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An Overview of Self-Healing Concrete in Sustainable Construction

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Abstract

Self-healing concrete represents an innovative solution in sustainable construction, tackling the issue of concrete cracks, which can compromise structural integrity, repairing cracks automatically, and enhancing durability and sustainability. This concrete incorporates methods like shape memory alloys, SAPs, and embedded healing agents to repair itself. An innovative method incorporates calcium lactate and bacterial spores within expanded clay pellets. When cracks appear, these pellets release their contents, triggering a healing process where bacteria produce limestone to fill the cracks. SAPs are also effective in healing smaller cracks and preventing water ingress, which is crucial for durability. Although there are challenges like reduced strength and higher costs, self-healing concrete offers a promising future in prolonging concrete structures' lifespan, cutting maintenance expenses, and lessening environmental impacts. It needs more research to get past its current problems and fully use its potential in the building industry. This would help the world's efforts to use sustainable and cost-effective building methods, making it an important sustainable material.

Keywords: GFRP; GFRP-RC beams; concrete; SLS design; crack width; crack spacing

INTRODUCTION

Self-healing concrete repairs cracks automatically, enhancing durability and sustainability. Concrete's low tensile strength leads to common cracks, posing a threat to its longevity. These cracks facilitate the passage of harmful liquids and gases, potentially corroding reinforcement steel bars. Controlling crack width and prompt healing are crucial for a prolonged service life. Achieving self-healing in concrete promotes extended structural durability and overall sustainability [1–3]. In 2001, a significant study by White et al. was featured in the journal Nature, focusing on the self-repair capabilities of polymer-based materials. This publication sparked interest in integrating similar self-healing characteristics into cement-based substances. Concrete can repair itself to some extent by letting water into cracks and reacting with latent cement particles. This causes the concrete to become even more hydrated and may seal the crack. Moreover, the mixture of CO2 and water leads to calcium carbonate formation from leached calcium hydroxide, aiding in the closure of cracks. However, this inherent self-healing mechanism in concrete is typically restricted to minor cracks [4–6]. This limitation has prompted extensive research and development efforts to modify concrete in a way that improves its natural ability to autonomously heal larger cracks.

LITERATURE REVIEW

Self-healing concrete utilizes a variety of strategies to improve its ability to mend cracks. One approach involves the use of synthetic fibers to limit the width of the cracks [7–8]. When heated, these alloys can revert to their original shape, effectively sealing the cracks. Another method is the use of superabsorbent polymers (SAPs) [9–12], which are added to the concrete mix to provide extra water for autogenous sealing and healing. SAPs can absorb and retain water, swelling to obstruct cracks from harmful substances and releasing the stored water in dry conditions to aid in further hydration. Moreover, by introducing microorganisms that can induce calcium carbonate formation, the rate of calcite development in the concrete matrix is enhanced [13–14]. These microorganisms consume available nutrients and produce calcium carbonate, which aids in closing the cracks. Additionally, there are innovative systems involving capsules or vascular networks [15–18]. These systems have healing agents made of polymers that are released when the capsules or networks are broken because of cracks. This starts the healing process.

Mechanism

Microcracks in concrete, often caused by excessive tensile forces, are effectively repaired through the activity of bacteria. These healing substances, which are bacterial spores and calcium lactate, are spread out evenly in the concrete in the form of expanded clay pellets. When cracks form, the pellets rupture, releasing spores and chemical precursors. Moisture and oxygen entering the cracks create a favorable environment for bacterial multiplication. Rainwater or atmospheric moisture triggers bacteria to produce limestone, repairing cracks within approximately seven days and sealing cracks up to 0.5–0.8 mm wide [19], [20]. Cracks in concrete measuring up to 0.2 mm are naturally repaired and considered non-detrimental to the structure's integrity and safety. This bacterial healing mechanism is capable of thoroughly repairing cracks as wide as 0.5 mm. Factors like oxygen and water, once detrimental to concrete, now initiate the repair process [19–21].

Process of Encapsulation

When bacterial spores are combined into concrete, their effective lifespan decreases to a couple of months. This decrease, as opposed to their much longer viability in dry conditions, is linked to continuous cement hydration causing reduction in pore size [22]. To address concerns about potential loss of concrete properties, encapsulation of bacteria and precursors is necessary. The clay pellets must meet specific criteria: 1. Sustain continuous mixing, 2. Bind properly with the paste. 3. Provide thermal insulation, 4. There should be moisture impermeability. 5. Should there be fire resistance? 6. It should have a neutral pH. 7. Bind properly with the paste. 8. Bacteria and calcium lactate should be released on crack occurrences [22]. These lightweight pellets, less than 2 mm in size, are heated in a rotary kiln at about 1000 °C, expanding and forming tiny pores or bubbles for process precursor accommodation [23].

Chemical Reactions

There are two main mechanisms for the precipitation of calcite or carbonate: firstly, through the hydrolysis of urea, and secondly, by utilizing carbon dioxide produced during bacterial respiration. In the urea hydrolysis method, the bacterial cell wall becomes negatively charged, attracting calcium ions (Ca2+) from its surroundings. This makes carbonate and calcium ions react, which coats the surface of the bacterial cell with limestone [24]. However, this process has a drawback as it encases the bacteria in limestone, eventually leading to their demise [25]. In contrast, the second method leverages carbon dioxide generated from bacterial respiration. The reaction happens in a place with a lot of calcium and a high pH, and hydroxide ions help keep the reaction spontaneous.

In concrete, calcium lactate serves as a nutrient-dense food source for bacteria. The metabolic conversion of this lactate results in the production of calcium carbonate. The bacteria utilize oxygen, moisture, and calcium lactate for their metabolic activities, which leads to the formation of calcium carbonate. When bacteria breathe out CO2, it reacts with portlandite (Ca(OH)2), which is found in cement, making fresh limestone [24].

From a chemical standpoint, the creation of one mole of calcium carbonate stimulates the formation of another mole of the same compound. In a similar vein, the interaction of 5 moles of carbon dioxide with 5 moles of portlandite leads to the generation of an additional 5 moles of limestone. This sequential reaction is capable of producing sufficient limestone to effectively seal concrete cracks.

Bacteria Selection

For bacteria to be effective in concrete self-healing, they must meet two essential criteria. First, they need to survive in the highly alkaline environment of concrete (pH around 12.8), a condition created when water mixes with cement. Second, they should be capable of spore germination in such harsh conditions. The Bacillus genus, known for its gram-positive nature and robust cell wall, fits these criteria well. The spores of these bacteria are small, usually between 0.8 and 1 µm, and can stay viable for extremely long periods, up to 200 years. In the right conditions, involving water, nutrients, and oxygen, these spores can germinate into active bacterial cells. Bacillus pasteurii, Bacillus subtilis, Bacillus sphaericus, Bacillus cohnii, Bacillus pseudofirmus, and Bacillus halodurans are some of the species in this genus that are thought to be good for concrete self-healing.

Advantages & Disadvantages

Advantages

Self-healing concrete is a highly beneficial innovation for repairing infrastructure cracks. It not only limits the corrosion of steel reinforcements but also increases resistance to moisture. Environmentally, it lowers carbon dioxide emissions, aligning with green initiatives. The technology is especially valuable in enhancing the strength and longevity of structures, which is vital for preserving historical monuments.

Disadvantages

A notable limitation of self-healing concrete is that clay particles occupy about 20% of its volume, replacing normal aggregates. This substitution leads to a 20-25% decrease in compressive strength, currently making it unsuitable for constructing high-rise buildings. While the cost of calcium lactate, a key healing agent, elevates the expense compared to standard concrete, ongoing research seeks more cost-effective alternatives. Continuous advancements in this field are anticipated to address these challenges, broadening the application scope of self-healing concrete.

METHODOLOGY

Research Approach

The study employed an inductive research approach, progressing from a general exploration to a specific focus while reviewing papers. The conclusion was then logically derived from the gathered facts.

Data Collection Method

The research utilized the secondary data collection method, focusing primarily on a review format. Although the paper did not incorporate primary research due to its nature, the objectives were successfully met through the synthesis of findings from previous researchers.

Literature Search Strategy

The research papers were primarily sourced from various databases such as Google Scholar and Scopus. Different keywords, including "self-healing," "self-repairing," and "concrete," were employed to identify authentic and relevant information. Typically, multiple keywords were combined for a single search to filter out irrelevant results. Additionally, lengthy keywords, like "self-healing concrete for sustainable construction," were avoided as they are considered less effective for obtaining valuable information.

Ethical Considerations

Ethical considerations were accorded paramount importance in this study. Since the paper relies on secondary research, the ethical burden is diminished, given that proper citation and referencing were diligently applied to the sources of information. Overall, the entire data collection process adhered to ethical standards, emphasizing transparency and public disclosure in the communication of the paper.

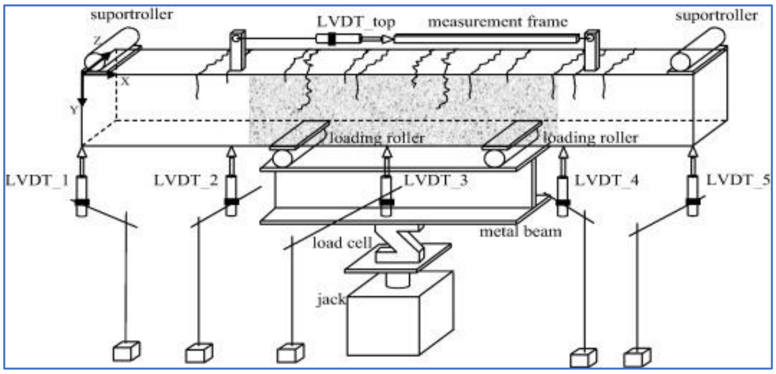

Figure 1. Main Setup [26]

DISCUSSIONS

Different Approaches

The research carried out at the Mangle Laboratory for Concrete Research in Belgium, explored self-healing methods on a laboratory scale. Two of the most promising approaches were chosen for application and tested for their effectiveness on a larger scale in this study.

Multiple Crack Formation

The objective of a particular study was to evaluate the effectiveness of crack healing in beams treated with self-healing methods (PU and SAP) in comparison to a standard reference beam (REF). It was vital to maintain uniform crack widths across all beams as the success of crack healing, particularly autogenous healing, depends on this consistency. Each beam was subjected to stress until reaching an average crack width of 250 μm. The recorded data shows varying numbers of cracks in the measured frame zone (Figure 1) of the REF, PU, and SAP beams, with counts of 20, 22, and 24, respectively.

The SAP beam, with its lower strength, was expected to exhibit more cracks due to the stress caused by SAP particles [27]. This resulted in different crack patterns affecting load and elongation, particularly in the beam's middle. While REF and PU beams had combined elongations from two loading stages, all beam types had an average crack width of around 250 µm. Figure 2 shows similar crack distributions across REF, PU, and SAP beams, denser in the middle and sparser near the supports. It also includes εxx DIC profiles for cracks on the opposite side of the beams, corresponding to end-of-loading profiles from DIC systems.

Table 1. Crack Width (Average) at End of Crack Creation

Beam	Cracks (Middle Zone)	Elongation (mm) (Middle Zone)	Crack Width (µm) (Average)
SAP	24	6.00	248.00
PU	22	4.55	250.00
REF	20	5.11	255.00

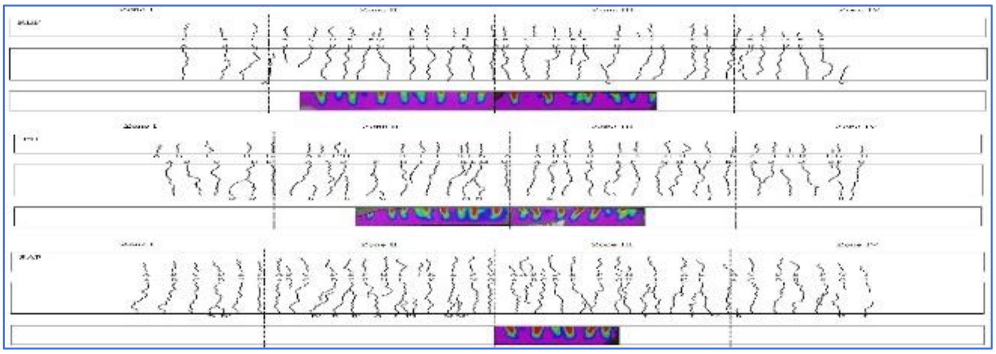

Figure 2. Visualization of the Crack Pattern [26]

Figure 3 illustrates beam displacements using LVDTs. REF and PU beams combine displacements from two stages. LVDT_1 and LVDT_5 show minimal displacement, while symmetric LVDT_2 and LVDT_4 display similar negative values. The highest negative displacement occurs at LVDT_3, the beam's centre. The SAP beam, with more mid-zone cracks, records higher displacements. Displacements at the centre are −20.76 mm, −22.91 mm, and −25.84 mm for REF, PU, and SAP beams, respectively. At crack formation, REF and PU register about 36 kN, and SAP reaches 42 kN, indicating SAPs act as crack initiators rather than enhancing mechanical properties.

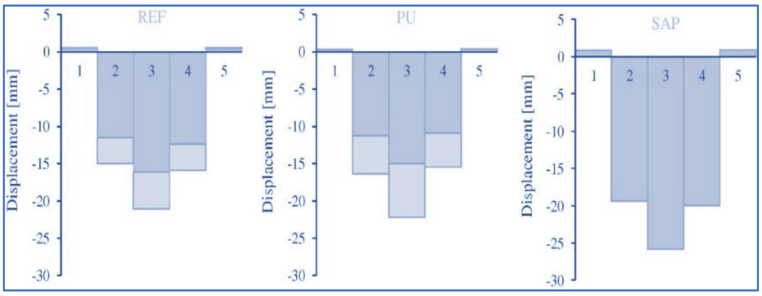

Figure 3. Beams Displacement at LVDT_1 to LVDT_5 (Vertical) [26]

Figure 3 shows beam vertical displacements measured by LVDTs during crack formation. After a 7-week healing period, beams were reloaded, revealing average crack widths of 182 µm (REF), 210 µm (PU), and 160 µm (SAP). PU's wider cracks indicate polyurethane filling. Figure 4 depicts LVDT_3 deflection against reload load, showing similar curves for all beams, making it unclear if mechanical properties recovered. The SAP beam endured the highest load, linked to greater crack density. This contrasts with lab-scale tests where partial mechanical recovery was seen, possibly lost here due to damage to healing agents during unloading.

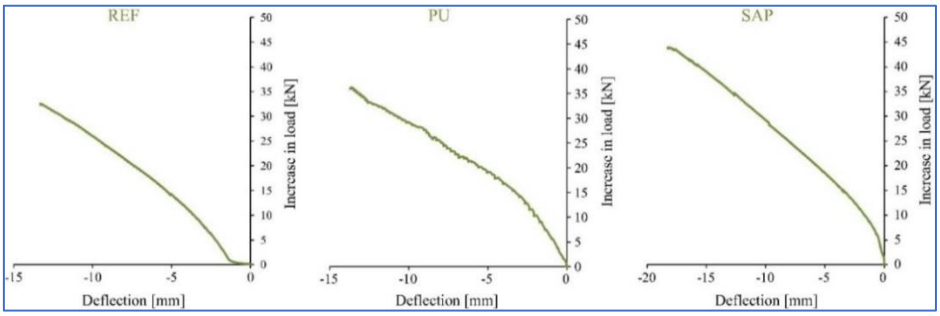

Figure 4. Deflection Recorded-LVDT_3 Plotted vs Load Increase (Reloading 300 µm Average Crack Width) [26]

Measurement of Water Ingress

For the polyurethane (PU) beam, crack formation coincided with the healing mechanism triggering, considering water ingress measurements immediately after formation. Figure 5A shows the PU beam's cracked zone had the lowest water ingress, values lower than REF and SAP beams, and somewhat lower than uncracked zone ingress in the PU beam. Figure 5 notes each crack code and its average width before healing, all within the 100–140 µm range. Before healing, water ingress in the SAP beam's cracks was higher due to SAP particles attracting additional water, possibly filling macropores. This may benefit later autogenous crack healing by releasing absorbed water for further hydration and calcium carbonate precipitation, as seen in improved healing efficiency after crack healing (Figure 5B). While REF and PU beams had higher water ingress after crack healing, the SAP beam showed lower ingress in the measured crack positions. The results in the uncracked zone remained more or less the same before and after crack healing. Higher water ingress for the REF and PU series contradicts expectations. A minimal difference is seen between the results before and after reloading healed cracks (Figures 5B and 5C). Note that water ingress measurements were challenging due to water intrusion and leakage from neighboring cracks, necessitating future test setup improvements.

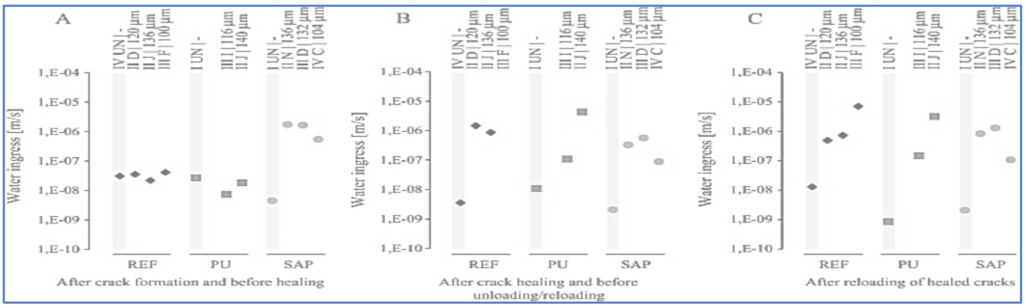

Figure 5. Water ingress for each test series [26]

Crack Healing Efficiency-Quantitative Analysis

A quantitative study on crack healing efficiency concerning crack width was performed, with the crack closing ratio computed as the difference between pre-and post-healing crack widths divided by the original width. This assessment focused on healing during a 6-week showering period, excluding immediate healing of the polyurethane (PU) beam. Cracks were grouped by initial width, and closing ratios were determined for each width category in every test series. Figure 6 shows that smaller cracks tend to heal more effectively than wider ones, with closing ratios ranging from 40–80% for widths of 0–50 μm. Ratios decrease to 10–30% for widths of 200–250 μm. Sealing ratios gradually decline across all test series with increasing crack width range. Significantly, the beam with embedded SAP particles (SAP) displays markedly higher sealing ratios compared to the REF and PU series, which have nearly identical sealing ratios for each range.

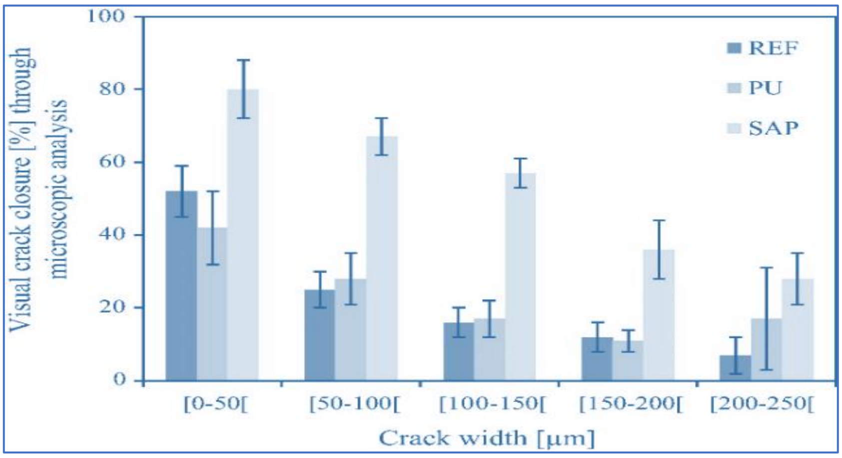

Figure 6. Crack Healing Ratio [26]

The inclusion of SAPs in the concrete matrix enhances autogenous crack healing, leading to an 80% sealing ratio for the smallest crack width range and around 30% for the largest range after 7 weeks. Unlike the REF beam, the PU beam doesn't exhibit a significant improvement, but the experiment incompletely reflects the PU beam's healing efficiency due to autonomous healing before the initial crack width measurement. This reveals additional autogenous healing during the 7 weeks.

Both self-healing methods demonstrate potential for real-scale application, yet the use of encapsulated polyurethane demands more preparation compared to SAP addition. Ongoing research aims to develop time-evolving encapsulation materials for efficient application. The current study suggests that embedded SAPs result in higher healing efficiency based on crack width reduction measurements, particularly in water-retaining structures and underground constructions.

Globally, concrete production reaches 12 billion tons annually, incurring high repair costs estimated at $147 per cubic meter [28-29]. Despite a 50-year service life expectation, maintenance responsibilities only extend to 10 years, leading to significant economic impact and expenditures, notably in the United States where 4 billion dollars are spent annually on concrete bridge repairs [30-31]. To address this, sustainable alternatives like self-healing concrete are crucial, where the autogenous self-healing capacity of concrete relies on natural processes like swelling, hydration, calcium carbonate production, and physical clogging [28]. However, this method is unreliable due to concrete composition variations and limited effectiveness in larger fractures. Alternatively, incorporating healing agents, chemical or biological, shows promise [32-33]. While chemical additives may influence concrete properties, bacterial addition, especially through micro-encapsulation, emerges as a sustainable and effective approach, offering protection and uniform characteristics in the alkaline concrete environment [33-35]. The cost of implementation remains a challenge, with current prices for bio-based additives high, necessitating further research for cost reduction [30]. Encapsulation materials evolving and industrial processing are explored for potential cost reductions. Environmental impact considerations highlight concerns about nitrogen oxide emissions during microbial hydrolysis of urea, urging the exploration of alternatives like calcium lactate [36]. Lastly, the industry's focus should prioritize the most effective healing approach, primarily working with microorganism encapsulation, using efficient bacterial species like Bacillus sphaericus, and promoting the reduction of CO2 emissions through sustainable practices [29], [31], [33], [35], [37]. Further research on cost-effective bacterial healing methods and government initiatives to extend product warranties and encourage sustainable production practices will enhance the viability of self-healing concrete on a larger scale [30].

CONCLUSION

Self-healing concrete automatically repairs cracks to enhance durability and sustainability. Cracks in concrete, typically due to low tensile strength, threaten its longevity by allowing harmful substances to corrode steel reinforcements. This technology aims for prolonged service life through immediate crack healing. Initially inspired by research on self-healing polymers, various methods have been developed to improve concrete's self-repair capability. These include the use of shape memory alloys, SAPs, micro-organisms that precipitate calcium carbonate, and embedded healing agents in capsules or vascular systems. One effective method involves embedding bacterial spores and calcium lactate in expanded clay pellets within the concrete. When cracks form, these pellets release their contents, initiating a healing process where bacteria produce limestone to seal the cracks. However, direct addition of bacteria shortens their lifespan due to the concrete environment, necessitating encapsulation for protection and efficiency. The research analyzed various self-healing approaches, focusing on their efficacy in sealing and recovering cracks. Methods employing SAPs showed promise in healing smaller cracks and reducing water ingress, a crucial factor for durability. The study also addressed the sustainability aspect of self-healing concrete, noting its potential to reduce repair costs and environmental impact. Despite challenges like reduced strength and higher costs, ongoing research and development aim to enhance its feasibility for widespread use in construction. Indeed, self-healing concrete represents a significant advancement in sustainable construction, offering a viable solution to extend the life of concrete structures while reducing maintenance costs and environmental footprint. However, further research and development are required to address its current limitations and fully realize its potential in the construction industry.

CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

REFERENCES

[1] Abrams, D. (1925). Autogeneous healing of concrete. concrete, 27(2), 50.

[2] Dry, C. (1994). Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibres into cement matrices. Smart Materials and Structures, 3(2), 118.

[3] Van Tittelboom, K., & De Belie, N. (2013). Self-healing in cementitious materials—A review. Materials, 6(6), 2182-2217.

[4] R. White, N.R. Sottos, P.H. Geubelle, J.S. Moore, M.R. Kessler, S.R. Sriram, E.N. Brown, S. Viswanathan, Autonomic healing of polymer composites, Nature 409 (2001) 794–797.

[5] C. Edvardsen, Water permeability and autogenous healing of cracks in concrete, ACI Mater. J. 96 (4) (1999) 448–454.

[6] H.-W. Reinhardt, M. Jooss, Permeability and self-healing of cracked concrete as a function of temperature and crack width, Cem. Concr. Res. 33 (7) (2003) 981–985.

[7] V. Li, E.H. Yang, Self healing in concrete materials, in: S. Van der Zwaag (Ed.), Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science, Springer Science, Dordrecht, The Netherlands, 2007, p. 388.

[8] A. Jefferson, C. Joseph, R. Lark, B. Isaacs, S. Dunn, B. Weager, A new system for crack closure of cementitious materials using shrinkable polymers, Cem. Concr. Res. 40 (5) (2010) 795–801.

[9] H.X. Dennis Lee, H.S. Wong, N. Buenfeld, Self-sealing cement-based materials using superabsorbent polymers, in: O.M. Jensen, M.T. Hasholt, S. Laustsen (Eds.), International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives in Concrete, RILEM Publications s.a.r.l, Lyngby, Denmark, 2010, pp. 171–178.

[10] D. Snoeck, S. Steuperaert, K. Van Tittelboom, P. Dubruel, N. De Belie, Visualization of water penetration in cementitious materials with superabsorbent polymers by means of neutron radiography, Cem. Concr. Res. 42 (8) (2012) 1113–1121.

[11] D. Snoeck, N. De Belie, Repeated autogenous healing in strain-hardening cementitious composites by using superabsorbent polymers, J. Mater. Civ. Eng. 04015086 (2015).

[12] D. Snoeck, K. Van Tittelboom, S. Steuperaert, P. Dubruel, N. De Belie, Selfhealing cementitious materials by the combination of microfibres and superabsorbent polymers, J. Intell. Mater. Syst. Struct. 25 (1) (2014) 13–24.

[13] H.M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, E. Schlangen, Application of bacteria as self-healing agent for the development of sustainable concrete, Ecol. Eng. 36 (2) (2010) 230–235.

[14] J.Y. Wang, H. Soens, W. Verstraete, N. De Belie, Self-healing concrete by use of microencapsulated bacterial spores, Cem. Concr. Res. 56 (2014) 139–152.

[15] C.M. Dry, Three designs for the internal release of sealants, adhesives, and waterproofing chemicals into concrete to reduce permeability, Cem. Concr. Res. 30 (12) (2000) 1969–1977.

[16] K. Van Tittelboom, N. De Belie, D. Van Loo, P. Jacobs, Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent, Cem. Concr. Compos. 33 (4) (2011) 497–505.

[17] C. Dry, Design of self-growing, self-sensing, and self-repairing materials for engineering applications, in: A.R. Wilson, H. Asanuma (Eds.), Smart Materials Conference, 2001, pp. 23–29.

[18] S. Pareek, A. Oohira, A fundamental study on regain of flexural strength of mortars by using a self-repair network system, in: 3rd International Conference on Self Healing Materials, Bath, UK, 2011, pp. 46–47.

[19] R. Spinks. “The Self-Healing Concrete that can Fix its Own Cracks.” The Guardian,6.29.2015,https://www.theguardian.com/sustainable-business/2015/jun/29/the-self-healing-concrete-that can-fixits-own-cracks.

[20] P. Patel. “Helping Concrete Heal Itself.” Chemical and Engineering News. 2.8.2016 http://cen.acs.org/articles/94/i6/Helping-Concrete-Heal-Itself.html.

[21] Seshagiri Rao.M.V, Srinivasa Reddy.V, Hafsa.M, Veena.P and Anusha.P, “Bioengineered Concrete – A Sustainable Self- Healing Construction Material”, Research Journal of Enginering Sciences, Vol 2, No.6, Page 4551, 2013.

[22] H. Jonkers. “Self-Healing Concrete with the use of Bacteria.” Fifth International Symposium on Life -Cycle Civil Engineering. 10.16.2016. http://www.ialcce2016.org/self-healing-concrete-with-the-use-ofbacteria/

[23] Wang.J.Y, Van Tittelboom.K, De Belie.N and Verstraete.W, “Potential of Applying Bacteria to Heal Cracks in Concrete”, Journal of Second International Conference on Sustainable Construction Materials and Technologies, June- 2010.

[24] C. Karthik, R. M Rao.P. “Properties of Bacterial-based Self-Healing Concrete.” International Journal of ChemTech Research. 2016. http://sphinxsai.com/2016/ch_vol9_no2/1/(182-188)V9N2CT.pdf

[25] E. Gruyaert. D Snoek. K. V. Tittelboom. J. Wang. “Self-healing of concrete.”

[26] Van Tittelboom, K., Wang, J., Araújo, M., Snoeck, D., Gruyaert, E., Debbaut, B., & De Belie, N. (2016). Comparison of different approaches for self-healing concrete in a large-scale lab test. Construction and building materials, 107, 125-137.

[27] Yao, Y., Zhu, Y., & Yang, Y. (2012). Incorporation superabsorbent polymer (SAP) particles as controlling pre-existing flaws to improve the performance of engineered cementitious composites (ECC). Construction and Building Materials, 28(1), 139-145.

[28] Sangadji S (2017) Can Self-healing mechanism helps concrete structures sustainable? Procedia Eng 171:238–249. https:// doi. org/ 10. 1016/j. proeng. 2017. 01. 331

[29] Seifan M, Samani AK, Berenjian A (2016) Bioconcrete: next generation of self-healing concrete. Appl Microbiol Biotechnol. https:// doi. org/ 10. 1007/ s00253- 016- 7316-z

[30] Silva FB, Boon N, De Belie N et al (2015) Industrial application of biological self-healing concrete: challenges and economical feasibility. J Commer Biotechnol. https:// doi. org/ 10. 5912/ jcb662

[31] Jonkers HM, Thijssen A, Muyzer G et al (2010) Application of bacteria as self-healing agent for the development of sustainable concrete. Ecol Eng. https:// doi. org/ 10. 1016/j. ecole ng. 2008. 12. 036

[32] Vijay K, Murmu M, Deo SV (2017) Bacteria based self healing concrete-a review. Construction and Building Materials, DOI:10.1016/j.conbuildmat.2017.07.040.

[33] Joshi S, Goyal S, Mukherjee A et al (2017) Microbial healing of cracks in concrete: a review. J Indus Microbiol Biotechnol. https:// doi.org/ 10. 1007/ s10295- 017- 1978-

[34] Muhammad NZ, Shafaghat A, Keyvanfar A et al (2016) Tests and methods of evaluating the self-healing efficiency of concrete: a review. Construct Build Mater. https:// doi. org/ 10. 1016/j. conbuildmat. 2016. 03. 017

[35] Stanaszek-Tomal E (2020) Bacterial concrete as a sustainable building material? Sustainability. https:// doi. org/ 10. 3390/ su12020696.