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Exploring Bacteria-Based Self-healing Potential in Cement-Lime Mortar Masonry

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Abstract. The integration of bacteria-based self-healing mortars has emerged as a promising solution to address repair due to recurring cracks and preserving masonry durability. Building upon a recent pilot study demonstrating the efficacy of a self-healing agent in the repair of masonry made with cement-based mortar, this follow-up study explores the potential of integrating the added-in healing agent in a pre-bagged cement-lime mortar - more commonly used in masonry applications. Through bond wrench tests and a 30-day healing period involving wet-dry cycles, the study evaluates aesthetic and flexural bond strength recovery of couplets built with solid clay bricks. Results showed that the addition of the agent altered the initial flexural bond strength, with bacteria-based masonry couplets four times stronger than the plain reference ones - without containing the agent. The mortar's color was also affected. Additionally, bacteria-based specimens demonstrated automatic repair, restoring up to 33% of the original flexural bond strength, while reference masonry couplets showed no evidence of autonomous healing. However, instances of leaching, possibly attributed to the agent's substrate, prompted a revision of the strategy employed for the healing environment. Further research will specifically target the observed leaching issue by exploring the effects of multiple healing environments.

Keywords: Lime · Masonry · Heritage · Repair · Self-healing · Bacteria

1 Introduction

Cracks in masonry structures pose significant challenges, compromising both their structural integrity and aesthetic appeal. Traditional repair methods like repointing offer temporary fixes but often fail to address the underlying causes of damage, leading to recurrent repairs and contradicting the principle of minimal intervention, crucial for conservation efforts.

In recent years, interest has emerged in integrating bacteria-based self-healing mortars into the repointing process, leveraging innovations initially developed for concrete repair [1, 2]. While this combined approach does not tackle the root causes of damage, it holds promise for autonomous repair, potentially providing a long-lasting solution. A pioneering study by Gaggero et al. [3] investigated the effectiveness of a cement-based polylactic acid (PLA) self-healing mortar, commercially available for concrete

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repairs in the Netherlands (Basilisk) [4], in restoring masonry couplets constructed with calcium silicate and clay bricks. The study yielded encouraging results, demonstrating the mortar's ability to self-recover the original force bond capacity even after multiple cycles of cracking and fill effectively cracks up to 0.2 mm in width. The efficacy of self-healing varied depending on the type of brick used, with wet-dry cycles showcasing superior performance in samples constructed with clay bricks, found in historical structures. Nevertheless, substantial research is still required before the practical application of this innovative approach. In case of heritage conservation, cement-based mortars, for instance, commonly face compatibility issues with existing masonry, whereas lime-based mortars are often preferred. Thus, a critical question arises: To what extend is the incorporation of the PLA bacteria-based healing agent compatible with lime-based mortars?

To address this gap, this follow-up study conducted at Delft University of Technology aims to explore the compatibility and effectiveness of the above-mentioned PLA bacteria-based self-healing agent in repairing masonry built with a cement-lime mortar. In pursuit of this objective, masonry couplets were constructed and subjected to controlled cracking cycles using bond wrench tests. The study evaluated the influence of the healing agent on the flexural bond strength and its capability to restore bonding integrity after a 30-day healing period. This paper outlines the materials and methods employed, presents the findings, and discusses the main conclusions drawn. These outcomes are currently used to delve deeper into the potential of the bacteria-based agent in lime-based mortars, typical of historical constructions. Ongoing efforts entail assessing the recovery in terms of flexural behavior, water tightness, and aesthetics across various healing environments, while also delving into the effects of the agent on (physical and mechanical) properties of the mortar - crucial for ensuring compatibility in practical applications.

2 Materials and Methods

To explore the potential compatibility between the selected poli-lactic acid (PLA) bacteria-based self-healing agent and cement-lime mortar masonry, couplets were constructed and subjected to subsequent bond wrench tests, with a 30-day healing period under wet-dry cycles in between.

To this purpose, clay bricks with nominal dimensions of 210 $\times$ 50 $\times$ 100 mm^3 and a compressive strength of 28.31 MPa were used to cast masonry samples. These bricks were paired with a ready-to-mix 1:2:9 (cement: lime: sand proportions by volume) cement-lime mortar. This masonry type, utilized extensively in a multi-scale experimental campaign to assess Dutch buildings subject to induced seismicity [5–7], is characterized by poor bond, a common feature of historical structures or those undergoing deterioration.

To confer autonomous self-healing properties to the mortar, a PLA bacteria-based self-healing agent [4], commercially available from Basilisk in the Netherlands, was incorporated at concentrations of 5% and 15% of the total binder mass. A previous pilot study [3] confirmed the compatibility of this agent with bricks when used in a cement-based mortar. The agent consists of dormant bacterial spores sourced from alkaliphilic strains related to Bacillus cohnii, embedded in a PLA substrate along with other necessary growth nutrients. The self-healing mechanism initiates upon crack formation, triggered by infiltrated water activating the dormant bacterial spores. In the presence of oxygen, these spores engage in aerobic conversion, transforming previously hydrolyzed PLA substrate (calcium lactate) into calcium carbonate. Simultaneously, the aerobic activity generates on-site carbon dioxide, facilitating the carbonation of the paste and resulting in substantial calcium carbonate precipitation that effectively seals the crack. Notably, a high-alkaline environment (pH 12–13) is required to catalyze the hydrolysis of the PLA substrate into calcium lactate, making the substrate suitable for bacterial action when needed. Therefore, key conditions for the autonomous self-healing process include a high-alkaline environment, the presence of water to activate dormant bacteria, and oxygen to sustain aerobic activity.

Specimens comprised masonry couplets—two bricks bonded together by a 10 mm thick mortar joint (Fig. 1a b c). Specimens were cast entirely with the bacteria-based mortar or a plain mortar (reference mortar), termed bacteria-based couplets and reference couplets, respectively. Repointed couplets were not included in this study, as the primary focus was solely on assessing the agent's compatibility with cement-lime mortars for repairing masonry.

Bond wrench tests were conducted to crack the specimens and evaluate the agent's healing capacity in recovering masonry bond. A setup suitable for in-situ testing (Fig. 1d), designed at Delft University of Technology [8, 9], featuring a support frame with a bottom screw clamp to restrain the lower brick and an electronic torque wrench to apply a bending moment to the brick-mortar interface, was used. The torque wrench had a maximum capacity of 100 Nm and showed the applied failure torque with an accuracy of $\pm 2\%$.

Samples underwent initial testing at 7 days, followed by a 30-day healing period under wet-dry cycles. This healing condition was chosen among others as identified by Gaggero [3] as particularly effective for clay bricks when combined with a PLA cement-based bacteria-based mortar. In this study, the wet-dry cycles were induced by wetting once per week the specimens stored in plastic boxes. Cycles were performed following two different procedures. In one series, the boxes remained open, allowing water to be absorbed or evaporated (Fig. 2a). In the other series, the boxes were closed for 4 days to retain moisture (Fig. 2b). These differences led to distinct humidity profiles (Fig. 2c). In the series with open boxes, there was a pronounced humidity peak followed by lower levels, here referred to as drastic wet-dry cycles. Conversely, in the series with closed boxes, the humidity remained consistently high, resulting in a narrower range, here referred to as moderate wet-dry cycles. After the healing period, samples were retested, and the healed torque was recorded.

3 Results

The performance of the self-healing repair mortar is here evaluated in terms of failure torque (T in Nm), from which the flexural bond strength can be assessed using the formula provided in EN 1052-5:2002 [8]:

$$f_w = \frac{T + F_2 \cdot e_2 - \frac{2}{3} \cdot d \cdot (T \big/ e_1 + F_2 + \frac{F_3}{4})}{\frac{b \cdot d^2}{6}} \tag{1}$$

Fig. 1. (a) Reference and bacteria-based masonry couplets at agent concentrations of (b) 5% and (c) 15%; (d) bond wrench test set-up used for testing.

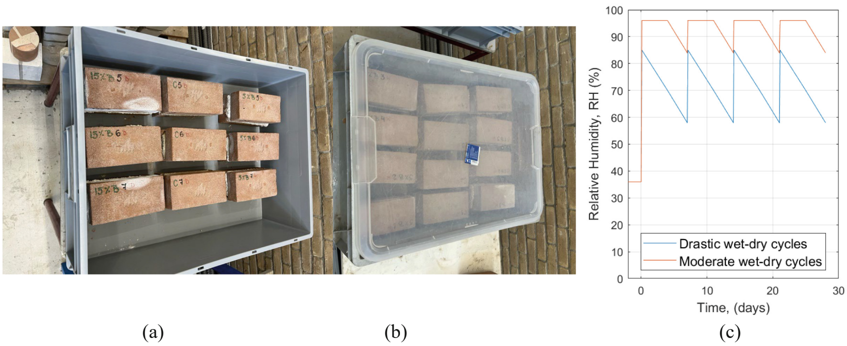


Fig. 2. (a) Drastic and (b) moderate wet-dry cycles; (c) humidity profiles for the two different wet-dry cycle conditions.

where F_2 is the normal force (11.3 N) due to the bond wrench apparatus weight, F_3 is the weight of the masonry brick pulled off the specimen and any adherent mortar (around 16.2 N), e_1, and e_2 indicates distances from the applied load (480 mm) and clamp's center of gravity (34.5 mm) to the specimen's tension face respectively, while *b* and *d* stand for the average length (210 mm) and width (100 mm) of the bed joint.

Table 1 lists the results obtained at 7 days on samples built with reference and bacteria-based mortar, the latter with agent concentrations (HA) of 5% and 15%. The flexural bond strength assessed from the torque values consistently remained below 0.1 MPa, confirming the poorly bonded nature of the masonry, which is characteristic of historical structures or those in a state of deterioration. Specifically, the flexural bond strengths were 0.01 MPa for reference couplets, 0.06 MPa for bacteria-based couplets with 5% HA, and 0.05 MPa for bacteria-based couplets with 15% HA. Due to the weak bond, some samples failed during installation, resulting in null torque being assigned to those instances. All specimens underwent testing until failure, with failure consistently occurring at the interface between the brick and mortar.

Before testing, at 7 days, it was observed that the incorporation of the PLA bacteria-based self-healing agent influenced the color of the mortar. Figure 3 depicts the visual differences in color between the reference mortar and the bacteria-based mortar at 7 days, with varying agent concentrations of 5% and 15%.

Subsequent assessments were conducted after a 30-day healing period under drastic and moderate wet-dry cycles. Each sample tested in Table 1 underwent retesting after this period, obtaining the healed torque documented in Table 2 for moderate wet-dry cycles and Table 3 for drastic wet-dry cycles. Notably, the set of reference specimens, where all samples failed during installation, resulted in null torque being reported regardless of the healing environment. Figure 4 illustrates the failure modes after retesting, highlighting high amount of leaching in couplets built with the bacteria-based mortar, especially those built with 15% HA and cured under drastic wet-dry cycles.

Table 1. Masonry bond capacity at 7 days of specimens built with reference mortar and bacteria-based mortar at 5% and 15% healing agent concentrations.

Specimen id.	Reference	5% HA	15% HA
	T^0 (Nm)	T^0 (Nm)	T^0 (Nm)
(1)	0	22.5	14.4
(2)	0	51.3	37.2
(3)	0	39.8	29.4
(4)	11.6	43.7	49.1
(5)	11	8.4	17.6
(6)	9.8	13.2	7.2
(7)	14.2	29.4	25.8
(8)	–	–	29.1
Avg.	**6.7**	**29.8**	**26.2**
St. Dev	6.4	16	13

Table 2. Healed bond capacity of specimens cured under moderate wet-dry conditions.

Specimen id.	T_H (Nm)		
	Reference	5% HA	15% HA
(1)	0	0	8.3
(2)	0	0	0
(3)	0	7.5	7.4
(4)	0	0	8.2
Avg.	**0**	**1.9**	**6.0**
St. Dev	0	3.8	4.0

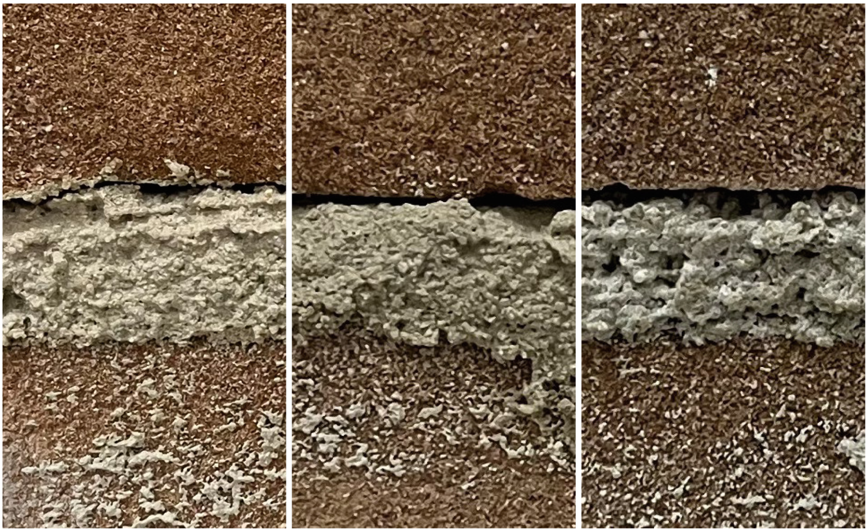
Table 3. Healed bond capacity of specimens cured under drastic wet-dry cycles.

Specimen id.	T_H (Nm)		
	Reference	5% HA	15% HA
(5)	0	0	10.5
(6)	0	7.3	8.2
(7)	0	0	7
Avg.	**0**	**2.4**	**8.6**
St. Dev	0	4.2	1.8

4 Discussion

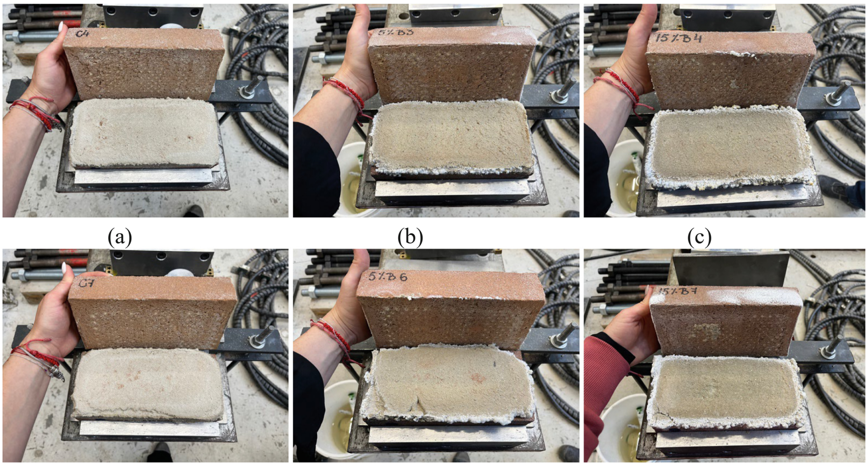
The integration of a poly-lactic acid (PLA) bacteria-based self-healing agent into cement-lime mortar masonry couplets was undertaken to assess its compatibility and effectiveness in masonry repair. This study sheds light on how the bacteria-based agent influences both the mechanical properties and visual appearance of mortar, emphasizing the role of mortar porosity and healing environment.

The incorporation of the PLA bacteria-based self-healing agent influenced both the color of the mortar (Fig. 3) and the bond capacity of masonry couplets (Fig. 5a). Despite the agent being biologically dormant at 7 days, its addition altered the chemical composition of the mortar which might have led to the observable changes in color and bond capacity. As shown in Fig. 5a, couplets built with bacteria-based mortar at 5% of agent concentration were 4.5 times stronger than reference ones, while couplets built at 15% concentration resulted 3.9 times stronger. Interestingly, an increase in agent concentration did not necessarily result in increased bond strength. These alterations emphasize the importance of systematic studies to comprehend the impact of the agent on the physical and mechanical properties of masonry. These findings hold significant implications for practical applications, especially in repairing existing structures, including historical heritage, through repointing. Achieving long-lasting repairs necessitates compatibility between existing and repair materials. Thus, a closer examination of the agent's effect on



(a) (b) (c)

Fig. 3. Mortar's color in masonry couplets built with (a) reference and bacteria-based mortar with agent concentrations (HA) of (b) 5% and (c) 15%.



(d) (e) (f)

Fig. 4. Failure modes after re-testing: (a) Reference, (b) 5% HA and (c) 15% HA cured under moderate wet-dry conditions; (d) reference, (e) 5% HA and (f) 15% HA cured under drastic wet-dry cycles.

factors like mortar porosity is warranted, given its significant role in regulating moisture transport.

Following a 30-day healing period under varying wet-dry cycle conditions, the bacteria-based couplets exhibited partial restoration of their original torque capacity, unlike the reference couplets which showed no bond recovery (Fig. 5bc). Higher agent concentrations (15% HA) facilitated more substantial recovery regardless of wet-dry cycle conditions, indicating that a higher content of bacteria-based agent promoted autonomous self-healing. However, further analysis suggests that the observed bond recovery may not be solely attributed to calcium carbonate precipitation, but rather to the migration of calcium lactate resulting from PLA substrate hydrolysis. This migration likely occurred due to evaporation, facilitated by the high solubility of calcium lactate, combined with lime-based mortar's high porosity and humidity fluctuations in the healing environment. Consequently, calcium lactate crystallization at the specimen surface (Fig. 4) likely contributed to the observed bond recovery. This phenomenon highlights the complex interplay between the mortar's composition (mortar's porosity) and healing conditions.

It is worth noting that this leakage (Fig. 4) was not observed in the study performed by Gaggero et al. [3], which explored the implementation of the agent in cement-based mortar under wet-dry cycles This discrepancy is likely due to the different porosity of the mortars – lime-based mortars are known for being more porous than cement-based ones: 50–65% in lime pastes vs. 30% in cement pastes [10, 11]. Therefore, the optimal healing condition not only depends on the brick type, as pointed out by Gaggero [3], but also on the mortar's porosity.

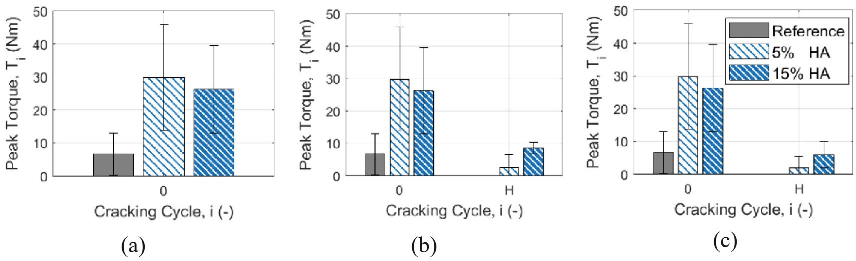


Fig. 5. Bond wrench test results at (a) 7 days (T_0), compared to those after a 30-day healing period (T_H) under (b) drastic and (c) moderate wet-dry cycles.

5 Conclusions

Masonry couplets built with cement-lime mortar incorporating a poly-lactic acid (PLA) bacteria-based self-healing agent were tested to evaluate the agent's compatibility and efficacy in masonry repair. The study showcases the influence of this bacteria-based agent on the mechanical properties and visual appearance of mortar and underscores the pivotal interplay between the mortar's composition (mortar's porosity) and healing environment.

The experiments reveal significant alterations in mortar color and bond capacity due to the incorporation of the PLA bacteria-based self-healing agent. Notably, the addition of the agent led to enhanced flexural bond strength. These findings underscore the necessity of systematic studies to grasp the full impact of the agent on masonry's physical and mechanical properties, crucial for achieving durable repairs, particularly in historical heritage structures.

Following a 30-day healing period under varying wet-dry cycle conditions, the bacteria-based couplets showed partial restoration of their original torque capacity, unlike the reference couplets which exhibited no bond recovery. However, the observed bond recovery was attributed to the migration of calcium lactate resulting from PLA substrate hydrolysis, highlighting the complex interplay between mortar composition (mortar porosity) and healing conditions.

Implementing self-healing technology in masonry is an emerging area with significant potential for providing long-lasting repair solutions, especially for heritage structures. The present study lays a foundation for further research in this area. Ongoing tests at Delft University of Technology are exploring the interplay between the healing environment, brick absorption properties, and mortar porosity on the healing performance, alongside investigating the impact of the bacteria-based agent on the properties of the mortar. These efforts promise to advance the understanding of bacteria-based self-healing agents in masonry repair and their practical implementation.

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