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REVIEW ARTICLE

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Exploring the Latest Innovations and Progress in Self-Healing Concrete Technology: A Review

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Abstract

Self-healing concrete is a milestone in the development of building materials that will have the ability to repair its cracks autonomously and enhance structure life. This paper takes an in-depth analysis of the recent innovations and developments concerning self-healing concrete technology from different perspectives on healing mechanisms: self, biological, and chemical approaches and factors affecting healing efficiency crack width, distribution of healing agent, and environmental conditions) with traditional ways of repairing concretes. It discusses global case studies, best practices, and prospects for self-healing concrete as a sustainable and resilient material in the construction industry.

Keywords: Self-healing concrete, Sustainable construction, Durability of concrete, Healing factors, Structural integrity.

1. Introduction

Self-healing of concrete is an extraordinary key characteristic, which can be considered as the first approach to endow structural materials, in particular concrete, design, and performance of living organisms (Onyelowe et al.2022). It is attracting increasing attention and great efforts have been made to improve the sensitivity or to develop new technical solutions. Self-healing techniques of concrete can be mainly divided into two categories, namely integrated, preventive, and autonomic repairs. (Amran et al.2022) Integrated techniques can effectively limit the onset of a damage propagation regime or suffer partial stress relief. Preventive techniques are closely related to the decrease of certain concrete properties and cracked width, and the related typical industrial facilities, for example, shape memory alloy (SMA) bars and micro-sized encapsulations loaded with a specified repairing chemical in a "micro closed construction" system. The autonomic repair approach is a two-stage process (Liu et al., 2021). An innovative sustainable solution within the field of autonomic concrete repair systems has proven its feasibility to adequately close the cracks through an energetic effect. Photographs clearly indicated continuous interfaces of the healed cracks.

Polymer-enriched concrete composites, which are capable of healing inner damage through the mixing of monomer and catalyst, are a typical example of self-healing concrete technology. In the presence of water, the polymerization can be initiated. Consequently, the components injected into the crack, as well as the crack part itself, are filled by the polymer matrix system (Tonndorf et al.2021). An amphiphilic ionic surfactant consisting of long and short hydrocarbon chains can accelerate the reaction rate of epoxy resin to realize the enhancement of self-healing ability at room temperature effectively. Compared with some representative efficient activation techniques, the ionic surfactant-assisted self-healing method assembles distinct operational advantages. The polymeric precursor, the cracks can further impede sorptivity and gaseous permeability of concrete and hence increase the resistance of concrete against high temperatures (Wu et al.2020). These explorations of ionic surfactant-assisted self-healing will ultimately place new efforts in the development of robust and easy practical chemical methods to enhance the self-healing ability and the sustainability of concrete.

2. Mechanisms of Self-Healing in Concrete

The subject of self-healing concrete is explored in this text. Specifically, the biological approaches, such as using bacterial spores and nutrients, in creating the self-healing capability of the concrete are discussed. Finally, the benefits and challenges are discussed. Self-healing concrete offers lower maintenance costs, reduces the need for human intervention, and represents an environmentally friendly alternative. It can prolong the lifespan of aging buildings and structures.

2.1. Autogenous Healing

It is based on different reactions and processes taking place within the concrete matrix, without any external stimulus or additional materials. The healing results from the growth of unhydrated cement particles, new hydrates and mineral ions migration as well as reduction of crack width which in effect enhances stress transfer abilities in concrete (Cai et al.2022). More importantly, this intrinsic healing mechanism enhances not only the structural continuity of concrete but also its service life. Ionic advection is believed to be the mechanism responsible for autonomous crack filling: pressure drives it from the external MSZ to the MSZ surrounding the crack. Autonomous crack filling follows after autogenous sealing; in some cases, C-S-H formed during the sealing process is consumed when monosulfoaluminate hydrates and other equilibrium products are hydrated. The consumption of C-S-H in turn leads to further growth of the newly formed hydrates, which creates additional expansive forces on steel rebars (Suleiman & Nehdi, 2021). This expansion applies more compressive stresses on the existing cracks as well, therefore inhibiting their further propagation. The pressure exerted by growing hydrates closes off the cracks completely with time as well. Moreover, migration of mineral ions is also a part of this self-healing process within the concrete structure. It is based on the different responses and phenomena arising within the concrete matrix, without any external stimulus or additional materials. By the growth of unhydrated cement grains, growth of new hydrates, and movement of mineral ions, autogenous healing manages to decrease effectively crack widths and improve stress transfer actions within the concrete (Cai et al. 2022). This free-from-artificial-means healing process enhances not only the structural integrity of the concrete but also its service life. It is based on the different responses and phenomena taking place within the concrete matrix, without any external stimulus or additional materials. In effect, autogenous healing reduces cracks widths by expansion of unhydrated cement particles, formation of new hydrates and mineral ions migration which further improves stress transfer capabilities within the concrete (Cai et al.2022). This healing mechanism enhances not only structural robustness but also the durability of concrete.

2.2. Biological Healing

The concept of utilizing biological reactions, more specifically bacterial self-healing agents, has been somewhat in existence since a few years ago. Bacteria are to seal cracks by the activation of them in the concrete to produce calcium carbonate. The cement and sand fractions in such systems are higher than that needed for crack sealing typically. For using bacteria in concrete production, one of the conditions is the choice of bacterial strains which can tolerate at least alkaline environment besides concrete. Furthermore, be capable of producing good quality calcium carbonate. Specific bio-adhesives are needed for binding to the carbonate surface properly and quite importantly, should not react with components (as is) and possibly cause swelling.

In the lab, a self-healing capability can be proven, even for bacteria types that practically cause too much swelling of concrete. The autogenous process has been tested, in which the bacteria used as nutrients the calcium lactobionate created by the hydration of the precursor of the self-healing material.

Such a self-healing process is both created and critiqued in the context of such a rigid scientific view, including basic material sustainability concerns. In it self-healing abilities are validly proven through experiments to be: single tensile loading self-replicating fractures, naturally freeze-thaw durabilities, static mechanical material properties, and long-term autonomously strengthening capabilities (Hassanin et al.2024). The paper presents and discusses the results of a newly performed, complete self-healing biological community test program.

Any such self-healing procedure is initiated and critiqued from a strict scientific viewpoint of material sustainability-fundamentals on which it provides for its self-healing potential, naturally freeze-thaw durability features, static mechanical material properties, and long-term autonomously strengthening capabilities that are experimentally validated through single tensile loading self-healing fracture tests (Hassanin et al. 2024). The newly conducted and extensive Self-Healing Community Program Test results are introduced and discussed in the paper.

2.3. Chemical Healing

Chemical Healing - Chemical healing mainly involves the use of crystalline-forming or noncrystalline-forming materials (e.g. expansive agents and polymers) that possess an intrinsically self-sealing capability. When the healing agents are autonomously released upon crack formation and contact exposed reactive source, a chemical reaction that restores the integrity of the structure is initiated (Žáková et al., 2020). Usually, the encapsulation technique is adopted when engineering products use the chemical healing route. The chemicals are usually loaded in microcapsules when they are either liquid, gel form, and are embedded throughout the bulk of cementitious composite to be made available for healing. The chemical nature of CS requires alkali-activated conditions to initiate the self-sealing effect and generally, the routes of 'initial-crack' healing and 'recracking' capability were established, showing higher self-healing efficiency than other encapsulation treatment.

The expansive treatments contain either expansive agents, calcium nitrate, or alkali metal nitrate such as sodium nitrate (NaNO3) and potassium nitrate (KNO3). The reaction starts when the nitrate salts come in contact with water to generate nitrite ions and high pH conditions induce nonferrous metal particles to form protective nitrite on their surfaces. Then, the nitrite becomes nitrate-bearing minerals which exert an expansive force of approximately 2 GPa, which can generate closing stress leading to the healing of the cracks (Amran et al.2022). The main drawback of chemical healing is that the use of high pH conditions would cause corrosion to the metal rebars and deteriorate the rebars-concrete interaction which would necessitate the development of a pH-resistant capsule to minimize the early degradation problem. Like other encapsulation technologies, expensive and cumbersome processes are required along with nonflexible formulated mixes before incorporation, which is not feasible for on-site construction.

4. Factors Affecting the Efficiency of Self-Healing Concrete

The paper will consider recent innovations and development of self-healing concrete such as definition, sources, methods, and factors that influence efficiency besides focusing on current advancements. Traditional concrete is unable to heal itself. Factors that influence efficiency are the number of micro-capsules distribution or polymer encapsulated bacteria. Having found local materials the researchers have consider optimal production. The healing properties of subsequent cracks depend upon filler to concrete. Also the concentration of organisms utilized affects healing efficiency

4.1. Crack Width and Depth

In structural design, the formation of cracks in concrete is generally permitted since concrete is a very brittle material. For instance, in reinforced concrete structures, once any tension force develops into the member, then cracks will form to carry this force. However, if the width of such cracks exceeds certain limit values, often their serviceability will decrease substantially. Following most design codes around the world, the maximum allowable crack width is 0.3 mm. Sometimes it is seen that for some cases, such as liquid-retaining structures or water-tanks when human health might be at risk (because bacteria could develop due to water spillage), then crack width should be limited to 0.2 mm or even 0.1 mm with some specific exceptions.

Self-healing concrete is biphasic or multiphase (cementitious and aggregate or even steel reinforcement) and multifunctional composite material(s) that heal the micrometer-sized microcracks caused both by the hydration heat as well as those that result from service load. Upon additional stimulation, the concrete is meant to heal all of its cracks: those which influence serviceability/ durability include at least one type of self-healing agent. The surface healing agents are designed to be triggered when there is a crack width opening initiated. Other methods about intrinsic self-healing are being developed (to bio-cementary concepts). The self-healing of concrete is important enough that it should be able to retain sufficient strength so far as this does not mean structure components cannot perform due to, for example, reduced mechanical properties; or recover functional properties of the material after it has been damaged.

Self-healing concrete is a two-phase composite material and multifunctional design; it atones for micro-cracks created by hydration heat and those created by service loads. In response to further stimulation, this concrete has been designed to reclaim full functionality of any cracks that impinge on durability. Such concrete generally contains at least one type of a self-healing agent able to act mechanically by blocking the surfaces of a free crack once the opening reaches a critical value, beyond which other inherent ways about the self-healing would be developed such as the concept of bio-cementary. The self-healing of concrete will have to play an important role when maintaining health (i.e., having mechanical properties sub-functionalities are not reduced) or restoring health up functional materials after damage events.

4.2. Healing Agent Distribution

The healing agents' distribution in the concrete matrix sensitively influences the self-healing efficiency, particularly at the start of the healing duration. If a healing agent is only residing on the surface of a crack, then during that time it will be swept out into the external environment on mass transfer phenomena, thereby depleting self-healing capabilities. Moreover, the healing agent should only be released upon atomization to ensure that it is properly injected into pre-cracks. The mechanical and microbiological healing agents for concrete differ in their nature (Hermawan et al., 2021). Hence, the dispersion of these two healing core materials needs to be handled differently. As regards mechanical healing agents, since they are

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heavier with low solubility, they should be embedded in concrete from the inner layer. The particle size is supportable to achieve the mechanical agents besides cracks releases conditions. A spherical shape and hydrophilic, positive charge surfaces will have a better impact. On the other hand, bio-healing agents are not very good in terms of mechanical strength or hydrophilicity and positive charge surface as well as having a micro scale which should be restricted within an appropriate range to avoid aggregation so that distribution within concrete can be enhanced. For the healing process to be effective, the distribution of healing agents in a matrix of concrete plays an important role and must be properly observed. This is very important during the early stages of the healing duration. When a healing agent is only present at the surface of a crack, it risks being lost to the surrounding environment, thereby jeopardizing self-healing (Papaioannou et al.2021). The healing agent should be released in atomized form to assure its penetration into pre-existing cracks. The characteristics of mechanical and microbiological healing agents for concrete are different, and as a result, the distribution of these two kinds of curing core materials needs to be dealt with using separate methodologies. Owing to their higher density but lower solubility, the mechanical healing agents' incorporation should be within the inner layers of concrete. Their particle size can be modified so that it helps in their effectiveness as well as their release in case there is a presence of cracks. Also, it may have more positive effects when being in a spherical configuration with hydrophilic and positively charged surface functionalities. On the other hand, bio-healing agents do not have very high mechanical strength along with hydrophilicity or positive charged surface functionalities Micro scale control is needed for nonuniformity prevention and good promotion to fulfil an effective distribution within the concrete structure.

4.3. Environmental Conditions

Recent studies revealed the healing mechanism of cracks filled with electrically charged smart crack filler to be effective for cracks at high steep grades as well as those in various environmental conditions. However, some challenges were still pending. To effectively fill the gel into 1.2 mm wide and 30 mm deep cracks under a positive repulsive DC electric field alone, positive-ish applied voltage was necessary because the gel-stainless steel interface polarized and produced positive charge on the surface (Aygun et al.2023). For faster healing and low healing charges via electric fields, the following are implemented: model helical and L-shaped stainless steel electrodes that were mechanically grounded before applying voltage to avoid polarization of the interface; and mechanically keep elevated temperature during healing to heat the internal gel for quicker filling of the crack was implemented to prevent polarization.

For faster healing and healing at low charges through the use of electric fields, an model helical and L-shaped stainless steel electrodes which were mechanically grounded before voltages was applied to prevent polarization of the interface being also kept mechanically during healing at an elevated temperature to heat internal gel for crack filling so fast and for earlier-filling cracks (Chen et al.2022). The custom smart concrete was subjected to another test on cracked concrete under the same tensile load at an elevated moisture to ascertain visually the velocity and volume of crack filling by the Gel—twice at DC voltage of +5 V, 150 °C for the helical stainless steel nearly fully restored to the neighboring samples of being rectangular and once at +5 V, 200 °C for the L-shaped stainless steel.

5. Comparison with Traditional Concrete Repair Methods

Exploring the newest innovations and progress in self-healing concrete technology. This section takes a closer look at different self-healing concepts and technologies. Introduction: Concrete is the most widely used building material globally and is highly sought after. The main component of concrete is cement, which currently contributes to a large percentage of the carbon dioxide emissions produced by the cement industry. Notwithstanding the numerous advantages that come with using concrete, real in-service structures have to be maintained at regular intervals (which are costly) during their lifetime for proper service function (Sanjuán et al., 2020) (Naik, 2020). This is done by carefully preparing the new cast concrete, pouring the site with the prepared mixture, and then letting it cure. In effect, this will make sure that any replaced concrete will work as one with what is on the ground, both in terms of function and appearance. The cost of going by the traditional concrete repair method can be so high; worse still, if not attended to or neglected can result in more fatal damaged to the entire construction. Delaying fixing deteriorated concrete can lead to safety risks and cause a lot of damages on your pockets. For underwater tasks, it would even be more complicated undertaking; this would demand some special tools that will facilitate safely handling as well as making work easier when replacing damaged concrete with fresh one. However, with self-healing concrete technology being researched on there is a brighter tomorrow where we shall have better ways that are also cost efficient when doing away with extensive manual interventions Protective coatings are very vital in stopping further damage and increasing the life of the repaired concrete. The use of chloride inhibitors as a protective coating helps in enhancing resistance offered by the concrete against chloride corrosion. This preventive technique can significantly increase the life of repaired concrete, reducing maintenance. 4. Where necessary, apply a bonding agent on the surface. A bonding agent plays a very vital role as a bridge between the old concrete and new material to be applied; it ensures a strong bond and uniform behavior. This is very important for continuity and uniformity to attain maximum strength and stability for the repaired concrete structure. 5. Cast new concrete material at times when damages caused are on a high scale; this is mandatory for proper repair works. New concrete is cast by carefully preparing the mixture and pouring it into place where it cures. This approach ensures that the repaired concrete will be indistinguishable from the existing structure, returning full functionality and appearance. The cost of concrete repair by this traditional means is very expensive and may result in a higher figure of having to do away with the entire structure. Undoing deteriorated concrete can be very unsafe, not to mention pocket-drilling, if proper action is not taken at once. Underwater conditions would call for an even more elaborate process to ensure safety while effecting proper repairs on the concrete using specialized equipment and techniques. (Barros et al.2023) (Amran et al.2022). Thanks to continuous research and development, scientists and engineers strive to make a revolution in the sphere of concrete repair by providing environmentally-friendly and durable innovations that will change the approach to maintenance of infrastructure.

6. Global Case Studies and Best Practices

A lot of thought and information has been put into this chapter while focusing so much on self-healing concrete (SHC) technology revolution—a very promising gift to the construction industry because of the immense prospects it holds. In an attempt to provide an in-depth understanding of the subject, this chapter is specially crafted by experts who have experience contributing to the enhancement of knowledge in various domains within this field. In course of their research, a variety of interesting and sometimes conflicting issues is brought out into the open, hence showing different groups of researchers—technologists and scientists involved in achieving similar goals with various opportunities available for exploration(Amran et al.2022). A major part of this chapter is its commitment to information value for those interested and making sure that a wide range of practical scenarios are available where SHC has been applied successfully. With extreme accuracy and detail, this chapter conducts an in-depth examination of various application environments that have seen the outstanding use of SHC. This detailed analysis takes into consideration many numbers of actual real-world structures and their performance upon integration with SHC technology. In order to quench every bit of curiousness from the minds of the readers, the applications are brought forth in about 10 notable SHC applications that have been implemented across the globe in recent years. Such a complete presentation allows readers to understand what SHC really achieves when integrated into real structures (Nnaji & Karakhan, 2020). Indeed, this chapter goes beyond mere summarization: it provides a complete and detailed research on state-of-the-art SHC technologies with seamless implementation in major regions of the world. The authors show their hearts and professionality in giving so much information on the subject, both illuminating the potential and challenges of SHC. With the increasing importance of SHC, professionals, researchers, or even hobbyists require such authentic source to have a complete insight into this revolutionary technology (Huseien et al.2022). This chapter serves as an invaluable contribution to the field, empowering individuals to navigate the complex landscape of self-healing concrete with confidence and expertise.

7. Discussion

The paper discusses the recent developments in technology towards self-healing of concrete with distinct mechanisms: autogenous, biological, and chemical healing. Individual mechanisms have their own advantages and limitations that are complementary to other mechanisms in achieving overall effective self-healing concrete for improved structural strength and durability. Although autogenous healing is entirely dependent on intrinsic properties, biological healing introduces bacteria for the same purpose, and chemical encapsulated materials ensure no infiltration passes through. The work emphasizes the prospect for such technologies to reduce maintenance expenditures and enlarge the life of concrete infrastructure; however, each method has its limitations and relies on environmental factors.

8. Conclusion

Developing self-healing concrete is definitely an innovative approach to the sustainability of construction because it provides a prospect to increase the term of structure service with lower cost of maintenance. The combined self-healing mechanisms may increase concrete resistance, but further research should also overcome each technology's limitations and adapt their use to specific conditions to ensure the most viable and effective self-healing concrete system for practical application.

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