Chapter

Use of Sustainable Materials in Self-Healing Concrete

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Abstract

Vulnerability to cracks is one of the major flaws of concrete infrastructure. The need to reduce the repair cost of this defect birthed the need for self-healing concrete. The incidence of cracks on concrete structures is a big threat to the stability of bridges, concrete roads, and other concrete infrastructures. This review assessed the use of self-healing technology on concrete using sustainable material as an active method of healing crack. This was done with the view of improving the stability, strength, and sustainability of infrastructure for national growth. The outcome of the review showed three prominent methods used in self-healing technology, which include autogenous healing, encapsulation of polymeric material, and microbial production of calcium-carbonate (biotechnological approaches). The review also revealed that calcium carbonate is a versatile material that can be used in crack healing for the filling of voids and improves the porosity of the concrete. The success of using the autogenous healing method depends on the diameter of the crack induced in the concrete structure. Additionally, this method can operate independently in different conditions regardless of the crack position. Correspondingly, lowering the water-cement ratio improves the autogenous healing process. The use of encapsulation of polymeric material and microbial production of calcium-carbonate methods showed that the presence of water and humidity is a critical factor to be considered. However, biotechnology using microbial action is prone to the production of ammonium ions ($NH4+$) through ureolytic activity, which results in nitrogen oxide emission into the atmosphere. Congruently, this may affect the durability of the concrete. Based on the uniqueness of this technology, it is recommended for the construction of sustainable infrastructure now and in the foreseeable future.

Keywords: self-healing, sustainability, concrete, asphalt, infrastructure

1. Introduction

The concept of self-healing concrete came from the principle of the self-healing properties of the skin, a form of natural defense mechanism. Nature plays an active role in this process by the development of clots to seal the break. This is the first process of skin healing. Self-healing technology is a novel branch of engineering aimed at the protection of concrete infrastructure from developing minor and major cracks. In a bid to improve the strength and durability of concrete which, is one of the most pervasive material in the world in terms of infrastructural construction, self-healing technology was adopted. The use of concrete has been adopted in the design and construction of major infrastructure for national growth. Globally, concrete is widely used for the construction of structural and pavement elements [1]. The first usage of concrete in the world was in the Roman Empire, for the construction of the Pantheon, which is a very great structure and still in a functional state till date [2]. Concrete microstructure consists of a multiphase nanostructured material in the composite form which ages over time. The structural strength of concrete to a large extent depends on the micro- and nanoscale structural properties of the constituent element.

Despite the uniqueness of concrete infrastructures using these innovative materials, they are still prone to cracks. The research of [3] as reported in [4] revealed that concrete crack is a result of shrinkage, weather action, thermal stresses, and so on. Using self-healing technology, the strength and durability of concrete can be improved using biotechnological method by adopting the calcite precipitation principle. Self-healing technology seems to be very effective if the crack size is not more than 0.8 mm at the early age. However, the research of [4] revealed that hydro-gel encapsulation, vascular systems, and capsules are also good methods of self-healing concrete structures. Recent research focuses on the use of biotechnology and nanomaterial and the use of autogenous principle in self-healing technology which is espoused in this review.

1.1 Self-healing technology

The concept of self-healing was birthed some few decades due to the crack induced in some water retaining structures [5]. One of the major causes of concrete structural failure is the crack that can occur both in the plastic and hardened states [6–9]. The effect of crack may not be pronounced at the early stage, but it affects the mechanical strength at the late age which involves a lot of money for repair. The research of [7] showed that the active treatment of cracks seems to be an effective method as compared with the passive method of crack treatment.

The main concept was to make sure that this concrete structure affected by crack regained its mechanical strength by the hydration of the cement particles present in it [10, 11]. The concept of autogenic healing was used in this approach. According to [11], autogenous healing is a procedure where materials self-heal by nature. The same author avowed that this self-healing may be due to the formation of the carbonate or the hydroxide of carbon (calcium carbonate and calcium hydroxide). Additionally, the sedimentation of particles and swelling of the cement matrix in the concrete proved to be likely causative factors [12]. Asserted the problem of sedimentation and swelling can be averted and corrected using the self-healing capacity of the material composition of concrete.

Self-healing is an example of the active process of crack treatment. This method can operate independently in different conditions regardless of the crack position. The design of materials with healing properties is now gaining acceptance in concrete technology due to its numerous advantages.

1.2 Sustainable materials used in self-healing concrete

Sustainable structures provide environmentally friendly infrastructure, add long-term value to facilities, and improve the structural stability of structures. In concrete technology, different materials have been used in self-healing technology through three main strategies as shown in **Table 1**.

i. Autogenous healing

ii. Encapsulation of polymeric material

iii. Microbial production of calcium-carbonate (biotechnological approaches)

1.2.1 Autogenous healing

This process of healing occurs when the continuity of two sides of cracks is restored without any external repair [25]. The same author avowed that water passing through concrete dissolve the calcium present in the cement mortar of concrete. The passage of water oftentimes is through the presence of cracks either in the hardened or plastic state. The calcium is transported in the insoluble form in the voids which eventually seal the crack without any external approach. The cracks did not only heal, but the mechanical properties were also restored. Additionally, the healed concrete becomes impermeable to water, thereby improving the mechanical strength. The principle of sealing cracks with calcium carbonate crystals from carbon dioxide in the surrounding soil, air, or water is the autogenous healing process. This reaction with the free calcium oxide and calcium hydroxide from the hydration of tricalcium silicate of the cement helps in crack healing also. However the main product that fills the void is the calcium carbonate [25].

Furthermore, the research of [26] showed that calcium carbonate is a versatile material that can be used in crack healing for the filling of voids and improved porosity. The research of [13, 14] showed that the presence of unhydrated cement in the concrete composition can affect autogenous healing. Additionally, the presence of water and humidity are also critical factors. The improvement of this approach of crack treatment depends on the water-cement ratio used in the concrete design. The lower the water-cement ratio, the better the autogenous healing process. Moreover, the success of this approach depends on the diameter of the crack induced in the concrete structure. The research of [18] showed that only cracks ranging from 0.1 to 0.3 can be filled using this approach.

1.2.2 Encapsulation of polymeric material

This process involves coating of the hydrophobic nanoparticles with an additional polymer layer. This process involves the foaming of the healing agent in the presence of moisture. It also involves the use of fibers in concrete. Encapsulation also uses capsules that can survive in concrete matrix. The addition of this capsule must not interfere with rheology and mechanical properties of the concrete both in the plastic and hardened states [27]; this factor according to the research of [19] as stated in [28] makes this method difficult. The research of [19, 28] stated that encapsulation involves the use of liquid, gas, or fine solid particles incorporating synthetic polymer in concrete technology. The research of [19] stated that to provide

Item	Material	Authors
1	Autogenous healing	[13–18]
2	Encapsulation of polymeric material	[19]
3	Biotechnological approaches	[20–24]

Table 1.
Self-healing methods.

protection to the constituents of the healing agent, the healing process begins when the capsule is opened to crack and the applied load breaks the capsule which invariably opens the healing agent [4]. This method can be categorized into the following:

1. Bacterial precipitation

2. Encapsulated chemical healing agents

The materials used in this method are as shown in **Table 2**.

The drawback of this approach is the tendency to repeat itself over time, and this invariably leads to repeated healing. Moreover, the moisture content required is high to make the healing process effective. Research of [42–44] showed that insufficient capillary action could render the method ineffective. The cost of production is another shortcoming of adopting this method.

1.3 Biotechnological approaches

Biotechnology involves the use of biomineralization in concrete technology. It is a process of mineral formation by living organism in nature. According to the same author, the process can be accomplished by inducing biological mineralization in an open environment as a result of uncontrolled microbial metabolic activity [21]. This process occurs in an anaerobic environment or at toxic-anoxic boundary as avowed by [22]. This is as a result of photosynthesis from bicarbonate solutions which results in carbonate production [45]. Besides, the use of this method is feasible when carbon dioxide is present in the surrounding. It can be inferred from this that photosynthesis pathway can be applied when concrete infrastructure is exposed to carbon dioxide in the presence of light.

Furthermore, the heterotrophic growth of different types of bacteria such as *Arthrobacter*, *Bacillus*, and *Rhodococcus* leads to the production of organic salt and carbonate minerals through urea analysis [46–48]. It also results in the increase in the pH consequently increasing the concentration of carbonate. This process is achieved by the conversion of carbon dioxide to carbonate [13, 49, 50]. Invariably, this aids the calcium carbonate precipitation which plays an active role in the blockage of cracks [51, 52]. Other bacteria used in self-healing technology are shown in **Table 3**.

The major drawback of this approach is the production of ammonium ions (NH4+) through ureolytic activity which results in nitrogen oxide emission into the atmosphere. It is estimated that the remediation of 1 m^2 of concrete needs 10 g/L

S/N	Material used	Authors
1	The use of hydrophobic solution adopting sonication technique	[29–31]
2	Melamine-based and polyurethane (PU) capsule material	[32, 33]
3	Perspex cast acrylic tubes and glass tubes	[34, 35]
4	Glass and ceramic cylindrical capsules	[36, 37]
5	Spherical capsules using sodium silicate solution	[32, 38]
6	The use of encapsulated epoxy in polystyrene-divinylbenzene microcapsules	[39]
7	Isocyanate prepolymer encapsulated in hollow cylindrical glass tubes	[34, 35]
8	Microcapsules to hold bisphenol F epoxy resin (Cailleux and Pollet)	[19]
9	Microcapsules made of silica gel with oil core were used	[41]

Table 2.
Materials used in encapsulation method of self-healing.

	Type of bacteria	Cement replacement	Importance	Source
1	*Bacillus aerius*	Rice husk	Strength, durability	[53]
2	*Bacillus megaterium*	No replacement	Compressive strength	[54]
3	*Bacillus sphaericus*	Normal concrete	Durability	[14, 55]
4	*Sporosarcina pasteurii*	Fly ash concrete	Strength, durability	
5	*Sporosarcina pasteurii*	Silica fume	Improvement in strength and durability	[56]
6	*Bacillus sphaericus*	No replacement	Alternative surface treatment for concrete	[52]
7	*Shewanella* species	No replacement	Compressive strength	[52, 57–59]
8	*Bacillus subtilis*		Compressive strength	[59]

Table 3.
Bacteria used in self-healing technology.

Item	Self-healing materials	Authors
1	Encapsulated sealants and adhesive	[19]
2	The adhesives can be stored in short fiber	[39, 40]
3	The adhesives can be stored in long fiber	[43, 60–62]
4	Expansive component in the concrete	[61, 62]
5	Bacteria to stimulate the self-healing mechanism	[63–65]

Table 4.
Self-healing materials.

of urea which produces 4.7 g of nitrogen. This amount is about one third of the nitrogen that is produced by each person everyday [52]. Furthermore, the presence of excessive ammonium in the concrete matrix increases the risk of salt damage by converting to nitric acid. Hence, an optimization to find the required amount of urea is beneficial to avoid excessive ammonium emission.

For cement-based materials, different methods can be found in literature (**Table 4**); the first breakthrough involves the use of encapsulated sealant or adhesive [19]. These are stored in fibers [39, 40] or in longer tubes [60]. Filling of the voids and cracks with expansive material can propel carbonation when water percolates [61, 62]. The use of bacteria to stimulate the self-healing mechanism is also a promising alternative [63–65]. Nanotechnology is a unique branch of science that uses nanomaterial in the design, construction, repair, and protection of infrastructures. It deals with the application of the physical world in a small scale by assessing the atom, molar molecule, and similar molecule of material [66–68]. With the increasing development of nanotechnology, the use of tiny nanoparticles and nanomaterial also increased in modern technologies [69].

2. Conclusions

This review assessed the use of self-healing technology for sustainable infrastructural development. Relevant literatures on the use of self-healing technology in concrete technology were assessed. The main concept was to make sure that concrete structure affected by crack regained its mechanical strength by the hydration of the cement particles present in it. Self-healing mechanism using the autogenous healing, encapsulation of polymeric material, and microbial production of calcium carbonate (biotechnological approaches) was studied. The review revealed that:

i. The major shortcoming using capsulation method is its repeatability over a long time which can also lead to repeated healing over a long time.

ii. Capsulation method requires high amount of moisture to make it effective.

iii. The cost of production of capsules for large concrete structures is also a major flaw of this approach.

iv. Insufficient capillary force of the crack causes lower than expected amount of healing agent being released into the matrix using capsulation method.

v. Heterotrophic growth of different genera of bacteria results in the production of carbonate minerals; invariably, this aids the calcium carbonate precipitation which plays an active role in the blockage of cracks.

vi. The activities of these bacteria lead to an increase in the pH of the medium, thereby increasing the carbonate concentration.

vii. Excessive production of ammonium in the concrete matrix using biotechnological approach increases the risk of salt damage by conversion to nitric acid.

viii. The effectiveness of autogenous healing of crack depends on the water-cement ratio used in the concrete design. The success of this approach depends on the diameter of the crack induced in the concrete structure.

3. Recommendations

i. Future studies should focus on the production of some of these self-healing materials in large quantity.

ii. Future studies should also focus on the effect of this technology on corrosion considering the versatile usage of reinforced concrete for infrastructural construction.

iii. It is also recommended that the use of biotechnology in self-healing should be done with caution and the right technology should be used because of its effect on durability.

Acknowledgements

The authors are grateful to the management of Covenant University for the access to the articles used for this review.

Conflict of interest

The authors declare that there is no conflict of interest.

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