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A Proof of Concept

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Innovative Application of Self-Healing Technology to Masonry: A Proof of Concept

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ABSTRACT

Cracks represent a prevalent form of damage in masonry structures, posing not only aesthetic concerns but also compromising structural durability; therefore, they are undesirable and need to be repaired. The repointing technique is traditionally implemented in this context, especially in historical masonry. However, this method fails to provide a long-term solution, leaving structures vulnerable to future damage. The paper investigates the applicability of a bio-based self-healing mortar to enable autonomous repair of masonry. This innovative mortar, developed to repair concrete structures, was implemented to explore the capacity of couplets to recover their original bond capacity and aesthetic aspect after multiple damaging events. Specimens built with calcium-silicate and clay bricks were subjected to subsequent cracking cycles using a crack-mouth-opening -displacement controlled bond-wrench test. Experimental results showed that self-repair, in terms of bond restoration and aesthetic filling of cracks, occurs even after multiple cracking cycles when the bio-based mortar is used with both types of bricks, optimizing the autogenous healing (intrinsic) of cement-based mortars. The effectiveness varied also according to the types of brick and healing environment used, e.g. under humid conditions (RH ~ 95%), 50% vs 80% of the original capacity was regained in fully separated couplets made respectively with clay and calcium-silicate bricks.

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1. Introduction

In pursuit of a secure, cost-effective, and sustainable future, there is a growing focus on preserving existing buildings and infrastructure through the implementation of effective repair techniques. This emphasis is particularly directed towards unreinforced masonry (URM), which constitutes a significant portion of both contemporary and historic structures worldwide, often susceptible to displaying damage over time. Such damage typically manifests as cracks at the brick-to-mortar interface or within the mortar and bricks themselves, detracting from the aesthetic appeal of the building and potentially compromising its structural integrity. In fact, cracks reflect a loss of strength, not being able to carry tensile stresses and having a much-reduced shear capacity. In addition, the component's watertightness or impermeability is compromised, allowing the ingress of water which might further weaken the masonry through salt crystallisation decay, freeze-thaw damage, and/or leaching. In this light, cracks in structures are undesirable and should be prevented or at least repaired.

The repointing technique is commonly used to repair cracks, at the brick-to-mortar interface or within the mortar joint, due to its limited invasiveness and the ability to preserve the original aesthetics of the structure (Korany 2011). Particularly suited for historical buildings where aesthetic integrity is paramount, this method involves removing deteriorated mortar and replacing it with compatible new material. However, while repointing restores strength, watertightness, and aesthetics, it does not prevent future damage. Factors like settlement or vibration, which initially caused the cracks, may lead to their reappearance, necessitating further repairs. This not only entails additional maintenance costs but also diverges from the primary goal of restoration, which aims for minimal intervention.

This paper presents pioneering research investigating the use of bacteria-based self-healing mortar as repointing material for masonry. Originally developed for the repair of concrete structures (Jonkers 2014; Mors and Jonkers 2015; Sierra-Beltran, Jonkers, and Schlangen 2014) and already commercialized in the Netherlands (Basilisk, Delft, The Netherlands), this innovative mortar can repair itself

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by recovering its original set of properties (watertightness, aspect) after degradation or damage has occurred. Its self-repair mechanism relies on the incorporation of "limestone-producing bacteria" within the mortar paste, along with their nutrients. Upon encountering water within a crack, dormant bacterial spores activate and metabolize nutrients, leading to the precipitation of limestone (calcium carbonate). This process, known as autonomous healing, enhances the mortar's innate ability to self-heal cracks up to 0.1 mm in width, the so-called "autogenous healing". As a result, massive limestone deposition is obtained, filling in and effectively sealing the crack. By enabling the repair of larger cracks through bacterial action, this technology offers the potential for substantial reductions in maintenance costs and the avoidance of further interventions. However, while the benefits of implementing this technology in masonry structures are promising, its adaptation from concrete to masonry warrants thorough validation.

To this purpose, a pilot investigation was conducted at Delft University of Technology to examine the mortar's feasibility in repairing masonry couplets, explore the influence of the healing environment on the healing process, and compare the effectiveness of bacterial healing to autogenous healing. In this context, two different types of brick (calcium-silicate and clay) were selected based on their distinct absorption properties, and three different healing conditions were considered: humid conditions (RH95%), wet-dry cycles, and drier conditions (RH70%). The efficacy of the technology was evaluated through two key parameters: (i) peak force recovery, measured periodically using a computer-controlled bond wrench test set-up on the specimens, and (ii) crack filling (an aesthetic property), documented through photographs taken before and after each healing period. This paper details the materials and methods employed, presents the results, and outlines the main conclusions drawn from this experimental study.

2. Materials and methods

The pilot program aimed to assess the viability of bio-based self-healing technology in masonry. In particular, the feasibility of the mortar to repair masonry couplets, the influence of the healing environment on the self-healing process, and the effectiveness of autonomous healing compared to autogenous healing were investigated. To achieve these objectives, couplets were built and subjected to multiple cracking-healing cycles; their capacity to recover the original bond and aesthetic aspect was thoroughly examined. The materials used and experiments conducted for this purpose are elaborated upon in this section.

2.1. Bio-based self-healing mortar and reference mortar

The cast of self-healing masonry specimens employed a one-component, ready-to-mix self-healing mortar, commercially available for concrete repair in the Netherlands by Basilisk, i.e. Basilisk Repair Mortar MR3.

The autonomous self-healing capabilities of the mortar stem from an added-in bio-based agent (Jonkers 2014), which includes a bacterial substrate in poly-lactic acid, bacterial spores derived from alkaliphilic (alkali-resistant) *Bacillus cohnii*-related strains, and a combination of essential organic and inorganic nutrient salts. This formulation relies on a high-alkaline environment, such as that found in cement-based mortars with a pH of 12–13, to catalyse the hydrolysis of the substrate into calcium lactate ($CaC_6H_{10}O_6$), thereby making it suitable for bacterial conversion. At this point, when cracks develop and water infiltrates, dormant bacteria spores activate, multiply thanks to specific growth-required nutrients, and, in the presence of oxygen, metabolically convert the previously hydrolysed substrate, resulting in calcium carbonate ($CaCO_3$) precipitation:

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

During the aerobic activity of the bacteria, carbon dioxide (CO_2) is produced on-site, which contributes to the natural carbonation of the cement paste due to atmospheric carbon dioxide diffusion. Consequently, additional calcium carbonate precipitates through the reaction between carbon dioxide and calcium hydroxide ($Ca(OH)_2$):

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

This combination of bacterial conversion and enhanced carbonation leads to massive calcium carbonate precipitation, effectively sealing the crack.

The employed mortar consists of Portland cement, limestone powder, fly ash, selected aggregates, and additives, as specified by the manufacturer. Further insights into the mortar's composition can be found in preliminary mix designs investigated during experimental studies conducted before the product's marketing phase (e.g. Sierra-Beltran, Jonkers, and Schlangen (2014)), being the composition of the commercialized version confidential. According to the manufacturer specifications, the R3-type mortar possesses a compressive strength of 37.7 MPa and a flexural strength of 7 MPa at 28 days.

Alongside the ready-to-mix bio-based self-healing mortar, a reference mortar lacking the added-in healing agent was implemented for casting reference specimens. This set of specimens served to distinguish between autonomous and autogenous healing, thereby validating the agent's benefits (Section 5.2).

2.2. Clay and calcium silicate bricks

Masonry specimens were cast using two types of bricks, i.e. clay and calcium-silicate (Table 1). These bricks were chosen due to their different absorption properties, herein quantified through the initial rate of absorption (IRA) (CEN 2011) and the rate's evolution over time, experimentally determined by Gaggero et al. in (Gaggero et al. 2019) (Figure 1). Please note that the bricks used in both this research and the study by Gaggero et al. (2019) were derived from the same production batch and stored in a closed space at room temperature.

Opting for bricks with completely different absorption properties was based on their role as mediators between the external healing environment and the crack location (brick-to-mortar interface or within the mortar). This intermediary role contributes significantly to creating the appropriate environment near the crack, guaranteeing the presence of essential elements: oxygen and water. Indeed, the self-healing process relies on the presence of water to activate dormant bacteria and oxygen for the bacterial conversion of nutrients (in this case poly-lactic acid PLA), which are also introduced into the mortar through the healing agent (the reader is referred to section 2.1). Consequently, the simultaneous presence of both elements at the crack site is essential for the success of self-healing, with the absorption properties of the brick serving as a critical factor in facilitating this condition. For instance, in this research, the clay bricks considered displayed a much quicker absorption rate compared to calcium-silicate ones, saturating within an hour when a brick's face is immersed in water.

2.3. Masonry couplets

Masonry specimens consisted of pairs of bricks joined together by a 10 mm thick mortar joint (Figure 2). These paired units, known as "couplets," were entirely cast with either the bio-based self-healing mortar or the reference mortar, henceforth referred to as bio-based couplets or reference couplets respectively. Notably, repointed couplets were deliberately excluded from the study, as the primary focus was solely on assessing the viability of the mortar for repairing masonry cracks.

To ensure uniformity across all specimens, plastic jigs were employed to align the bricks accurately and maintain a consistent 10 mm mortar joint during construction. In addition, a different mix fluidity was employed for both brick types due to their different absorption properties — specifically, water-to-cement

Table 1. Properties of clay and calcium-silicate bricks employed: dimensions, compressive strength, and initial rate of absorption.

Type	Length (mm)	Width (mm)	Height (mm)	Compressive strength (MPa)	Initial rate of absorption (kg/m^2)
Clay	210	100	50	28.31	3.3
Calcium-silicate	210	100	70	13.26	1.0

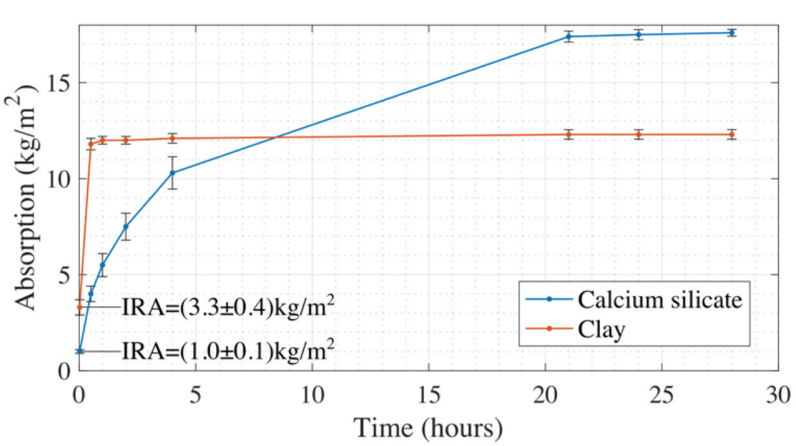


Figure 1. Cumulative water absorption rate of both types of bricks determined by Gaggero et al. (2019).

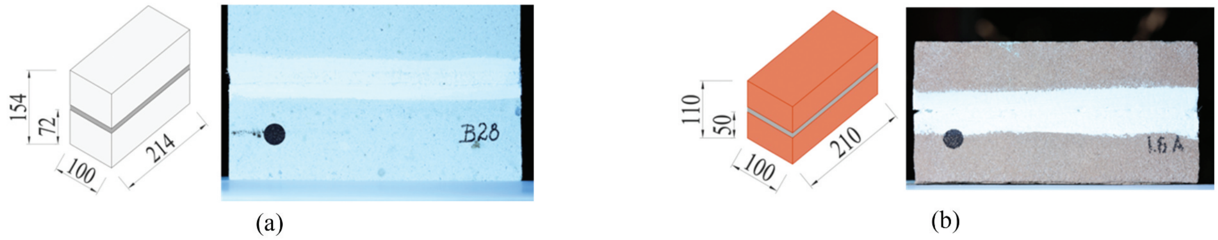


Figure 2. (a) Calcium-silicate and (b) clay brick masonry couplets.

ratios of 0.45 and 0.72 for calcium-silicate and clay couplets, respectively. These ratios were experimentally determined by Gaggero and Korswagen (2021) to enhance masonry bond properties. Given the common high scatter of results observed in bond tests, the enhancement of bond strength can lead to reduced variability (Gaggero and Esposito 2021), thereby enabling more solid conclusions to be drawn from experimental data. Furthermore, the implementation of a different mix fluidity according to the brick type led to a different failure mechanism: at the brick-to-mortar interface for calcium-silicate couplets and within the mortar joint for clay couplets. This allowed exploration of the mortar's capacity in two different scenarios that could have varied effectiveness in terms of repair. Although cracks at the brick-to-mortar interface are more common in masonry structures, this scenario might be expected to progress more slowly, with calcium carbonate production potentially occurring only on one side of the crack.

2.4. Cracking cycles

Systematic bond wrench tests were conducted to induce cracking in (bio-based and reference) specimens and assess their healing capabilities. For this purpose, a CMOD (crack-mouth-opening-displacement) control setup (Figure 3), developed at Delft University of Technology (Gaggero and Esposito 2021), was employed. Unlike the standard force-controlled configuration, which may lead to sudden and complete failure of specimens, this setup allows for precise regulation of the cracking process, ensuring consistent crack initiation and propagation across different specimens.

Following the standard procedure (CEN 2005), the test involves applying an eccentric vertical load to the couplet while being rigidly restrained from its bottom brick via a bottom clamp. In this case, a 500 kN hydraulic jack, operating in displacement control, was used to apply the vertical load at the free end of a lever arm connected to the specimen through a top clamp. The relative vertical displacement between the two clamps, securing the specimen from its bottom and top, served as the control variable, while two LVDTs affixed on the opposite tension sides of the sample monitored the actual width of the induced bending crack.

This setup facilitated the pre-cracking of specimens at specific intensities, such as 0.2 mm or 1 mm, before initiating the healing phase. Specimens pre-cracked to a CMOD of 0.2 mm were classified as partially cracked couplets, indicating that partial load transfer is still possible. Meanwhile, couplets tested until failure, termed as fully cracked couplets, signifying no load transfer is possible due to complete breakage. The latter case enabled observation of the

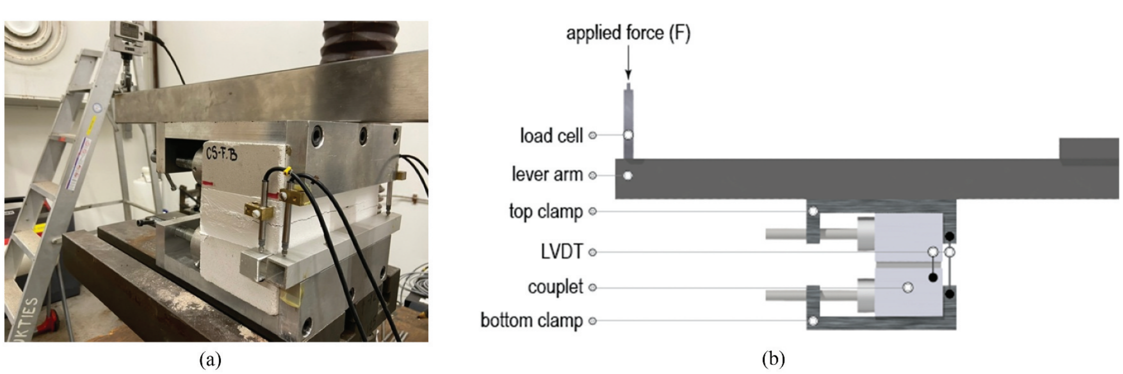


Figure 3. (a) Computer-controlled bond-wrench test set-up used for testing (Gaggero and Esposito 2021) with (b) schematic view.

fracture area, determination of the location of failure (brick–mortar interface or within the mortar joint), and examination of the presence of calcium carbonate precipitation.

2.5. Healing periods

Between subsequent tests, i.e. following cracking cycles, the specimens underwent a 65-day healing period in specific environments tailored to facilitate the self-healing process by providing the required water and oxygen. Depending on the specimen set under consideration, diverse healing environments were employed, including humid conditions (with relative humidity around 95%), wet-dry cycles, and drier conditions (with relative humidity around 70%).

Humid conditions were maintained within a fog room, whereas drier conditions were simulated in a conditioning room. Wet-dry cycles were induced by periodically wetting the specimens stored in plastic boxes once a week, allowing water to be absorbed by the lower bricks or to evaporate. It's noteworthy to mention that wet-dry cycles have been recognized as particularly effective in promoting the carbonation of mortars, facilitating the self-healing process.

2.6. Assessment of self-healing capacity of bio-based and reference couplets

The performance of multiple cracking-healing cycles provided a framework for assessing the self-healing capacity of (bio-based and reference) couplets in terms of mechanical recovery and aesthetic restoration.

Mechanical recovery was assessed in terms of peak-force recovery from subsequent cracking cycles conducted with the bond wrench test. Specifically, the original capacity of the specimen, measured as the peak force obtained after casting at 7 or 28 days (denoted as F_0), was compared to the healed peak force obtained in subsequent cracking cycles (denoted as F_i), with each cycle executed after a specified healing period. This comparison facilitated the quantification of the degree of recovery against the original capacity. The healing ratio (%), denoted as (F_i/F_0, where "i" indicates the number of the cracking cycle), was computed for this purpose. A healing ratio of 100% indicated full recovery, meaning the specimen regained its original capacity (F_0) . Ratios less than 100% represented partial recovery, indicating that a fraction of the original capacity was restored (e.g., 50% denoted half of the original capacity), while a ratio of 0% indicated that the mortar was unable to restore any capacity. Healing ratios higher than 100% suggested that the couplet exhibited increased strength, surpassing its original capacity.

Simultaneously, visual assessment was employed to evaluate the aesthetic restoration of the specimens, focusing on the filling of induced cracks. Before-and-after photographs taken at each cracking-healing cycle were compared to gauge the extent of aesthetic restoration. To enhance crack visibility, the bed joints of all specimens were painted white using water-based acrylic paint, chosen for its water permeability to minimize interference with the self-healing process. Additionally, a 15 mm diameter circle marked on each specimen's face provided a reference scale in the accompanying photographs.

3. Experimental results

The results obtained from the multiple cracking cycles are listed by the set's goal in Table 2. According to the set's goal, the specimen's type (mortar and brick type), cracking specifics (hardening time at which pre-cracking was carried out, CMOD cracking intensity, i.e. partially or fully separated, and the number of specimens tested) and healing environment used is specified. The peak force F_i obtained with the bond wrench test is reported specifying the number of the relative cracking cycle by the subscript "i". Since the width of the crack induced in each specimen was always the same for subsequent cycles, only the width for the first cracking cycle was reported (CMOD).

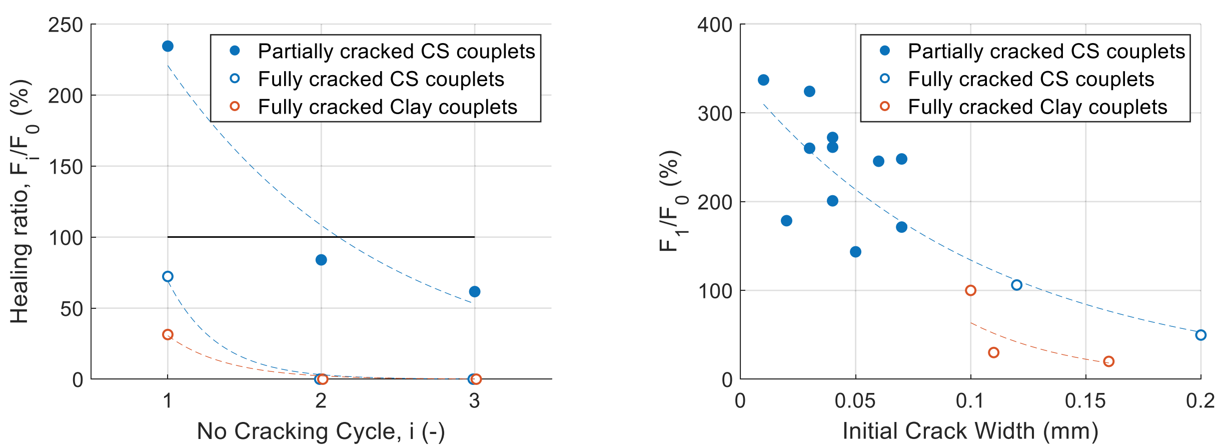
4. Viability of bio-based mortar for self-repairing masonry couplets

This section delves into the viability of implementing the proposed bio-based mortar for autonomous repair of masonry couplets, specifically focusing on its efficacy under humid conditions. Assessment covers both mechanical (Figure 4) and aesthetic (Figure 5) aspects of restoring clay and calcium-silicate bio-based couplets. Figure 4a illustrates the healing ratio relative to the number of cracking cycles, while Figure 4b presents the healing ratio computed in the initial cycle in relation to the width of the repaired crack. The latter parameter was determined as the average of the two LVDTs monitoring the induced crack on either side of the specimen post-load removal, indicating the residual crack at the end of the test. Trend lines have been incorporated into both graphs to highlight discernible patterns. For detailed information on the assessment of the healing ratio, the reader is referred to Section 2.6.

The findings reveal that autonomous self-repair in terms of peak force recovery (Figure 4) indeed

Table 2. Experimental results obtained per set-goal: width of the induced crack (CMOD) and peak force (F_i) measured with the bond-wrench test for cracking cycle i, with relative coefficient of variation specified in brackets (%). The specimen's type (mortar and brick type) tested, cracking specifics (hardening time at which pre-cracking was carried out, CMOD cracking intensity, i.e. partially or fully separated, and the number of specimens tested) and healing environment used are indicated for each set.

Set-goal	Mortar type	Brick type	Hardening time at pre-cracking (days)	Partially/ Fully separated	(No. tests)	Healing environment	Experimental results: CMOD (mm)		F_i: F_0 (N)		F_1 (N)		F_2 (N)		F_3 (N)	
Applicability of the self-healing mortar	Bio-based	CS	7	Partially	(11)	RH~95%	0.04	(46)	98	(25)	229	(26)	82	(37)	60	(81)
				Fully	(2)		0.2	(35)	83	(28)	60	(25)	0	(-)	0	(-)
		Clay		Fully	(3)		0.1	(21)	261	(54)	82	(11)	0	(-)	0	(-)
Influence of healing environments	Bio-based	CS	28	Partially	(5)	RH~95%	0.2	(32)	245	(30)	107	(102)	-		-	
					(5)	Wet-dry cycles	0.2	(14)	298	(18)	67	(53)	-		-	
					(5)	RH~70%	0.2	(23)	277	(41)	62	(56)	-		-	
		Clay		Partially	(5)	RH~95%	0.3	(19)	453	(12)	214	(50)	-		-	
					(5)	Wet-dry cycles	0.3	(17)	414	(34)	230	(36)	-		-	
					(5)	RH~70%	0.3	(27)	404	(32)	198	(45)	-		-	
Bacterial vs autogenous healing	Bio-based	CS	28	Partially	(5)	RH~95%	0.1	(57)	52	(45)	182	(30)	50	(66)	-	
				Fully	(5)		0.3	(35)	61	(41)	45	(120)	2	(224)	-	
			93	Partially	(5)		0.1	(40)	321	(28)	61	(24)	-		-	
				Fully	(5)		0.5	(36)	299	(70)	5	(140)	-		-	
			158	Fully	(10)		-		329	(40)	-		-		-	
	Reference		28	Partially	(5)		0.1	(16)	48	(20)	146	(80)	17	(60)	-	
				Fully	(5)		0.2	(19)	37	(30)	12	(60)	0.0	(-)	-	
			93	Partially	(5)		0.1	(13)	164	(40)	16	(10)	-		-	
				Fully	(5)		0.7	(54)	129	(30)	0	(-)	-		-	
			158	Fully	(5)		-		113	(52)	-		-		-	



(a) (b)

Figure 4. Performance of bio-based couplets built with clay and calcium silicate bricks: (a) peak force after multiple cracking-healing cycles with the relative healing ratio (F_i/F_0) computed against the original capacity assessed at 7 days; (b) healing ratio (F_2/F_0) against the width of the repaired crack.

occurs irrespective of the type of brick when employing the bio-based self-healing mortar. Despite a noticeable performance gap between the two brick types studied, pre-cracked bio-based couplets exhibited the capacity to repair induced cracks either fully or partially. The effectiveness of the process was notably influenced by both the number of cycles performed (Figure 4a) and the crack width (Figure 4b).

The investigation into the multiple cracking-healing cycles of calcium-silicate couplets (represented in blue) indicate that the autonomous self-healing properties of the mortar are effective even for multiple damaging events, provided cracks do not exceed 0.1 mm. On average, these couplets regained 240% of the original strength after the first healing cycle, followed by subsequent cycles showing 90% and 60% recovery, respectively. This trend underscores an inverse relationship

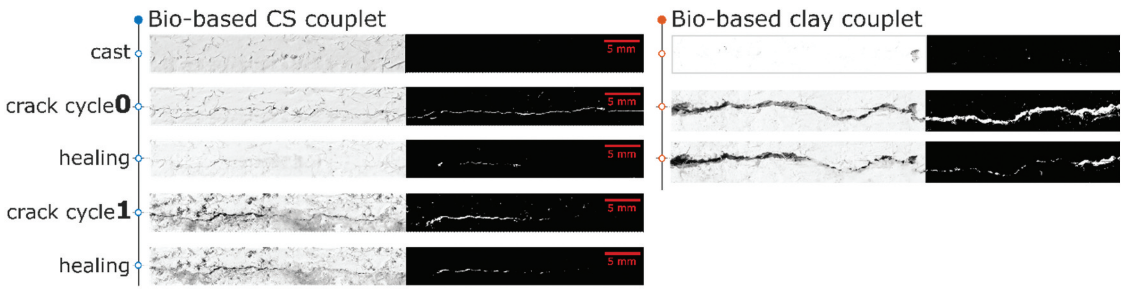


Figure 5. Fully cracked bio-based couplets before and after multiple cracking-healing cycles.

between healing efficiency and the number of cracking cycles, as depicted in Figure 4a. As damage accumulates, the healing properties gradually diminish, likely due to bacterial nutrient exhaustion. However, this challenge can be addressed in the strategy's design phase by adjusting agent dosages to anticipate both the frequency and size of expected cracks. Notably, crack width significantly influences performance, with fully cracked couplets exhibiting lower recovery rates compared to partially cracked ones, capable of regaining up to 80% of their original capacity only after the initial healing cycle. Figure 4b further illustrates this relationship, showing how the width of the repaired crack inversely affects the healing ratio. Within the fixed time frame of this study (65 days), larger cracks were reasonably repaired less effectively than smaller ones, suggesting a need for longer healing durations for specimens with larger crack amplitudes and multiple cracking cycles.

The findings from clay couplets (depicted in orange) corroborate the previously discussed influence and shed light on the role of the healing environment, resulting in a less efficient healing process compared to CS couplets. Specifically, fully cracked clay specimens only managed to recover 30% of their original force capacity, contrasting with the 80% recovery observed in CS specimens. This difference primarily stems from the humid healing environment (RH > 95%), which left the couplets saturated after the healing period, hindering healing development due to the lack of essential oxygen for aerobic bacteria conversion. This excessive moisture can be attributed to the clay bricks' absorption properties and earlier saturation compared to CS bricks (Figure 1). To potentially enhance results with clay bricks, employing a fog room with lower relative humidity or incorporating wet-dry cycles could be explored. Thus, achieving optimal healing conditions necessitates consideration of the specific characteristics of the brick type under study.

Visual observation of calcium carbonate deposition (Figure 5) highlights the mortar's effectiveness not only in mechanical repair but also in enhancing visual appeal. The photographs captured before and after each healing cycle, reported in Figure 5, show that cracks can be filled with calcium-carbonate deposition, fully or partially recovering the original aesthetics of the specimens. In alignment with the observations regarding mechanical recovery, the restoration of aesthetics declines as the number and width of induced cracks increase.

5. Sensitiveness and effectiveness of the self-healing process

5.1. Comparison against multiple healing environments

This section explores the impact of various healing environments on the efficacy of repairing bio-based couplets. Building upon the insights from Section 4, where notable differences in performance were observed under humid conditions (RH95%) for bio-based specimens constructed with CS and clay bricks, alternative settings such as wet-dry cycles and dry conditions (RH70%) were investigated. The outcomes obtained from the three different healing environments is depicted in Figure 6, in terms of healing ratio (Section 2.6).

The findings confirmed that the healing environment can significantly influence the performance of bio-based couplets. Optimal conditions are found to be contingent upon the type of brick used, particularly its absorption properties. Comparative evaluation of the results obtained with the selected environments (Figure 6) indicates that humid conditions and wet-dry cycles led to improved performance for CS and clay couplets, respectively. CS bricks, with their slow water absorption process, require a humid environment (RH95%) to consistently provide the necessary water for successful healing, whereas the wet-dry cycle environment, characterized by alternating high water supply and drying periods, proved optimal for clay bricks, which can absorb water faster and reach saturation earlier than CS bricks. On the other hand, excessive moisture, as

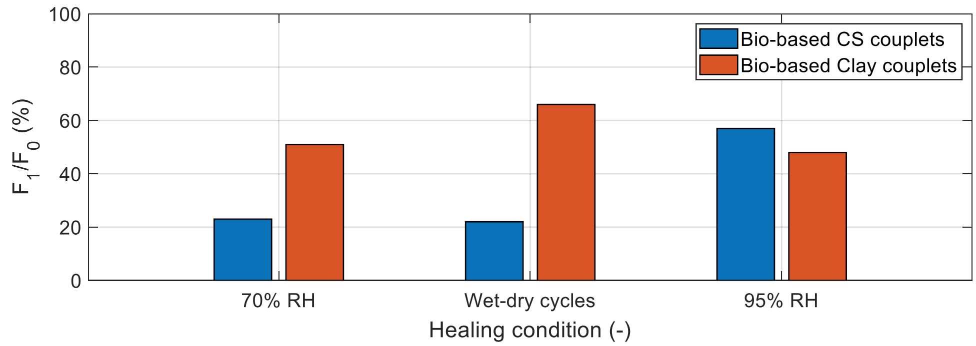


Figure 6. Comparison of peak force recovery across various environments for clay and CS couplets. Mean values derived from five specimens.

evidenced in the humid atmosphere (RH95%), proves detrimental for clay bricks, as noted in Section 4. Consequently, an excess or shortage of water, such as that encountered regardless of brick type in the curing room with lower relative humidity (RH ~ 70%), might prove to be deleterious.

Prior to practical implementation, it is advisable to conduct a preliminary suitability study aimed at identifying the optimal healing conditions tailored to the specific brick type and prevailing environmental conditions on-site. For instance, the climate in the Netherlands, characterized by an average annual humidity of about 80% and frequent rainfall throughout the year, presents favourable conditions for the adoption of this technology, particularly when paired with clay brick masonry.

5.2. Comparison against control mortar

This section explores the effectiveness of bio-based couplets by quantifying and comparing the contributions of autonomous healing (due to the added-in bio-based agent) and autogenous healing (mostly due to delayed hydration of un-hydrated cement grains). A clear distinction between these two mechanisms is crucial to verify the implementation of the agent, with autogenous healing representing the inherent capability of cement-based materials to repair cracks up to 0.1 mm in width, primarily through mechanisms such as cement paste rehydration. To this purpose, tests on two sets of couplets were considered: one constructed entirely with the proposed bio-based mortar (referred to as bio-based couplets) and the other with the relative reference mortar (referred to as reference couplets) which has the same composition as the bio-based mortar but lacks the healing agent. Both sets underwent identical curing history, being air-cured for the initial 28 days followed by placement in a fog room at 95% relative humidity. Specimens were tested at 28, 93 and 158 days to evaluate the influence of hardening time in both types of specimens (Figure 7). Furthermore, specimens tested at 28 and 96 days were then subjected to multiple healing-cracking cycles to validate the agent's effectiveness. This evaluation covered mechanical (Figures 8 and 10) and aesthetic (Figure 9) aspects, where applicable.

The analysis of peak force over time (Figure 7) suggests that autogenous healing concludes after 93 days (under humid conditions) and the inclusion of the bio-based agent may enhance masonry bond strength Upon examining the behavior of reference

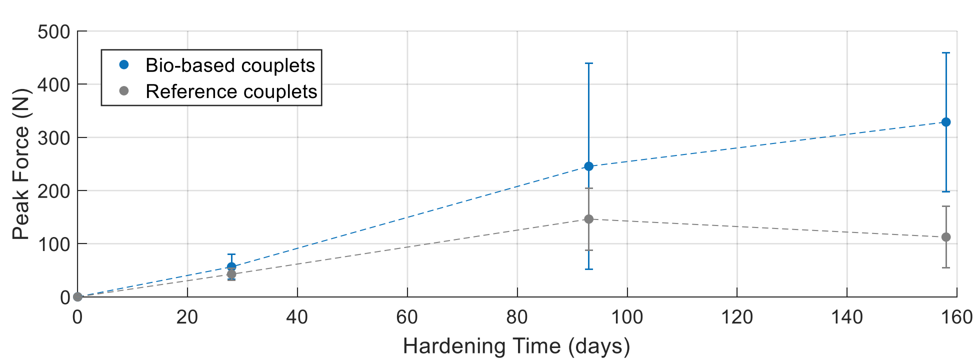


Figure 7. Peak force versus hardening time for bio-based and reference couplets. Each data point is based on mean values of ten specimens.

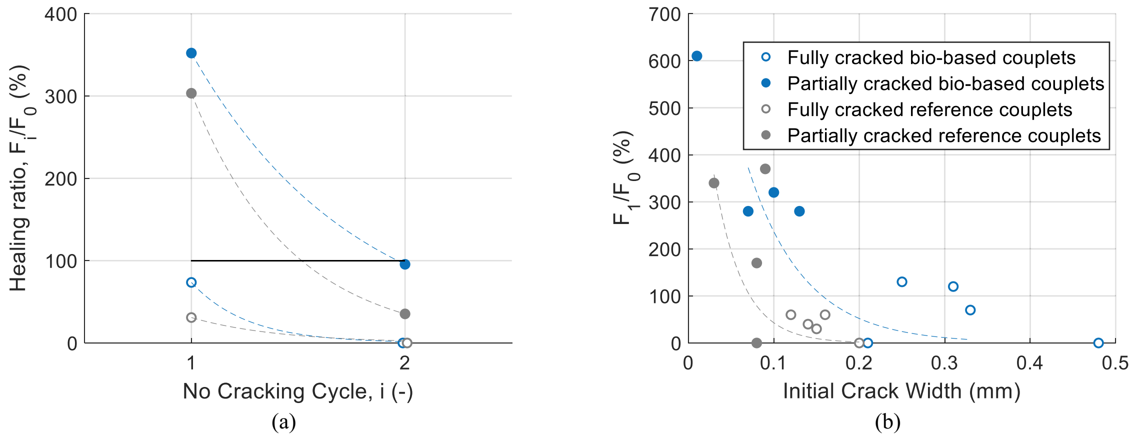


Figure 8. Effectiveness of bio-based couplets compared to reference couplets pre-cracked at 28 days: (a) peak force after multiple cracking-healing cycles with the relative healing ratio (F_i/F_0) computed against the original capacity obtained at first cracking cycle; (b) ratio (F_2/F_0) against the initial crack width, evaluated at the end of the first cracking cycle.

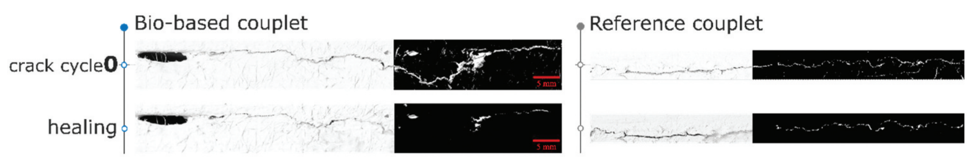


Figure 9. Bio-based and reference couplets before and after the first healing cycle.

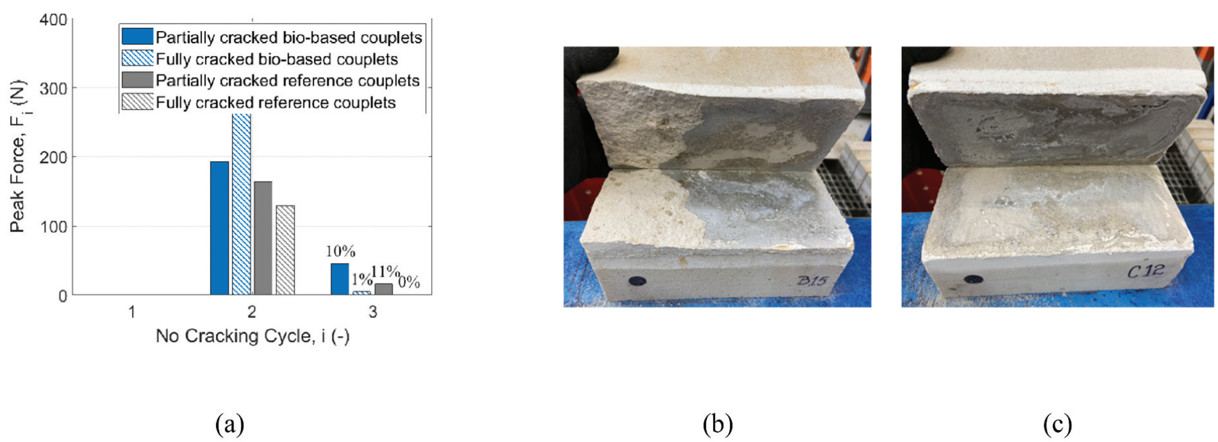


Figure 10. Effectiveness of bio-based couplets compared to reference couplets pre-cracked at 93 days: (a) peak force after multiple cracking-healing cycles with the relative healing ratio (F_i/F_0) computed against the original capacity obtained at first cracking cycle; failure mode obtained in (b) self-healing and (c) control couplets at 158 days.

couplets (depicted in blue), a force plateau emerges after 93 days, indicating the completion of cement paste hydration. This observation can reasonably be extended to bio-based couplets, given their identical mortar composition to the reference ones. Notably, bio-based couplets exhibited a force increase, likely attributable to the healing agent's presence. Although the tests were conducted on undamaged couplets, suggesting inactive bacteria, the incorporation of nutrients and other constituents from the agent may potentially boost bond strength.

The evaluation of multiple cracking-healing cycles on masonry couplets initially cracked at 28 days underscores the efficacy of the bio-based agent in optimizing both mechanical restoration (Figure 10) and aesthetic crack filling (Figure 9) resulting from autogenous healing. Notably, a comparison of healed peak force values from multiple cracking-healing cycles (Figure 10a) demonstrates the superior ability of bio-based couplets, outperforming control specimens, in recovering their original strength. For instance, fully cracked couplets cast with the bio-based mortar regained an average of

64% of their original peak force after the first healing cycle, whereas control specimens only recovered 37%. Furthermore, under conditions where cracks were confined to 0.1 mm, the bio-based mortar nearly restored its original peak force capacity (90%) after two subsequent crack-healing cycles, while reference mortar achieved less than half (40%). Besides the better performance as the number of cycles increases, bio-based couplets also showed a higher healing capability than control ones as the crack width increases (Figure 8b). Anyhow, an inverse relationship was observed between the healing ratio and the number of healing cycles (Figure 8a) and between the healing ratio and crack width (Figure 8b). These findings align with those discussed in the preceding Section 4, indicating no significant differences in bond capacity and healing percentage among bio-based couplets. Eventually, visual observation of calcium carbonate deposition (Figure 9) highlights the mortar's effectiveness in enhancing visual appeal. The images, documented before and after the first healing cycle and presented in Figure 9, illustrate the contrast: while cracks in bio-based couplets are filled with calcium carbonate deposition, those in reference couplets remain visibly open.

A less effective healing process was evident for specimens cracked at later stages, with only up to 10% of the original peak force, on average, being recovered (Figure 10a) for both bio-based and reference couplets. On one hand, the autogenous healing observed in control specimens, primarily attributed to delayed hydration of the cement paste, can be deemed concluded after 93 days. Consequently, no recovery due to autogenous healing could be expected, elucidating the inability of control specimens pre-cracked at 93 days to effectively heal induced cracks. Conversely, bio-based specimens face a different challenge: the occurrence of partial failure within the brick, such as delamination of the brick surface at the brick-to-mortar interface (Figure 10b). This inevitably rendered the autonomous self-healing properties of the mortar ineffective.

6. Conclusions

The repointing technique is often used to repair masonry cracks, especially in historical buildings, due to its limited invasiveness and the ability to restore the original strength, watertightness and aesthetic condition of the structure. However, without addressing the underlying causes of damage, recurring cracks may necessitate repeated repointing interventions. Introducing bio-based self-healing mortars present a promising avenue for autonomous crack repair, potentially reducing maintenance costs. While extensively studied and implemented in concrete structures, its adaptation to masonry remains unexplored. To assess its viability, a pilot program was conducted at Delft University of Technology, employing a currently marketed bio-based self-healing mortar initially developed for concrete repairs. The study involved subjecting masonry couplets built with clay and calcium-silicate bricks to multiple cracking-healing cycles using crack-mouth-opening-displacement (CMOD) controlled bond wrench test set-up, evaluating peak force restoration and assessing aesthetic recovery through before-and-after photographs.

The proposed bio-based mortar successfully enabled the self-repair of masonry couplets built with calcium-silicate (CS) and clay bricks. For both types of specimens, pre-cracked couplets entirely made with the bio-based self-healing mortar showed their capacity to partially or totally repair and fill induced cracks up to 0.2 mm width. This autonomous recovery was possible even after multiple damaging events, encompassing both force peak recovery and aesthetic restoration. For instance, CS couplets with cracks of up to 0.1 mm managed to recover 240%, 90%, and 60% of their original force capacity after successive cracking-healing cycles. Visual confirmation of the recovery further solidified the findings, as cracks visibly disappeared, being filled in with calcium carbonate deposition. This contributes to emphasizing the mortar's role in also enhancing the aesthetic appeal of the repaired surfaces.

The performance of bio-based couplets was notably affected by the number of cycles performed and the dimensions of cracks induced, with consistent healing time maintained throughout. As damage accumulated, the effectiveness of healing gradually decreased, likely due to bacterial nutrient depletion. To address this issue, adjusting agent dosages during the design phase could help anticipate crack frequency and size, thereby improving healing efficacy. Additionally, larger cracks were found to negatively impact the mortar's performance, indicating the necessity for longer healing durations when dealing with bigger cracks.

The successful implementation of clay and CS brick, having different absorption properties and surface roughness, showcased the versatility of the technology's application and the importance of the healing environment. In fact, the efficiency of the self-healing process varied according to the type of brick considered, mainly due to the healing environment used in combination. The importance of compatibility between brick's absorption characteristics and healing conditions was hereby highlighted. For instance, while calcium-silicate (CS) bricks exhibit superior healing efficacy in humid environments, clay bricks excel in wet-dry cycles, facilitating mortar carbonation — an advantage particularly beneficial for lime-based mortars prevalent in heritage structures. This underscores the technology's promising potential for heritage restoration, given the widespread use of porous clay bricks in such contexts. However, it is advisable to conduct a preliminary suitability assessment to determine the ideal healing conditions tailored to the specific brick type and prevailing environmental factors on-site. Regions like the Netherlands, known for frequent rainfall, offer favourable conditions for the successful implementation of this technology.

The repair potential of the bio-based mortar was further validated through a comparative analysis with reference couplets, with the latter devoid of the self-healing agent. The innate capacity of cement-based materials to repair cracks up to 0.1 mm, through the so-called "autogenous healing", was confirmed but appeared dwarfed by the efficacy of the bio-based mortar at this task. The bio-based couplets exhibited a superior ability to outperform control specimens in recovering their original strength. Remarkably, the bio-based mortar nearly restored its original peak force capacity (90%) after two subsequent crack-healing cycles, contrasting starkly with the reference mortar which achieved less than half (40%) when cracks were up to 0.1 mm. Moreover, aesthetic restoration was also greatly enhanced: cracks in bio-based couplets were filled with calcium carbonate deposition, whereas those in reference couplets remained visibly open.

The presented study provides initial insights into the application potential of self-healing technology in masonry laying the foundation for future investigation. Further research is required to determine the feasibility of the proposed repair measure as it is based on a limited number of tests and was conducted on a commercially available cement-based mortar, which is not commonly used for the repointing of masonry due to compatibility issues. Ensuring compatibility between the added-in agent and lime-based mortar is crucial for the successful implementation of such technologies in practical masonry applications.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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