HBRP PUBLICATION

Journal of Advanced Cement & Concrete Technology
Volume 5 Issue 1

An Appraisal of Autogenous and Autonomous Self-Healing in Concrete in Building Construction

Karan Das[1], Kuldeep Kumar[2]*
[1]PG Student, [2]Ph.D. Scholar
Department of Building Engineering and Management,
School of Planning and Architecture, New Delhi, India.
Corresponding Author
E-mail Id:*-ar.kuldeepverma@gmail.com*

ABSTRACT

Concrete is a brittle material and is prone to cracking. Crack repairs are not only expansive but also increases the carbon footprint as it is 2nd most used material on earth. Designing a novel concrete material possessing the ability to self-repair cracks would enhance its sustainability and reduce the maintenance cost as well. Self-healing can be described as the ability to repair the damages itself without any external intervention or help.

Self-healing process in concrete can be autogenous (based on an optimal mix composition) or autonomous (when additional capsules containing some healing agents are inserted into binder phase). The first approach that is in autogenous, unhydrated cement particles are used to mend the fracture, while in autonomous method bacteria is used to precipitate calcite, which is released into the crack from a broken capsule which is activated by water and oxygen. The disadvantage of autonomous approach is the loss of fresh concrete workability, low efficiency, and bacteria survival during mixing and also its high cost. On the other hand, autogenous self-healing has been found to be more efficient, cost effective, and safe.

Keywords:*-Self-healing, concrete, cementitious materials, exposure, fly-ash, calcite, cracking*

INTRODUCTION/ BACKGROUND

Concrete is one of the most popular structural materials and most used thing in the world after water. Over the years, different composition in concrete have been proposed to improve or work on its properties. Concrete is a brittle material with low tensile strength. To increase the tensile strength of concrete additional reinforcement must be implemented, usually made of steel [1]. Unfortunately, due to its brittleness, concrete is prone to cracking not only due to the external mechanical loading but also because of drying or autogenous shrinkage. The cracks create a passage for acidic ions to reach the reinforcement leading to its corrosion and consequently to the deterioration of concrete. Consequently, the material’s strength decreases, which is a serious issue. One of the most sought features in material science is self-healing, or the ability of a material to recognise and repair internal damage without the need for human intervention. Recently, researchers have focused on the self-healing properties of cementitious materials and the elements that influence their utilisation in the construction sector, such as the concrete's design qualities [11]. Succeeding in healing concrete cracks could lead to more sustainable construction and lowering of the maintenance costs. It is pertinent to note that [13] have highlighted several relevant characteristics that affects the performance and quality of concrete construction projects. According to[14], it is essential to standardize the design and the required materials for the concrete works which can help in addressing the issues of cracking in the concrete during the construction stage.

Furthermore [12] emphasized on the fact that there is a lack of efficient in handling and supervision of concrete works as well which leads to the poor workmanship, hence an innovative technology of self-healing can be instrumental in addressing these issues.

AIM

The aim of the study is to critically critical review of autogenous or autonomous self-healing in concrete building construction.

OBJECTIVES

(i) To understand the mechanism behind the autogenous self-healing of concrete
(ii) To use that knowledge to maximise the potential of it

RESEARCH QUESTIONS

- What is the most reliable self-healing approach for concrete considering the efficiency, impact on fresh and hardened properties, cost, safety, and full-scale applications?
- How does the concrete age affect the efficiency of the self-healing?
- How does the mix composition affect the efficiency of the self-healing process?
- How and to what extent does the addition of Supplementary Cementitious Materials contribute to the self-healing process?

METHODOLOGY

- Literature Study:
  - To study both Autonomous and Autogenous Self-healing concrete and their respective concrete properties.
  - To study the materials, present in both type of self-healing concrete and methods applied.
  - Analysing various papers and journal and their contribution on self-healing concrete.
- Analysis of various experimental studies on self-healing properties of concrete.
- Observation of the results of both experimental studies and the literature study.
- Formulation of Conclusion.

LITERATURE REVIEW

SELF-HEALING CONCRETE

The self-repair of tissues and bones in biological materials has always been an interesting concept. Self-healing can be described as an ability to repair the damages itself without any external intervention or help. The initiation of the mechanism is the occurrence of the "injury". The Biological system initiates an inflammatory response, followed by the cell proliferation and finally, matrix remodelling. It is a time taking process and the synthetic process follows the similar steps however the rate of healing is much faster. Same happens with the cement-based composites, there are two types of self-healing process. One is Autogenous and other is Autonomous.

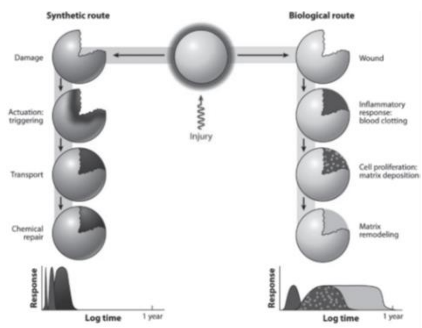

Fig.1:-*Synthetic & biological route of self-healing of tissue*

HBRP PUBLICATION

Journal of Advanced Cement & Concrete Technology
Volume 5 Issue 1

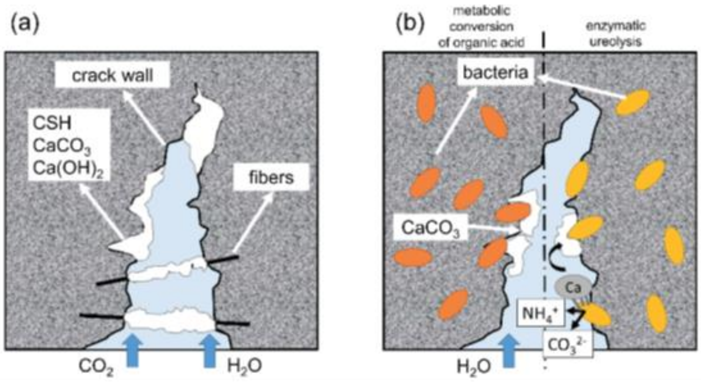

Fig.2:-(a) autogenous and (b) autonomous self-healing of concrete

AUTONOMOUS SELF-HEALING

- **CAPSULE BASED APPROACH**

In this type of crack healing in concrete includes concrete capsules (either spherical or cylindrical) that contains a healing agent. When the crack happens, the capsules break, and the inside agent (sometimes special bacteria) fills the crack due to gravitation forces. The efficiency of such encapsulated agents can be observed in the aggressive conditions related to temperatures that can produce very difficult cracks to handle. Such issues related to variation in temperature are significant in terms of quality od concrete during the construction process which needs attention, wherein this approach is beneficial in mitigating the problem of cracks [7]. The mechanism of the capsule-based self-healing systems consists of three components. The first is the trigger, which depicts the process of activating the capsule by damaging its walls. The next component is the healing agent, i.e., the substance, being the core of capsule, which is released into the crack upon activation.

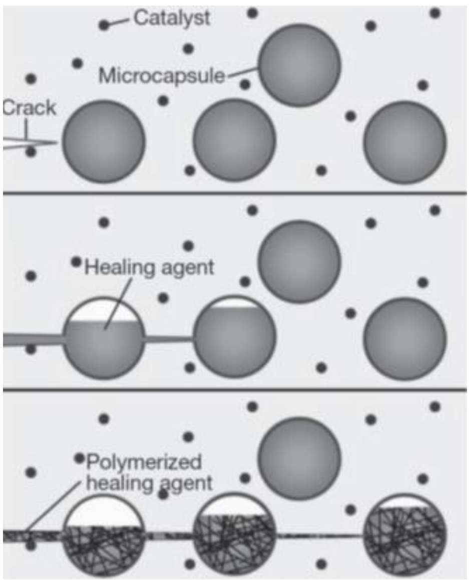

Fig.3:-Mechanism of Crack-Healing

USING SAP PARTICLES

Super Absorbent Polymers (SAP) are water-absorbing particles added to cementitious mixes. SAP particles have the ability to absorb liquid and, after expanding, can act as a crack filler. The entire process begins when the concrete components are mixed together and the SAP particles absorb some water, which is then added to the cementitious mixtures. As a result, pores form, making crack locations easier to forecast because cracks would most likely follow the direction of the pores. When moisture and wetness get into the cracks, SAP particles absorb it and swell until a gel forms, which acts as an agent for self-healing concrete. Using SAP particles in the cementitious mixture to make concrete with better self-healing approaches is not recommended for marine structures as the seawater will seal the cracks which will stop the SAP particles from swelling and limit the autonomous self-healing of those cracks. As a result, this shortage will affect the durability of concrete in marine environments.

USING POLYURETHANE

Because of magnesium sulphates' presence in marine infrastructures, the cracks may be repaired by brucite precipitation due to seawater. In case the width of the crack is over 10 μm, the penetration of chloride into the mixture will be faster, which will shorten the life span of the reinforced concrete. The solution to that is laid in involving the mechanisms of autonomous healing. When polyurethane capsules are added to fissures with a width of 300 μm, they can have a self-healing efficiency of 75% when it comes to chloride diffusion. "Autonomous crack healing of mortar samples using encapsulated polyurethane has a beneficial effect on chloride diffusion resistance for crack widths between 100 and 300 μm." When adding the polyurethane to the mixture, according to [2], their experiment was more focused on samples of mortar rather than reinforced concrete, but the findings were quite positive in terms of durability. "Autonomous crack healing with encapsulated polyurethane can increase the durability." This will also help the project managers and stakeholders at site to prioritize the concreting work packages so that the use of autonomous healing approach through the use of polyurethane can be applied for the affected concrete members [14].This finding could be used to prove that an important service life extension of structures can be achieved with self-healing cementitious materials in chloride-containing environments".

USING GGBFS

GGBFS (ground granulated blast furnace slag) is a common raw material for alkali-activated composites. It has a larger percentage of amorphous silica, making it a good reactive material. Because of its chemical reactions with other substances, the activator's job is to provide strength (GGBFS). The calcium hydroxide-based activator utilised in the experiment by [4] was chosen because of its high efficiency, low cost, and long durability when compared to other activators. According to the findings of the experiment [4] autogenous self-healing is the most effective way for repairing cracks in maritime structures. However, it necessitates a unique approach that entails substituting nearly half of the Portland cement with Ground Granulated Blast Furnace Slag and using $Ca(OH)_2$ as activators in the form of coated granules.

USING BACTERIA BASED APPROACH

One of the first applications of bacteria to seal cracks in concrete was mentioned by Gollapudi et al. in 1995. The use of bacteria modified mortars, which could be applied externally for concrete repair was the topic of many research projects [3,10,16]. Recently, the use of bacteria for self-healing concrete was also studied.

Mechanism of the bacterial self-healing: Bacterial self-healing of concrete is governed by two basic mechanisms: bacterial metabolic conversion of organic acid and enzymatic ureolysis. Calcium carbonate is the self-healing material that plugs the crack. Bacteria act as a catalyst in the first phase, converting a precursor compound into a suitable filler material. Calcium carbonate-based minerals are formed as a result, acting as a type of bio-cement to seal the fractures. Calcium lactate is one of the calcium precursors that is frequently employed in research due to its good effect on concrete strength.

In this case, the reaction occurring in the crack can be formulated as follows:

$$\mathbf{Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O}$$

In addition to this reaction, the produced CO_2 reacts locally with $Ca(OH)_2$ inside of the crack leading to the production of five more $CaCO_3$ molecules thus making the process six times more effective than the autogenous self-healing [3].

The technology of bacteria-based self-healing for cementitious configuration in low-temperature marine environments is a viable method for solving crack problems in hostile situations. The behaviour of bacteria provides a biological context for stressing the concept of autonomous self-healing in this method. When seawater gets into the crack, the bacterium-based beads in the structure swell, causing a barrier that releases the bacteria. The spores immediately begin to germinate because of chemical reactions with other minerals, eventually leading to the healing of the fracture. This approach is also very cost-effective. "The composite demonstrated an excellent crack-healing capacity, reducing the permeability of cracks 0.4 mm wide by 95 percent, and cracks 0.6 mm wide by 93 percent following 56 days of submersion in artificial saltwater at 8°C,". This technology's compressive strength makes it an extremely durable building material.

AUTOGENOUS SELF-HEALING

A process in which the recovery of a material from damage only depends on its original components is known as autogenous self-healing. In other words, the self-healing ability of concrete and other cementitious material is possible only due to their specific chemical composition and, in addition, under favourable environmental conditions. The healing of cracks in water retaining structures, culverts and pipes was noticed by the French Academy of Science in 1836[18]. Afterwards, many researchers not only observed the presence of autogenous healing products in the cracks of concrete but also tried to verify its physicochemical background.

MECHANISM OF THE AUTOGENOUS SELF-HEALING

This approach is dependent on the properties that make up the mixture itself. When the cracks occur, water is an essential factor for autogenous healing of concrete. Addition of fly ash and bacterial spores into the cementitious composition, for instance, can explain the autogenous self-healing of concrete. When adding fly ash as pozzolanic materials instead of cement in the concrete mixture, hydration of the un-hydrated parts should promote the autogenous healing of concrete cracks when occurred. Furthermore, by incorporating bacterial spores into the cementitious mixture and allowing water to enter the crack after it has hardened and cracked, a chemical reaction will be triggered, resulting in an agent to fill the crack. "It is plausible that water plays a key part in autogenous self-healing as water was the medium for the diffusion of ions and the creation of reaction products," Liu et al. concluded after testing crack healing with immersion in water. They came to the conclusion that the efficacy of autogenous self-healing of cracks in cement paste is affected by wet-dry cycles. A cycle of 12 hours wetting followed by 12 hours drying is more efficient than a cycle of 1 hour wetting followed by 23 hours drying.

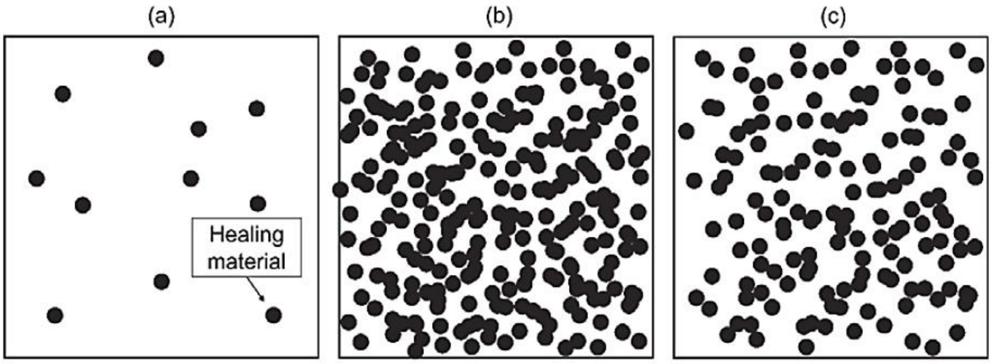

***Fig.4:**-Simplified schematic representation of the fraction of the healing material available in cement paste: (a) microcapsules (2% of cement content), (b) unhydrated cement particles after 7 days of hydration (approx. 50% of cement content), (c) unhydrated*

- **EFFECT OF ADMIXTURES AND BINDERS**

In the last decade, the effects of the concrete mix composition and the presence of mineral additives on the autogenous self-healing of concrete were studied. It was observed that the use of expansive additive (CSA: calcium sulfoaluminate) and crystalline additive (CA: reactive silica and some crystalline catalysts) enhanced the surface crack closing (Sisomphon, 2012). These modifications raised the maximum healed crack width from 150 μm to 400 μm.

The water permeability of the restored specimens has significantly decreased. Calcium carbonate precipitation was seen, notably around the crack's opening. By elevating the pH of the samples, the additions increased the environmental conditions for calcium carbonate precipitation. CA-containing concrete mixes showed the most consistent behaviour and the quickest healing rates.

Self-healing of a crack having width of up to 200 μm within 42 days was observed for self-healing concrete containing alternative binders (blast furnace slag and fly ash)[17].

- **FULL-SCALE APPLICATION & PRICE**

  Unfortunately, majority of research is till done at the small scale, in the laboratory, serving primarily as a “proof of concept”. In addition, the price of the autonomous self-healing methods is relatively high. Some of the methods were cost-effective, cheaper than a manual injection of the cracks. For examples: SAP and several bacterial methods. At the same time the microcapsule based self-healing methods were significantly more expensive. e.g., PU Capsules.

The autogenous methods do not contribute to a higher price as they consist only of original concrete components.

Nevertheless, it is important to remember that the higher amount of binder promoting the continued hydration mechanism has an influence on the production costs.

According to[5] it is essential to relate the aspects of self-healing technology with the value-adding aspects so that the full-scale application cost can be feasible for the application of this technology in the construction industry. [8] mentioned that the rapid growth in population and urbanisation has led to increase in the demand for buildings, and hence, scale of application is of particular significance. Another downside related to a higher amount of binder is its environmental impact. The effect on the CO_2 emissions of the mix composition of UHPC in comparison to ordinary concrete might be estimated as twice as high [9].Therefore, to balance the high carbon footprint, the self-healing process should be efficient enough.

***Table 1:**-Comparison between Autogenous & Autonomous Self-healing*

AREA	AUTONOMOUS SELF-HEALING METHOD	AUTOGENOUS SELF-HEALING METHOD
FRESH CONCRETE	• Low survival rate of capsules during mixing • Loss of workability with increased number of capsules	• Loss of workability due to fibres • Higher amount of cement resulting in increased hydration heat, shrinkage
EFFICIENCY	• Too low stress crated by forming crack are not able to break the capsules • Lack of water & oxygen hinders the healing process in the case of bacteria-based approach • The maximum volume fraction of capsules is limited due to workability issues and loss of strength which leads to a lower healing efficiency	• Age of the specimen at cracking has a great influence on the healing efficiency • The healing process might take several days/weeks • Only limited crack width can be fully healed
PRICE & FULL SCALE	• Very high price in comparison to the methods used for autogenous healing • Difficult to apply on the full scale	• Higher CO2 footprint due to higher amount of binder

FINDINGS

Autogenous self-healing methods based on traditional concrete technology appear to be cheaper, easier, and safer than autonomous methods. Therefore, the autogenous method appears to be a significantly more feasible solution for real life applications. However, there are several issues which must not been fully addressed by now:

The mechanism behind the autogenous self-healing concrete is not fully understood, by now. A detailed analysis of the physio-chemical processes allowing concrete to repair its cracks should be performed.

The efficiency of the autogenous self-healing should be improved. There is still not a lot of information about the successful internal crack closure.

CONCLUSIONS

The following conclusion can be formulated based on the data obtained from literature:

- A large amount of cement in the concrete mix does not ensure the efficient autogenous self-healing of cracks.

- Water alone is inefficient in promoting self-healing.
- Fly ash supports the formation of a thick layer of calcite over the crack mouth. It does not support the flexural strength recovery due to the lack (or limited) formation of healing products inside the crack, in particular the load bearing phase C-S-H.

ADDRESSING RESEARCH QUESTIONS

- **RQ1: What is the most reliable self-healing approach for concrete considering the efficiency, impact on fresh and hardened properties, cost, safety, and full-scale applications?**

- Based on the performed critical literature review, it can be stated that the autogenous self-healing is more reliable than autonomous methods with respect to the impact on fresh and hardened concrete properties. It is also more cost effective, safer, and feasible in terms of full-scale applications. Nevertheless, the efficiency of the process still must be improved.

- **RQ2: How does the concrete age affect the efficiency of the self-healing?**

- The self-healing efficiency diminishes with the age of the concrete for the mixes with a high amount of cement and a low water-to-cement ratio. It is presumably related to the densification of the cement matrix with age rather than to the decreasing amount of unhydrated cement.

- **RQ3: How does the mix composition affect the efficiency of the self-healing process?**

- The mix composition is a governing factor when it comes to the efficiency of the autogenous self-healing process. A commonly accepted hypothesis states that the healing is more effective for mixes which have a high amount of unhydrated binder available. This would favour mixes with a low water-to-cement ratio and high amount of cement.

- **RQ4: How and to what extent does the addition of Supplementary Cementitious Materials contribute to the self-healing process?**

- Fly ash appeared to have contributed to the highest external crack closure ratio, with a visible thick layer of calcite covering the crack mouth; however, no flexural strength recovery was observed in this case, presumably due to a limited formation of load bearing healing products inside the crack. Further studies are needed to confirm this phenomenon.

REFERENCES

1. Das, S., Rastogi, A. & Kumar, K., (2021). Applicability of Risk Assessment Tools and Techniques for a Construction Project. *Journal of Research in Infrastructure Designing,* 4(3), pp. 1-18.
2. Heede, P. V. d., Maes, M. & Belie, N. D., (2014). Influence of active crack width control on the chloride penetration resistance and global warming potential of slabs made with fly ash+silica fume concrete. *Construction and Building Materials, Volume 67, Part A,* pp. 74-80.
3. Jonkers, H., (2007). Self-healing concrete: a biological approach. In Self-Healing Materials. *Springer Netherlands,* pp. 195-204.
4. Kim, H. G., Atta-ur-Rehman, Qudoos, A. & Ryou, J.-S., (2018). Self-healing performance of GGBFS based cementitious mortar with granulated activators exposed to a seawater environment. *Construction of Building Materials, Volume 188,* pp. 569-582.
5. Paul, V. K. & Basu, C., (2016). Scenario Planning and Risk Failure Mode Effect and Analysis (RFMEA) based Management. *Korean Institute of Construction Engineering and Management,* 6(2), pp. 24-29.

6. Paul, V. K., Khursheed, S. & Singh, R., (2020). Comparative study of construction technologies for underground metro stations in India. *IJRT*, 6(2), pp. 3-5.
7. Paul, V. K. & Seth, V., (2017). Benchmarking and objective selection of technologies for housing in India using quality function deployment. *Journal of Construction in Developing Countries*, Volume 22, pp. 63-78.
8. Pulupula, S. & Dua, S., (2021). Study of the Efficiency of Insulated Concrete Formwork and Similar Fast-Paced Construction Systems in the Indian Context. *Journal of Building Construction*, 3(3), pp. 1-9.
9. Rajczakowska, M. N. L. H.-C. K. H. H. &. C. A., (2019). Does a High Amount of Unhydrated Portland Cement Ensure an Effective Autogenous Self-Healing of Mortar?. *Concrete & Building Materials, 12(20)*, p. 3298.
10. Ramakrishnan, V., Panchalan, R. K., Bang, S. S. & Khokhlova, A., (2013). Improvement of concrete durability by bacterial mineral precipitation.
11. Rastogi, A. & Paul, V. K., (2020). A Critical Review of the Potential for Fly Ash Utilisation in Construction-Specific Applications in India. *Journal of Environmental Research, Engineering and Management*, 76(2), pp. 65-75.
12. Saini, A., Khursheed, S., Paul, V. K. & Kumar, K., (2021). Analysis of Indirect cost of Construction Projects in India. *International Journal of Sustainable Building Technology*, 4(2), pp. 9-23.
13. Seshadhri, G. & Paul, V. K., (2017). User requirement related performance attributes for government residential buildings. *Journal of Facilities Management*, 15(5), pp. 409-422.
14. Seshadhri, G. & Paul, V. K., (2018). User satisfaction index: An indicator on building performance. *Journal of Civil Engineering and Structures*, 2(1), pp. 14-33.
15. Sisomphon, K. C. O. &. K. E. A. B., (2012). Self-healing of surface cracks in mortars with expansive additive and crystalline additive. *Cement and Concrete Composites, 34(4)*, pp. 566-574.
16. Tittelboom, V. K., De Belie, N., De Muynck, W. & Verstraete, W., (2010). Use of bacteria to repair cracks in concrete. *Cement & Concrete Research,40(1)*, pp. 157-166.
17. Van Tittelboom, K. G. E. R. H. D. B. N., (2012). nfluence of Mix Composition on the Extent of Autogenous Crack Healing by Continued Hydration Or Calcium Carbonate Formation. *Construction & Building Material*, *37*, pp. 349-359.
18. Wu, M., Johannesson, B. & Geiker, M., (2012). A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material. *Construction and Building Materials, 28(1)*, pp. 571-583.