: GypsumEditField
        function GypsumEditFieldValueChanged(app, event)
            value = app.GypsumEditField.Value;
```

```
        end

        % Value changed function: FibersEditField
        function FibersEditFieldValueChanged(app, event)
            value = app.FibersEditField.Value;
        end

        % Value changed function: HDPEEditField
        function HDPEEditFieldValueChanged(app, event)
            value = app.HDPEEditField.Value;
        end

        % Value changed function: EPSEditField
        function EPSEditFieldValueChanged(app, event)
            value = app.EPSEditField.Value;
        end

        % Value changed function: SCEditField
        function SCEditFieldValueChanged(app, event)
            value = app.SCEditField.Value;
        end

        % Value changed function: LQEditField
        function LQEditFieldValueChanged(app, event)
            value = app.LQEditField.Value;
        end

        % Button pushed function: CALCULATEButton
        function CALCULATEButtonPushed(app, event)
            NA1 = app.NAEditField.Value*1.39/100;
            LQ1  = app.LQEditField.Value*8.7/100;
            SC1 = app.SCEditField.Value*12.12/100;
            EPS1 = app.EPSEditField.Value*0.1/100;
            HDPE1 = app.HDPEEditField.Value*1/100;
            MF1 = app.FibersEditField.Value*100/100;
            TI1 = app.TilesEditField.Value*15.27/100;
            WO1 = app.WoodEditField.Value*60/100;
            GY1 = app.GypsumEditField.Value*80/100;
            GL1 = app.GlassEditField.Value*1.8/100;
            BR1 = app.BrickEditField.Value*16.56/100;

            RA = (app.LQEditField.Value + app.SCEditField.Value)*10.98/100;
            BRTL = (app.BrickEditField.Value + app.TilesEditField.Value)*15.92/100;


            WA = 1.9 - 0.4*NA1 + 1.05*BR1 + 0.91*TI1 + 2.33*0.5*WO1 + 0.977*GY1 + 0.844*MF1 + 0.78*SC1 + 0.77*LQ1 - 2.2*HDPE1;

            if(app.CEMIII525Button.Value)
                CS = 0.97*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1 -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 + 179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA);
                CSX = 0.97*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1 -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 + 179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA)/0.72;
                CS28 = 0.97*(144 - 0.22*WA - 62.5*NA1 - 3.76*BRTL - 8.2*RA - 53.6*GL1 - 354*HDPE1 - 2.8*GY1 + 0.93*MF1 - 6.64*WO1 - 32561*EPS1);
                CS28v = 0.97*(151 - 0.206*WA - 68.1*NA1 - 3.76*BRTL - 0.208*BRTL^2 - 8.9*RA - 57.6*GL1 - 361*HDPE1 - 2.91*GY1 + 0.95*
```

```
                    MF1 - 6.71*WO1 - 32533*EPS1);
                CSF = (CSX + CS28 + CS28v)/3;
        elseif(app.CEMIII425Button.Value)
                CS = 0.97*0.958*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA);
                CSX = 0.97*0.983*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA)/0.72;
                CS28 = 0.97*0.983*(144 - 0.22*WA - 62.5*NA1 - 3.76*BRTL -
                    8.2*RA - 53.6*GL1 - 354*HDPE1 - 2.8*GY1 + 0.93*MF1 - 6.64*
                    WO1 - 32561*EPS1);
                CS28v = 0.97*0.983*(151 - 0.206*WA - 68.1*NA1 - 3.76*BRTL -
                    0.208*BRTL^2 - 8.9*RA - 57.6*GL1 - 361*HDPE1 - 2.91*GY1 +
                    0.95*MF1 - 6.71*WO1 - 32533*EPS1);
                CSF = (CSX + CS28 + CS28v)/3;
        elseif(app.CEMI525Button.Value)
                CS = 0.97*1.108*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA);
                CSX = 0.97*0.929*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA)/0.72;
                CS28 = 0.97*0.929*(144 - 0.22*WA - 62.5*NA1 - 3.76*BRTL -
                    8.2*RA - 53.6*GL1 - 354*HDPE1 - 2.8*GY1 + 0.93*MF1 - 6.64*
                    WO1 - 32561*EPS1);
                CS28v = 0.97*0.929*(151 - 0.206*WA - 68.1*NA1 - 3.76*BRTL -
                    0.208*BRTL^2 - 8.9*RA - 57.6*GL1 - 361*HDPE1 - 2.91*GY1 +
                    0.95*MF1 - 6.71*WO1 - 32533*EPS1);
                CSF = (CSX + CS28 + CS28v)/3;
        elseif(app.CEMI425Button.Value)
                CS = 0.97*0.714*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA);
                CSX = 0.97*0.674*(-245 + 206.2*NA1 + 18.49*BR1 + 21.25*TI1
                    -1.19*WO1 + 3.73*GY1 + 4.22*MF1 + 24.3*SC1 + 33.2*LQ1 +
                    179.8*GL1 + 80*HDPE1 -22577*EPS1 - 0.793*WA)/0.72;
                CS28 = 0.97*0.674*(144 - 0.22*WA - 62.5*NA1 - 3.76*BRTL -
                    8.2*RA - 53.6*GL1 - 354*HDPE1 - 2.8*GY1 + 0.93*MF1 - 6.64*
                    WO1 - 32561*EPS1);
                CS28v = 0.97*0.674*(151 - 0.206*WA - 68.1*NA1 - 3.76*BRTL -
                    0.208*BRTL^2 - 8.9*RA - 57.6*GL1 - 361*HDPE1 - 2.91*GY1 +
                    0.95*MF1 - 6.71*WO1 - 32533*EPS1);
                CSF = (CSX + CS28 + CS28v)/3;
        end

        Air = (41.612 - CS)/1.6377;
        if(Air > 0)
            Air = Air;
        else
            Air = 0;
        end


        app.WAofCATextArea.Value = num2str(WA);
        app.dayCSMPaTextArea.Value = num2str(CS);
        app.EquivalentaircontentTextArea.Value= num2str(Air);
        app.dayCSXMPaTextArea.Value = num2str(CSF);

    end

```

```
        % Value changed function: WAofCATextArea
        function WAofCATextAreaValueChanged(app, event)
            value =    WA;
        end

        % Value changed function: dayCSMPaTextArea
        function dayCSMPaTextAreaValueChanged(app, event)
            value = CS;
        end

        % Value changed function: EquivalentaircontentTextArea
        function EquivalentaircontentTextAreaValueChanged(app, event)
            value = Air;
        end

        % Value changed function: dayCSXMPaTextArea
        function dayCSXMPaTextAreaValueChanged(app, event)
            value = CSF;
        end

        % Callback function
        function CSnewTextAreaValueChanged(app, event)
        value = CS28;

        end

        % Callback function
        function CSnewsqTextAreaValueChanged(app, event)
            value = CS28v;

        end
    end

    % Component initialization
    methods (Access = private)

        % Create UIFigure and components
        function createComponents(app)

            % Create UIFigure and hide until all components are created
            app.UIFigure = uifigure('Visible', 'off');
            app.UIFigure.Position = [100 100 640 480];
            app.UIFigure.Name = 'MATLAB App';

            % Create NAEditFieldLabel
            app.NAEditFieldLabel = uilabel(app.UIFigure);
            app.NAEditFieldLabel.HorizontalAlignment = 'right';
            app.NAEditFieldLabel.Position = [59 368 35 22];
            app.NAEditFieldLabel.Text = 'NA %';

            % Create NAEditField
            app.NAEditField = uieditfield(app.UIFigure, 'numeric');
            app.NAEditField.Limits = [0 100];
            app.NAEditField.ValueChangedFcn = createCallbackFcn(app,
                @NAEditFieldValueChanged, true);
            app.NAEditField.Position = [109 368 114 33];

            % Create BrickEditFieldLabel
            app.BrickEditFieldLabel = uilabel(app.UIFigure);
            app.BrickEditFieldLabel.HorizontalAlignment = 'right';
            app.BrickEditFieldLabel.Position = [242 373 46 22];
```

```
            app.BrickEditFieldLabel.Text = 'Brick %';

            % Create BrickEditField
            app.BrickEditField = uieditfield(app.UIFigure, 'numeric');
            app.BrickEditField.Limits = [0 100];
            app.BrickEditField.ValueChangedFcn = createCallbackFcn(app,
                @BrickEditFieldValueChanged, true);
            app.BrickEditField.Position = [303 373 114 33];

            % Create TilesEditFieldLabel
            app.TilesEditFieldLabel = uilabel(app.UIFigure);
            app.TilesEditFieldLabel.HorizontalAlignment = 'right';
            app.TilesEditFieldLabel.Position = [244 330 44 22];
            app.TilesEditFieldLabel.Text = 'Tiles %';

            % Create TilesEditField
            app.TilesEditField = uieditfield(app.UIFigure, 'numeric');
            app.TilesEditField.Limits = [0 100];
            app.TilesEditField.ValueChangedFcn = createCallbackFcn(app,
                @TilesEditFieldValueChanged, true);
            app.TilesEditField.Position = [303 330 114 33];

            % Create GlassEditFieldLabel
            app.GlassEditFieldLabel = uilabel(app.UIFigure);
            app.GlassEditFieldLabel.HorizontalAlignment = 'right';
            app.GlassEditFieldLabel.Position = [238 282 50 22];
            app.GlassEditFieldLabel.Text = 'Glass %';

            % Create GlassEditField
            app.GlassEditField = uieditfield(app.UIFigure, 'numeric');
            app.GlassEditField.Limits = [0 100];
            app.GlassEditField.ValueChangedFcn = createCallbackFcn(app,
                @GlassEditFieldValueChanged, true);
            app.GlassEditField.Position = [303 282 114 33];

            % Create WoodEditFieldLabel
            app.WoodEditFieldLabel = uilabel(app.UIFigure);
            app.WoodEditFieldLabel.HorizontalAlignment = 'right';
            app.WoodEditFieldLabel.Position = [238 236 50 22];
            app.WoodEditFieldLabel.Text = 'Wood %';

            % Create WoodEditField
            app.WoodEditField = uieditfield(app.UIFigure, 'numeric');
            app.WoodEditField.Limits = [0 100];
            app.WoodEditField.ValueChangedFcn = createCallbackFcn(app,
                @WoodEditFieldValueChanged, true);
            app.WoodEditField.Position = [303 236 114 33];

            % Create GypsumEditFieldLabel
            app.GypsumEditFieldLabel = uilabel(app.UIFigure);
            app.GypsumEditFieldLabel.HorizontalAlignment = 'right';
            app.GypsumEditFieldLabel.Position = [224 193 64 22];
            app.GypsumEditFieldLabel.Text = 'Gypsum %';

            % Create GypsumEditField
            app.GypsumEditField = uieditfield(app.UIFigure, 'numeric');
            app.GypsumEditField.Limits = [0 100];
            app.GypsumEditField.ValueChangedFcn = createCallbackFcn(app,
                @GypsumEditFieldValueChanged, true);
            app.GypsumEditField.Position = [303 193 114 33];

```

```
            % Create FibersEditFieldLabel
            app.FibersEditFieldLabel = uilabel(app.UIFigure);
            app.FibersEditFieldLabel.HorizontalAlignment = 'right';
            app.FibersEditFieldLabel.Position = [443 372 52 22];
            app.FibersEditFieldLabel.Text = 'Fibers %';

            % Create FibersEditField
            app.FibersEditField = uieditfield(app.UIFigure, 'numeric');
            app.FibersEditField.Limits = [0 100];
            app.FibersEditField.ValueChangedFcn = createCallbackFcn(app, @FibersEditFieldValueChanged, true);
            app.FibersEditField.Position = [510 372 114 33];

            % Create HDPEEditFieldLabel
            app.HDPEEditFieldLabel = uilabel(app.UIFigure);
            app.HDPEEditFieldLabel.HorizontalAlignment = 'right';
            app.HDPEEditFieldLabel.Position = [439 328 56 22];
            app.HDPEEditFieldLabel.Text = 'HDPE % ';

            % Create HDPEEditField
            app.HDPEEditField = uieditfield(app.UIFigure, 'numeric');
            app.HDPEEditField.Limits = [0 100];
            app.HDPEEditField.ValueChangedFcn = createCallbackFcn(app, @HDPEEditFieldValueChanged, true);
            app.HDPEEditField.Position = [510 328 114 33];

            % Create EPSEditFieldLabel
            app.EPSEditFieldLabel = uilabel(app.UIFigure);
            app.EPSEditFieldLabel.HorizontalAlignment = 'right';
            app.EPSEditFieldLabel.Position = [451 282 43 22];
            app.EPSEditFieldLabel.Text = 'EPS %';

            % Create EPSEditField
            app.EPSEditField = uieditfield(app.UIFigure, 'numeric');
            app.EPSEditField.Limits = [0 100];
            app.EPSEditField.ValueChangedFcn = createCallbackFcn(app, @EPSEditFieldValueChanged, true);
            app.EPSEditField.Position = [509 282 114 33];

            % Create SCEditFieldLabel
            app.SCEditFieldLabel = uilabel(app.UIFigure);
            app.SCEditFieldLabel.HorizontalAlignment = 'right';
            app.SCEditFieldLabel.Position = [458 236 36 22];
            app.SCEditFieldLabel.Text = 'SC %';

            % Create SCEditField
            app.SCEditField = uieditfield(app.UIFigure, 'numeric');
            app.SCEditField.Limits = [0 100];
            app.SCEditField.ValueChangedFcn = createCallbackFcn(app, @SCEditFieldValueChanged, true);
            app.SCEditField.Position = [509 236 114 33];

            % Create LQEditFieldLabel
            app.LQEditFieldLabel = uilabel(app.UIFigure);
            app.LQEditFieldLabel.HorizontalAlignment = 'right';
            app.LQEditFieldLabel.Position = [459 193 35 22];
            app.LQEditFieldLabel.Text = 'LQ %';

            % Create LQEditField
            app.LQEditField = uieditfield(app.UIFigure, 'numeric');
            app.LQEditField.Limits = [0 100];
```

```
            app.LQEditField.ValueChangedFcn = createCallbackFcn(app, @LQEditFieldValueChanged, true);
            app.LQEditField.Position = [509 193 114 33];

            % Create SelectcementtypeButtonGroup
            app.SelectcementtypeButtonGroup = uibuttongroup(app.UIFigure);
            app.SelectcementtypeButtonGroup.TitlePosition = 'centertop';
            app.SelectcementtypeButtonGroup.Title = 'Select cement type:';
            app.SelectcementtypeButtonGroup.Position = [26 193 197 157];

            % Create CEMIII525Button
            app.CEMIII525Button = uiradiobutton(app.SelectcementtypeButtonGroup);
            app.CEMIII525Button.Text = 'CEM III 52.5';
            app.CEMIII525Button.Position = [52 95 89 27];
            app.CEMIII525Button.Value = true;

            % Create CEMIII425Button
            app.CEMIII425Button = uiradiobutton(app.SelectcementtypeButtonGroup);
            app.CEMIII425Button.Text = 'CEM III 42.5';
            app.CEMIII425Button.Position = [52 64 95 32];

            % Create CEMI525Button
            app.CEMI525Button = uiradiobutton(app.SelectcementtypeButtonGroup);
            app.CEMI525Button.Text = 'CEM I 52.5';
            app.CEMI525Button.Position = [52 38 95 32];

            % Create CEMI425Button
            app.CEMI425Button = uiradiobutton(app.SelectcementtypeButtonGroup);
            app.CEMI425Button.Text = 'CEM I 42.5';
            app.CEMI425Button.Position = [52 11 82 33];

            % Create Panel
            app.Panel = uipanel(app.UIFigure);
            app.Panel.TitlePosition = 'centertop';
            app.Panel.FontWeight = 'bold';
            app.Panel.Position = [27 34 592 106];

            % Create WAofCATextAreaLabel
            app.WAofCATextAreaLabel = uilabel(app.Panel);
            app.WAofCATextAreaLabel.HorizontalAlignment = 'right';
            app.WAofCATextAreaLabel.FontWeight = 'bold';
            app.WAofCATextAreaLabel.Position = [24 69 81 22];
            app.WAofCATextAreaLabel.Text = 'WA of CA [%]';

            % Create WAofCATextArea
            app.WAofCATextArea = uitextarea(app.Panel);
            app.WAofCATextArea.ValueChangedFcn = createCallbackFcn(app, @WAofCATextAreaValueChanged, true);
            app.WAofCATextArea.Editable = 'off';
            app.WAofCATextArea.HorizontalAlignment = 'center';
            app.WAofCATextArea.FontWeight = 'bold';
            app.WAofCATextArea.Position = [14 33 101 37];

            % Create dayCSMPaTextAreaLabel
            app.dayCSMPaTextAreaLabel = uilabel(app.Panel);
            app.dayCSMPaTextAreaLabel.HorizontalAlignment = 'right';
            app.dayCSMPaTextAreaLabel.FontWeight = 'bold';
            app.dayCSMPaTextAreaLabel.Position = [164 69 92 22];
            app.dayCSMPaTextAreaLabel.Text = '7-day CS [MPa]';
```

```
            % Create dayCSMPaTextArea
            app.dayCSMPaTextArea = uitextarea(app.Panel);
            app.dayCSMPaTextArea.ValueChangedFcn = createCallbackFcn(app, @dayCSMPaTextAreaValueChanged, true);
            app.dayCSMPaTextArea.Editable = 'off';
            app.dayCSMPaTextArea.HorizontalAlignment = 'center';
            app.dayCSMPaTextArea.FontWeight = 'bold';
            app.dayCSMPaTextArea.Position = [160 33 101 37];

            % Create dayCSMPaTextArea_2Label
            app.dayCSMPaTextArea_2Label = uilabel(app.Panel);
            app.dayCSMPaTextArea_2Label.HorizontalAlignment = 'center';
            app.dayCSMPaTextArea_2Label.FontWeight = 'bold';
            app.dayCSMPaTextArea_2Label.Position = [302 69 99 22];
            app.dayCSMPaTextArea_2Label.Text = '28-day CS [MPa]';

            % Create dayCSXMPaTextArea
            app.dayCSXMPaTextArea = uitextarea(app.Panel);
            app.dayCSXMPaTextArea.ValueChangedFcn = createCallbackFcn(app, @dayCSXMPaTextAreaValueChanged, true);
            app.dayCSXMPaTextArea.Editable = 'off';
            app.dayCSXMPaTextArea.HorizontalAlignment = 'center';
            app.dayCSXMPaTextArea.FontWeight = 'bold';
            app.dayCSXMPaTextArea.Position = [300 33 101 37];

            % Create EquivalentaircontentTextAreaLabel
            app.EquivalentaircontentTextAreaLabel = uilabel(app.Panel);
            app.EquivalentaircontentTextAreaLabel.HorizontalAlignment = 'right';
            app.EquivalentaircontentTextAreaLabel.FontWeight = 'bold';
            app.EquivalentaircontentTextAreaLabel.Position = [431 69 152 22];
            app.EquivalentaircontentTextAreaLabel.Text = 'Equivalent air content [%]';

            % Create EquivalentaircontentTextArea
            app.EquivalentaircontentTextArea = uitextarea(app.Panel);
            app.EquivalentaircontentTextArea.ValueChangedFcn = createCallbackFcn(app, @EquivalentaircontentTextAreaValueChanged, true);
            app.EquivalentaircontentTextArea.Editable = 'off';
            app.EquivalentaircontentTextArea.HorizontalAlignment = 'center';
            app.EquivalentaircontentTextArea.FontWeight = 'bold';
            app.EquivalentaircontentTextArea.Position = [456 33 101 37];

            % Create CALCULATEButton
            app.CALCULATEButton = uibutton(app.UIFigure, 'push');
            app.CALCULATEButton.ButtonPushedFcn = createCallbackFcn(app, @CALCULATEButtonPushed, true);
            app.CALCULATEButton.BackgroundColor = [0.8 0.8 0.8];
            app.CALCULATEButton.FontSize = 13;
            app.CALCULATEButton.FontWeight = 'bold';
            app.CALCULATEButton.Position = [165 149 345 30];
            app.CALCULATEButton.Text = 'CALCULATE';

            % Create PredictivemodelLabel
            app.PredictivemodelLabel = uilabel(app.UIFigure);
            app.PredictivemodelLabel.FontSize = 18;
            app.PredictivemodelLabel.FontWeight = 'bold';
            app.PredictivemodelLabel.FontColor = [0.149 0.149 0.149];
            app.PredictivemodelLabel.Position = [254 450 154 23];
            app.PredictivemodelLabel.Text = 'Predictive model ';
```

```
            % Create Label
            app.Label = uilabel(app.UIFigure);
            app.Label.FontSize = 14;
            app.Label.FontWeight = 'bold';
            app.Label.Position = [92 429 492 22];
            app.Label.Text = 'Concrete compressive strength based on level of
                contamination of RCA';

            % Show the figure after all components are created
            app.UIFigure.Visible = 'on';
        end
    end

    % App creation and deletion
    methods (Access = public)

        % Construct app
        function app = app1

            % Create UIFigure and components
            createComponents(app)

            % Register the app with App Designer
            registerApp(app, app.UIFigure)

            if nargout == 0
                clear app
            end
        end

        % Code that executes before app deletion
        function delete(app)

            % Delete UIFigure when app is deleted
            delete(app.UIFigure)
        end
    end
end
```