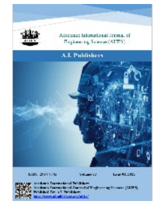
Academic International Journal of Engineering Science
ISSN: 2984-7745
Aca. Intl. J. E. Sci. 2023; 1(2) 01-10
Journal homepage: www.aipublishers.org/aijes



Document heading

# A Review of Self-Healing Concrete Technologies for Sustainable Infrastructure

**Fe del Mundo**

College of Engineering, Technological University of Philippines, Philippines

Email: Mundo@gmail.com

**Article Info.**
**Article history:**
Received 4 May 2023
Revised 9 June 2023
Accepted 7 July 2023
Published 12 July 2023
**Keywords:**
Self-healing concrete, Autogenous healing, Bacterial concrete, Microbial induced calcite precipitation, Encapsulated healing agents
**How to cite:**
Fe del Mundo. A Review of Self-Healing Concrete Technologies for Sustainable Infrastructure. Aca. Intl. J. E. Sci. 2023;1(2) 01-10.
**DOI**:
https://doi.org/10.59675/E121


## Abstract

Self-healing concrete is a revolutionary innovation in the science of construction materials, which has an autonomous capacity to repair, which is one of the primary drawbacks of concrete cracking and progressive weakening. This review looks at the key self-healing strategies that have been developed over the last 20 years such as autogenous healing in which the surrounding hydration and carbonation promote the healing process, bacterial-based biological systems in which microbial induced calcite precipitation acts to promote healing, and encapsulated chemical healing agents which are released once the crack is formed. The evaluation of each technology is in terms of efficiency of healing, constraints in terms of practical crack width, environmental necessities, cost implications and practicability. The article examines the latest progress in encapsulation devices, bacterial spore protectant mechanism, and the hybrid systems of combining various mechanisms of healing in order to have the overall effect of crack healing. It has been shown in performance data that bacterial systems are capable of healing cracks with a width of up to 0.5-0.8 millimeters and a high recovery of the strength and that autogenous techniques can seal micro-cracks with a width of less than 0.15 millimeters. Issues of implementation such as scalability of production, standardization of quality control, long-term validation of performance and integration of the construction practices are critically looked at. The life-cycle assessment has shown that the potential environmental impact can be reduced by 20-30 percent by using longer structural life and lowering maintenance rates. The results indicate that self-healing concrete technology, specifically hybrid solutions have a lot of potential to revolutionize sustainable infrastructure construction with a significant portion of construction budgets estimated to be spent on construction repair and maintenance being diminished by a significant margin, and even the carbon emissions produced by concrete production and replacement being reduced significantly.

## Introduction

Concrete is currently the most consumed construction material in the world with a yearly production of over 10 billion cubic meters and despite its very applicable characteristics, cracks and consequent degradation has been of great concern to the infrastructure durability and sustainability [1]. Construction business is a major emitter of carbon dioxide in the world with cement manufacturing contributing about 39 percent of all carbon dioxide emissions in the world [2]. With the aging of the infrastructure systems and the increasing demand on systems and resources, there has been an increasing urgency to identify materials that can be more likely to extend service life and reduce environmental impact.

Concrete structures are traditional structures which are bound to form micro-cracks within their service life because of the stresses caused by shrinking, thermal changes, mechanical forces and attacks by aggressive environments [3]. These micro-cracks which are usually not visible to the naked eye act as channels through which water and aggressive agents find their way into the concrete matrix resulting in reinforcement corrosion, freeze-thaw damage, and progressive structural deterioration. The traditional methods of concrete durability are based on the preventive techniques, like protective applications and addition of extra cementitious materials, or the reactive techniques that are expensive manual repair measures, which have to be repeated during the lifespan of a structure.

The financial cost of concrete corrosion is astonishing, with infrastructure tour and mend services of 40-50 percent of the entire construction expenses in industrialized countries [4]. Lack of adequate resources to maintain infrastructure in the developing countries leads to faster degradation of infrastructure posing safety risks to individuals and hindering economic growth. In addition, the environmental cost of the repeated repair cycles is adding to the already huge carbon footprint in concrete production, and with every repair intervention, materials have to be extracted, transported, and applied in ways that produce further emissions.

The self-healing concrete was developed in the early 2000s as one of the biomimetic solutions based on the natural ability of biological organisms to heal the damage in an autonomous manner [5]. The basic principle is to either incorporate curing agents or fabricate material properties that allow the automatic sealing of cracks in case they are damaged and this is achievable without outside intervention. Once cracks develop and exposes these healing processes to triggering conditions like moisture, air or mechanical rupture, repair mechanisms will take place naturally and the cracks will be sealed, and in some cases, mechanical properties may be regained to levels before the damage.

The possible effect of the mass self-healing of concrete is much deeper than the direct structural gains. Concrete-related CO2 reduction by 20-30 percent through the implementation of these technologies studied in research projects would prolong the life of the structures, lower their level of repair, and lower the number of materials used [6]. Moreover, self-healing concrete can be considered to be in line with the principles of the circular economy and sustainable development objectives since it will help to decrease the waste of resources, decrease the production of construction waste, and facilitate more resilient infrastructure systems that can adjust to the shifting environment conditions.

This review gives an in-depth study of self-healing concrete technologies, evaluating them in terms of scientific background, implementation approach, performance nature, and the direction toward a general acceptance in the development of sustainable infrastructure. This paper discusses three main types of healing methods including autogenous, bacteria-based and encapsulation systems, and it also discusses new hybrid technologies which integrate a combination of different mechanisms in order to improve functioning.


Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

## Literature Review

Self-healing concrete is conceptually based on observations of autogenous healing in ancient Roman concrete structures, the presence of unhydrated cement particles and calcium carbonate precipitation led to such extraordinary long-term durability of millennia [7]. Nevertheless, the systematic investigation of engineered self-healing accelerated in the 2000s, and the initial steps to the systematic investigation of this field were made by scholars of the Delft University of Technology and other research institutions, who started to consider the organized methods of how to introduce healing functionality to cementitious materials.

Initial broad overviews as carried out by Dry and others [8] made basic classifications of self-healing systems into autogenous and autonomous. The principle of autogenous healing depends on natural concrete capabilities especially the hydration of unhydrated cement particles remnant and the formation of calcium carbonate in the carbonation reaction. Their study proved that autogenous healing is effective in sealing cracks that are normally less than 50-100 micrometers in size, but is not effective with larger cracks that are experienced in the structural business [9].

The use of bacteria-based healing by Jonkers and Schlangen [10] was a breakthrough in self-healing technology as an autonomous process. Their innovative research proved that alkaliphilic military could be embedded into concrete and survive in extreme alkaline conditions and in the event of a crack and ingress of moisture, the bacteria would produce calcium carbonate which served to seal the crack up to 0.5 millimeters. This biological method provided the possibility of repeated healing cycles in the life of a construction, since bacterial spores would be in dormant state decades and wake up whenever the construction had cracks that admitted the water.

The studies that followed further advanced the bacterial healing system by investigating the different species, nutrient sources, and mechanisms of protection to improve the healing of bacteria and their viability over an extended period of time [11]. The Bacillus species, especially B. pseudofirmus and B. cohnii, became a good candidate because of alkaliphilic behavior, sporulation ability and effective calcite precipitation. Protection strategies developed into basic mixing to complex encapsulation in porous aggregates or hydrogel matrix to protect bacteria against cement chemistry as well as be activated by cracking.

Another independent healing method that developed was encapsulation technologies, which were based on self-healing polymer models. White et al. [12] showed that hollow vessels filled with liquid healing agents could rip open due to the development of cracks that were released to form chemical that could polymerize or precipitate to seal a gap. Various capsule materials, geometries and chemical agents were broadly studied by Van Tittelboom and De Belie [13], and design principles regarding the maximization of the healing efficiency of the capsules without compromising the mechanical properties of concrete were developed. Their study showed that the choice of capsule shell material, chemistry of healing agents and spatial distribution play an important role in determining the outcome of healing.

The recent literature is starting to adopt hybrid systems which involve the combination of various mechanisms of healing so as to be able to respond to various crack situations and be able to enlarge the range of healing capabilities in response to structural lifetimes. Wang et al. [14] established that the construction of systems that combined bacteria-based healing and the use of additional cementitious materials were found to be more effective in contrast to mechanisms that were used alone. The benefits of these hybrid systems include the ability to take advantage of the synergistic effects that may allow healing a broader range of cracks, accelerate healing kinetics and have increased healing capacity due to the combination of several complementary mechanisms.



Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

There has been a considerable development with regard to performance evaluation techniques and standardized testing protocols have been developed to measure healing efficiency, completion of crack seals, strength recovery, and reduction of permeability [15]. The RILEM Technical Committee 221-SHC has come up with extensive testing recommendations that facilitate comparison of various healing technologies and research organizations. Practical performance Field demonstrations and pilot projects have been useful in providing real-world performance data to identify the potential and reality of self-healing concrete implementation in construction practice [16].

According to economic studies that were carried out by other research teams, although the material costs involved in self-healing systems are currently higher by between 10-50 percent compared to traditional concrete, self-healing systems have good life-cycle cost benefits due to their lower maintenance needs and longer service life [17]. Such economic advantages are, however, extensive upon application-specific characteristics such as maintenance cost structure, repair accessibility to cost, and failure impact. The most promising economic profiles of self-healing concrete adoption are in the applications where maintenance is expensive or access is difficult like tunnels, bridges, and marine structures.

## Technologies and Self-Healing Mechanisms

### Self-regulated Healing Processes

Autogenous or intrinsic healing is the concrete tendency to fill the cracks under natural chemical reactions without the healing agents being introduced. Concrete structures have been experiencing this phenomenon over a hundred years but it has only taken a systematic study and design to achieve improved performance [18]. The major processes that cause autogenous healing are constant hydration of dry cement particles, precaution of calcium carbonate in the form of carbonation to produce microscopic crystals, and mechanical insertion of cracks by floating concrete particles or silt in infiltrating water.

The continued hydration is a situation where water is able to enter into the cracks and touch the unhydrated cement clinker that remains in the concrete matrix. Such particles, especially those in a high concentration of young concrete or low water- cement ratio mixtures, may experience retarded hydration processes that give rise to calcium silicate hydrate and calcium hydroxide that slowly occupy crack spaces [19]. The effectiveness of this mechanism is affected by a number of factors such as concrete age, cement type and fineness, water availability and width of crack. It has been confirmed that hydration based healing is most effective on cracks smaller than 50 micrometers and on concrete that is less than one year old.

The most important autogenous healing process on older concrete and larger cracks is the calcium carbonate precipitation. Dissolved carbon dioxide in water reacts with calcium hydroxide that is available in concrete creating calcium carbonate crystals that settle on crack faces [20]. This carbonation technology has a top limit of 200-300 micrometers wide cracks that can be sealed, but more difficult cracks reduce the efficiency of healing. Temperature, humidity, CO 2 concentration, are environmental factors that have a significant effect on carbonation speed and the outcome of healing.

The techniques of engineering to increase autogenous healing are the optimization of concrete mix design with additive cementitious materials that bring perennial reactivity, the incorporation of expansive minerals that cause the shrinkage of cracks and the ultimate design of concrete with the right amount of permeability that enables water to enter the structure but restrains deep penetration [21]. Another improvement strategy is referred to as crystalline admixtures, which involve the addition of chemicals that reacts with water and unhydrated cement to produce needle-like crystals that develop



Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

into cracks and fill the gaps. Although the principle of autogenous healing is relatively cost-effective and it does not need any special additives to standard concrete components, its shortcomings in crack width performance and stability in the process of healing are the reasons behind the creation of more advanced autonomous healing.

**Bacteria Based Biological Cure**

One of the most inventive and the most properly studied autonomous healing methods is bacteria-based self-healing, which uses the metabolic activity of microorganisms to induce the formation of minerals that seals cracks. The groundbreaking discovery of Jonkers [22] showed that the alkaliphilic species of Bacillus could survive encapsulation in the concrete, escaped in the very hostile alkaline environment, more than pH 12, and reemerged when moisture and oxygen is present as a crack forms.

The process of healing consists of bacterial conversion of the calcium-based nutrients to calcite precipitation, which is microbially induced, and is commonly abbreviated as MICP. At the time when cracks develop and water enters the building, the dormant bacteria spores start to germinate and utilize organic nutrients that can be calcium lactate or calcium acetate [23]. The byproduct of the metabolic process is calcium carbonate which settles on the surfaces of cracks and seals openings gradually. The cycle is repeated until the available nutrients and conditions of the environment are favorable to the bacteria, which could potentially repeat the process in a series of healing procedures throughout the life of the structure.

The selection of the bacteria species, the type and concentration of nutrients, the mechanisms of protection against bacterial death, and the environmental factors in the healing process are considered the critical aspects of bacterial healing performance [24]. The Bacillus species have been the most appropriate; specifically, B. pseudofirmus, B. cohnii, and B. alkalinitrilicus, because of the alkaliphilic nature, spore-forming ability and efficient precipitation of the calcite. Formation of spores is essential because it enables bacteria to endure adverse conditions of the concrete mixing and hostile alkaline condition over a long period of time, possibly decades.

The choice of nutrients harmonizes the metabolic efficiency of bacteria and actual compatibility because certain organic substances can have an adverse effect on concrete or promote the corrosion of steel in reinforced buildings. Calcium lactate is a new environmental friendly nutrient used because it has a moderate influence on fresh concrete performance and can be converted to calcium carbonate effectively [25]. But the organic content should also be used with the care of not producing a lot of porosity and preventing the strength of the concrete.

The viability of bacteria protection is a highly important part of system design. Direct mixing of bacteria into concrete usually gives out low survival rates because of the stern process of mixing and the alkaline environment. Physical protection Physical protection is offered by encapsulation in porous aggregates like the expanded clay, lightweight aggregates or recycled glass and bacterial activation occurs when the cracks open the aggregate [26]. Other methods involve terms such as encasing bacteria in hydrogel scaffolds or protecting by means of protective polymers that prevent the cement chemistry on bacteria but permit water vapor to infiltrate when the cement cracks.

The recent technical developments in encapsulation have made bacteria much more resistant to death and also to curing with certain systems having proven capable of healing cracks up to 0.8 millimeters in width and restoring strength more than 90 percent of its original value [27]. Long term bacterial viability as demonstrated in field trials in marine environments and wastewater treatment facilities have been proven through the detection of viable bacteria in concrete samples after 5-10 years of service.

The difficulties of bacterial healing systems comprise comparatively greater expenses related to the cultivation and encapsulation of bacteria, the question of bacterial viability during multiple-decade



Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

service lives and the possible adverse effects that the porous carriers have on the mechanical properties of concrete, and the unpredictability of healing properties amidst varying environmental conditions [28]. Besides, the environmental effects of the release of genetically modified or non-native species of bacteria into the environment are also questions which need to be considered carefully though the existing systems are using naturally occurring species.

**Imprisoned Chemical Healing Agents**

The self-healing systems through encapsulation use a healing agent in a protective vessel, which tears open when a crack goes through it, releasing chemicals to react to seal cracks. It is a modification of self-healing polymers, which provide accurate control over the composition of the healing agents, their amount, and the time of release [29]. Different types of encapsulations have been created such as spherical microcapsules, tubular vessels, hollow fibers or vascular network of three dimensions within concrete matrices.

Microcapsule systems usually use polymer shells between 10 and 1000m diameter of solid healing factor like mineral precursors, 2 component resin epoxy, cyanoacrylate adhesives or encapsulated bacteria [13]. The shell material should have enough strength to endure the concrete mixing, transportation and placement without being too hard such that it does not fracture after cracks collide with capsules. Usually used shell materials are melamine-formaldehyde, urea-formaldehyde, polyurethane, and gelatin-based polymers which are chosen on the basis of compatibility with healing agents and concrete chemistry.

The choice of the healing agent is based on the needs of application, the healing processes preferred and compatibility with the concrete alkalinity and moisture. The mineral precursor solutions like the sodium silicate are reacted with the calcium ions in concrete to produce calcium silicate, which precipitates on cracks and provides great compatibility with the concrete chemistry and also binds effectively with other cementitious matrix [13]. Epoxy systems are fast healing and strong recovery but they have to be used in formulations of two components where one part has to be stored separately and mixed on release and this is a serious technical challenge in designing capsules.

The cyanoacrylate adhesives are hardened instantly when it comes in contact with the water or hydroxide ions present in large numbers in concrete and is also capable of offering rapid crack sealing without using several components. Nevertheless, their long-term stability in alkaline conditions and possible brittle nature are a cause of concern and restrain their use [29]. More current studies are done on bio-based curing agents such as plant oils which polymerize when exposed to air and which provide long-lasting alternatives to petroleum-based chemicals.

Tubular systems use larger hollow glass or polymer tubes with a diameter of 1 to 5 millimeters in diameter which give more volume capacity of the healing factor and can solve bigger cracks than microcapsules [13]. The most advanced technological approach is three-dimensional vascular networks based on biological circulatory systems, and includes channels that are connected to one another and can transport healing factors to various sites and may allow repeated healing with external replenishment. Nonetheless, vascular networks pose serious practical issues such as difficult manufacturing, possible adverse effects of the channel network on the mechanical characteristics of concrete and difficulties with integration with other normal construction procedures.


Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

## Characteristics of Performance and Implementation

### Healing Effectiveness and Cracking Barriers

The practical relevance of self-healing concrete is fundamentally limited by the largest possible crack width that can be repaired, and which is a variable that differs significantly between the various healing mechanisms and which directly affects practical relevance. Continued hydration (autogenous healing) shows effective healing of micro-cracks of up to 50 micrometers with a declining effect with cracks of about 100 micrometers [18]. Autogenous healing by carbonation extends this range to about 200-300 micrometers when better environmental conditions are available, but the recovery of healing and strength is lost significantly after 150 micrometers.

Cracks that are far broader are healed with bacteria-based systems with laboratory research showing that cracks between 300 and 800 micrometers can be sealed with the assistance of bacteria based on the type of bacteria used, nutrient supply, encapsulation technique, and curing conditions [27]. Field applications normally aim at cracks of up to 400-500 micrometers in order to assure positive healing results. The bacterial system healing process is slow and takes weeks to months, whereby the first crack sealing happens within days after which further mineral precipitation which increases sealing integrity and mechanical property recovery happens.

The encapsulated chemical healing agents show different capacities of crack healing as a result of the type of agent, the size of the capsule, and density of the distribution. Mineral precursor systems usually fill cracks of up to 300 micrometers as is the case with improved autogenous healing. Tubular systems may have the potential of healing larger cracks of more than 1 millimeter since volumes of the healing agent are larger but practical applications are yet to be fully executed [13].

The healing efficiency is measured in different measures such as visual crack sealing ratio, water permeability recovery, ultrasonic pulse velocity of internal healing and mechanical property regain by use of strength test. Total sealing of surface cracks does not always mean total healing in depth or restoration of the mechanical properties, and needs multi-method evaluation [15]. It has always been shown that recovery of permeability is often faster than recovery of mechanical properties, and in most systems more than 95% recovery of permeability has been observed when the recovery of the strength is no more than 70-80% of initial values.

### Factors in the Environment and Production

The environmental factors in the presence of crack formation and post-crack formation also play a significant role in determining the effectiveness of healing in all the self-healing processes. The water supply is the most important because nearly all healing activities demand the presence of moisture in the form of a reactant, a medium of transportation, or an activator [18]. The autogenous healing process can best be sustained in a continuous wet or wet dry cycle that offers water exposure in intermittent bursts, and without over-drying. Bacterial healing also needs enough moisture to germinate the spores and also to metabolize but can withstand periodic drying when healing has begun.

Mechanism mechanism-dependent and complex, temperature effects. Autogenous curing with hydration and carbonation usually takes advantage of moderate temperatures ranging 15-25 o C which are favorable to reaction rates, but do not result in intense drying. The bacterial systems typically need a temperature with which they can maintain metabolic activity, which is normally 20-35 C of mesophilic species commonly used but studies on the use of thermophilic bacteria are underway to examine the use of higher temperatures [24].



Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

Scaling self-healing concrete between laboratory and construction volumes can be highly difficult in terms of production and quality control. The bacterial systems demand regulated growth, sporulation and encapsulation processes which bring in biological material handling factors that are new to the traditional concrete production. To preserve the virulence of bacteria during the process of production, storage, and installation, special attention should be paid to temperature, moisture and time restrictions, making supply chain logistics complicated [28].

Quality control should ensure distribution of healing agents, determine viability of biological components as well as validate capsule integrity beyond standard concrete test. Setting the acceptance criteria and testing procedures that can be effectively applied to construction sites is still a challenge that is going to be solved through collaboration and the efforts of standardization of the industry. The aspect of cost also plays a major role in adoption, with self-healing concrete usually 10-50 percent more expensive than traditional concrete based on the technology to heal it, although life-cycle analysis is more and more showing that it is economically viable when used in high-maintenance applications [29].

## Conclusion

Self-healing concrete technologies have evolved beyond the inspirational biomimetic modeling to materials that have been tested to exhibit significant capacity of revolutionizing infrastructure sustainability. The variety of healing approaches- autogenous, bacteria-based biological and encapsulated chemical agents offer a choice of approaches that fits various application needs, performance requirements and cost-effectiveness. The validation of performance is able to confirm that self-healing concrete is able to successfully seal cracks, re-establish permeability resistance and also recover mechanical properties within the right conditions, which directly addresses a considerable amount of deterioration of concrete infrastructure in regards to cracks.

Nevertheless, effective implementation of widespread implementation necessitates management issues that cut across the parameters of scalability in production, standardization of quality control, validation in long-term performance, and interconnection with the practice of construction. The environmental benefits of 20-30% reduction of emission through the long service life are supported by life-cycle assessment, which is in line with the global sustainability goals. Validation of field performance, standard specifications development, hybrid system optimization, integration with new construction technologies should be the priorities of future research. Self-healing concrete is a technology that is currently set to become a normal element of sustainable infrastructure development as these technologies become more mature in the future.

## Questions for Discussion

1. What techniques can be used to standardize testing procedures so that different self-healing systems can be compared and performance specifications set on the engineering practice?
2. Which infrastructure applications present the most promising opportunities of near term adoption of self-healing concrete in terms of economic and performance factors?
3. What can be done to optimize hybrid self-healing systems to deliver continuous healing to the broadest possible range of crack width and to the broadest range of environmental conditions?
4. Which rules and incentive systems might speed up utilization of self-healing concrete in governmental infrastructural projects?



Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.

## References


1. Mehta PK, Monteiro PJM. *Concrete: microstructure, properties, and materials*. 4th ed. New York: McGraw-Hill; 2014.
2. United Nations Environment Programme. *Global status report for buildings and construction*. Nairobi: UNEP; 2021.
3. Neville AM. *Properties of concrete*. 5th ed. Harlow: Pearson; 2011.
4. American Society of Civil Engineers. *Infrastructure report card*. Reston (VA): ASCE; 2021.
5. De Rooij M, Van Tittelboom K, De Belie N, Schlangen E, editors. *Self-healing phenomena in cement-based materials*. Dordrecht: Springer; 2013.
6. Talaiekhozan A, Keyvanfar A, Shafaghat A. A review of self-healing concrete research development. *J Environ Treat Tech*. 2014;2(1):1–11.
7. Jackson MD, Moon J, Gotti E. Material properties of ancient Roman seawater concrete. *J Am Ceram Soc*. 2013;96(8):2598–606.
8. Dry C. Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals. *Smart Mater Struct*. 1994;3(2):118–23.
9. Edvardsen C. Water permeability and autogenous healing of cracks in concrete. *ACI Mater J*. 1999;96(4):448–54.
10. Jonkers HM, Schlangen E. Self-healing of cracked concrete: a bacterial approach. In: *Proceedings of FRACOS*; 2007. p. 1821–6.
11. Wiktor V, Jonkers HM. Quantification of crack-healing in novel bacteria-based self-healing concrete. *Cem Concr Compos*. 2011;33(7):763–70.
12. White SR, Sottos NR, Geubelle PH. Autonomic healing of polymer composites. *Nature*. 2001;409(6822):794–7.
13. Van Tittelboom K, De Belie N. Self-healing in cementitious materials—A review. *Materials*. 2013;6(6):2182–217.
14. Wang JY, Snoeck D, Van Vlierberghe S. Application of hydrogel encapsulated carbonate precipitating bacteria. *Cem Concr Compos*. 2014;49:97–108.
15. Sisomphon K, Copuroglu O, Koenders EA. Self-healing of surface cracks in mortars. *Cem Concr Res*. 2012;42(9):1077–88.
16. De Belie N, Gruyaert E, Al-Tabbaa A. A review of self-healing concrete for damage management. *Adv Mater Interfaces*. 2018;5(17):1800074.
17. Schlangen E, Joseph C. Self-healing processes in concrete. In: Ghosh SK, editor. *Self-healing materials*. Weinheim: Wiley-VCH; 2009. p. 141–82.
18. Reinhardt HW, Jooss M. Permeability and self-healing of cracked concrete. *Cem Concr Res*. 2003;33(7):981–5.
19. Termkhajornkit P, Nawa T. The fluidity of fly ash-cement paste containing naphthalene sulfonate. *Cem Concr Res*. 2004;34(6):1017–24.
20. Jacobsen S, Sellevold EJ. Self-healing of high strength concrete. *Cem Concr Res*. 1996;26(1):55–62.
21. Li VC, Herbert E. Robust self-healing concrete for sustainable infrastructure. *J Adv Concr Technol*. 2012;10(6):207–18.
22. Jonkers HM. Self-healing concrete: a biological approach. In: Van der Zwaag S, editor. *Self-healing materials*. Dordrecht: Springer; 2007. p. 195–204.
23. Achal V, Mukherjee A, Reddy MS. Microbial concrete: way to enhance durability. *J Mater Civ Eng*. 2011;23(6):730–4.

24. De Muynck W, De Belie N, Verstraete W. Microbial carbonate precipitation. *Ecol Eng*. 2010;36(2):118–36.
25. Wang J, Van Tittelboom K, De Belie N. Use of silica gel for self-healing concrete. *Constr Build Mater*. 2012;38:1197–202.
26. Khaliq W, Ehsan MB. Crack healing in concrete using bacteria. *Constr Build Mater*. 2016;102:349–57.
27. Erşan YÇ, Silva FB, Boon N. Screening of bacteria for self-healing concrete. *Appl Microbiol Biotechnol*. 2015;99(14):6075–89.
28. Seifan M, Samani AK, Berenjian A. Bioconcrete: next generation concrete. *Appl Microbiol Biotechnol*. 2016;100(6):2591–602.
29. Yang Z, Hollar J, He X. A self-healing cementitious composite using oil core/silica shell microcapsules. *Cem Concr Compos*. 2011;33(4):506–12.




Aca. Intl. J. E. Sci. 2023; 1(2) 01-10.**DOI**: https://doi.org/10.59675/E121.