International Journal of Infrastructure Research and Management
Vol. 13 (1), June 2025, pp. 55 - 61

MICROCRACK SELF-HEALING TECHNOLOGY FOR CEMENT-BASED MATERIALS

Li Mei Ying[1,2] & Norul Wahida Kamaruzaman[1]
[1]*Infrastructure University Kuala Lumpur, MALAYSIA*
[2]*Xi'an Siyuan University, CHINA*

ABSTRACT

Crack self-repair technology of cement-based materials refers to the ability to repair cracks within the cement-based material structure without external repair measures. It can be divided into engineering self-healing technology and intrinsic self-repair technology, depending on the repair mechanism and the presence or absence of additional healing materials. In this paper, the mechanisms and characteristics of various crack self-repair technologies are summarized, the recent research progress on crack self-repair in cement-based materials is discussed, and suggestions for future research directions are proposed. Many researchers have experimentally demonstrated that mineral admixtures offer potential for improving the self-healing ability of microcracks in cement-based materials. However, the self-healing technology involving mineral additives is still in the exploratory stage, with limited and insufficiently systematic research findings. Further studies are needed to evaluate the effects of mineral additives on the self-healing performance of microcracks in cement-based materials, and to identify the composition and characteristic parameters of these mineral materials that enhance self-repair capacity. Such advancements would support the increased recycling of mineral additives, reduce construction waste, lower environmental pollution in the production of cement-based materials, and yield significant social, economic, and ecological benefits.

Keywords:
Cement-based materials, self-healing effect, microcracks, healing mechanism, self-healing concrete, green technology concrete

INTRODUCTION

As one of the most important materials in engineering construction, cement-based materials are prone to cracking due to various factors, which can seriously affect project quality (Kong & Norul, 2025). The traditional manual repair methods are not only costly, but also time-consuming and labour-intensive, gradually revealing significant limitations (Sun et al., 2024). In recent years, transforming the repair of microcracks in cement-based materials from a passive to an active process has become a major research focus among scholars both domestically and internationally. The goal is to address the issue of concrete cracking at its root. Many researchers have confirmed that cement-based materials possess an intrinsic self-healing capability, which allows them to sense microcracks within concrete structures (Li & Norul, 2025) trigger a self-repair mechanism, and restore material properties in real time (Kong & Norul, 2023), thereby extending the service life of the structure (Fernandez et al., 2021). According to the repair mechanism and the presence or absence of external repair materials, the self-healing technologies for cement-based materials can be classified into: Engineering self-healing technologies (e.g., hollow pipe network systems, microcapsules, bacteria and microorganisms, swelling and crystallization additives). Intrinsic self-healing technologies, also referred to as spontaneous or natural self-healing (Liu & Lu, 2023).

SELF-HEALING TECHNOLOGY OF HOLLOW PIPE NETWORK SYSTEM

Mimicking the vascular networks of living organisms, hollow fibers or pipe networks can be used to store and transport self-healing functional components. When cracks form and cause the hollow pipe to rupture, the flowing repair agent is released into the crack, where it coagulates and hardens. In this way, the hollow pipe network system effectively delivers the organic polymer repair agent to the damaged area, enabling autonomous crack repair (Zhang et al., 2020).

Fiber-reinforced concrete materials incorporate appropriate amounts of carbon fiber, steel fiber, glass fiber, or mixed fibers into ordinary concrete to reduce early shrinkage cracks, temperature-induced cracks, and long-term shrinkage cracks in concrete structures. When the concrete is subjected to loading, the fibers help control crack width and inhibit crack formation. The addition of human slag to concrete has been shown to effectively promote crack healing (Eisa, 2020). Similarly, combining rubber scraps and steel fiber in reinforced concrete beams has been found to improve mechanical properties, particularly when more than 10% rubber content is used. Adding polypropylene fiber to foam concrete enhances its resistance to cracking and increases toughness, while incorporating bamboo fiber can reduce or delay crack formation and improve the tensile strength of concrete (Liu et al., 2020).

Hollow fibers also help address the inherent drawbacks of concrete, such as high brittleness and low tensile strength, by altering the internal microstructure, reducing crack formation, and improving both impermeability and durability. However, the high production cost and time-consuming fabrication of fiber materials limit the widespread adoption of this technology.

MICROENCAPSULATION SELF-HEALING TECHNOLOGY

The microencapsulation method was first proposed by White et al. in 2001, and its repair effectiveness is influenced by multiple factors (Zhang et al., 2022):
(1) The total number, size, and degree of dispersion of capsules within the cement-based material;
(2) Whether the capsule material ruptures when the cement-based material cracks;
(3) The type and fluidity of the repair solution inside the capsule;
(4) The causes of cracking in cement-based materials, including crack size and spatial distribution.

In recent years, researchers have conducted extensive and in-depth investigations into microcapsule shell materials suitable for self-healing in cement-based materials. The principle of microcapsule self-healing technology involves encapsulating a liquid repair agent within a microcapsule or hollow fiber, which is then evenly mixed into the concrete. When the concrete experiences stress and microcracks form, the capsule wall ruptures due to mechanical force, releasing the internal repair agent. This agent then flows into the crack and, through capillary action, reacts and solidifies with components in the cement matrix, ultimately bonding and healing the crack (Ren et al., 2020).

Lin et al. (2020), in the preparation of a microencapsulated self-healing concrete, added three types of fluorosilicates as curing agents and found that sodium fluorosilicate exhibited the best self-healing performance. Shen et al. (2020) reported that when a component is damaged, the wall of the microcapsule breaks, releasing epoxy resin into the crack, which heals the damage. The tensile strength recovery rate after repair was 45%. Subsequent studies demonstrated that calcium nitrate microcapsule-based self-healing concrete exhibited significantly higher sealing efficiency in steel fiber-reinforced concrete beams compared to the control group at both 21 and 42 days. The largest sealed crack reached 290 μm (Shang et al., 2020).

The preparation method for microcapsule self-healing concrete is relatively simple and cost-effective. However, microcapsules are prone to rupture during the mixing and vibration processes, which may prevent them from functioning as intended. Therefore, it is essential to develop new concrete manufacturing techniques to ensure microcapsules remain intact until activated. Additionally, the repair adhesive contained in the microcapsules or fibers should possess adequate bond strength to restore or even enhance the structural performance of the repaired concrete.

BACTERIAL MICROBIAL SELF-HEALING

The earliest research on the introduction of bacteria into concrete dates back to the 1990s, when Gollapudi et al. (1995) first succeeded in implanting bacteria into cement-based materials to induce calcium carbonate precipitation, thereby enhancing the self-healing of cracks. Given the important role of calcium carbonate in the self-healing process of cement-based materials, researchers have sought to increase its formation by introducing bacteria and microorganisms into concrete, thereby exploring new self-healing pathways. This autonomous repair technology, based on biomineralization, has demonstrated effective crack healing performance.

In earlier studies, microbial self-healing referred to the use of aerobic microorganisms that undergo mineralization to generate sediments for crack repair. Calcium carbonate, the product of this reaction, exhibits good compatibility with concrete structures (Xu et al., 2019). Wang et al. (2020) reported that the mechanical properties of self-healing concrete using expanded perlite-immobilized microorganisms decreased with higher carrier content. After 28 days, the concrete cracks were filled, and the compressive strength recovery rate reached nearly 63%.

Despite these promising results, microbial self-healing remains in the laboratory research stage. Microorganisms have strict environmental requirements for growth, which presents challenges for experimental implementation (Zhang et al., 2021). Moreover, the presence of water, oxygen, nutrients, and specific microbial strains significantly affects both the compatibility of microorganisms with the concrete matrix and the durability of the material during the mineralization process.

SWELLING AND CRYSTALLIZATION ADDITIVES SELF-HEALING

Many studies have shown the presence of alum and other compounds in the self-healing products found at fracture sites, which may be attributed to a re-cementation effect. Based on this concept, expansive and crystallization additives have been developed to enhance the self-healing performance of cement-based materials. As hydrophilic substances, swelling and crystallization additives can react rapidly with water to generate crystalline compounds that fill cracks. The inclusion of these crystalline additives significantly improves the self-healing properties of concrete (Rong et al., 2024).

Guo et al. (2019) found that the main factors influencing the impermeability of concrete are the structural morphology and quantity of crystals formed. Yao et al. (2020) reported that the addition of osmotic crystalline waterproofing materials and nano-silica promoted crystal formation at concrete crack sites. Subsequent experiments determined that a water–cement ratio of 0.5 was optimal for internally mixed permeable crystalline concrete, producing the highest number of internal crystals and effectively repairing cracks.

Simultaneously, researchers investigated the effects of calcium-based mineral additives, chemical expansion agents, and crystalline components on the self-healing performance of steam-cured mortar. The results indicated that steam curing, in combination with these mineral additives, significantly enhanced self-healing efficiency. Both crack sealing and impermeability were markedly improved. It was therefore concluded that swelling and crystallization additives, when used in combination with auxiliary materials, can maximize self-healing performance (Zhang et al., 2024).

To summarize, the most commonly studied engineering self-healing methods such as hollow fiber tube systems, microcapsules, bacterial and microbial mineralization, and swelling and crystallization additives can enhance the crack-healing capabilities of cement-based materials.

However, their complex construction processes and high costs hinder large-scale application. Addressing these cost-related challenges remains a critical barrier. Among these methods, only crystallization precipitation-based self-healing has been applied in practical engineering due to its relative simplicity and cost-effectiveness. While international scholars have made notable advancements in crystallization-based self-healing technologies, relevant research outcomes in China remain limited.

INTRINSIC SELF-HEALING TECHNIQUES

Intrinsic self-healing technology, also known as spontaneous or natural self-healing, refers to the inherent repair capability of cement-based materials. This mechanism promotes the automatic healing of early-stage microcracks within the material's structure. The self-repair process in cement-based materials occurs as “unhydrated” cement particles within the crack continue to hydrate, forming insoluble crystalline precipitates. These precipitates contribute to crack closure. At points where cracks are exposed to the external environment, the hydration products react with water and carbon dioxide in the air to form compounds such as calcium carbonate, which accumulate within the crack and assist in restoring the material’s integrity either fully or partially (Lv et al., 2024).

The primary mechanism of intrinsic self-healing is attributed to the precipitation of calcium carbonate, as evidenced by the frequent appearance of white calcium carbonate deposits on the outer surface of healed cracks. This is primarily due to the high solubility of calcium hydroxide, a byproduct of cement hydration, which dissolves in water and subsequently reacts with dissolved carbon dioxide to form self-healing crystals. These crystals adhere to the crack surfaces and gradually fill the voids.

One of the most critical steps in the intrinsic self-healing process involves the reaction of dissolved $Ca(OH)_2$ with carbon dioxide in water to form calcium carbonate, which is particularly significant in the later stages of healing. As calcium hydroxide dissolves, the concentration of calcium ions (Ca^{2+}) increases until it reaches supersaturation, facilitating the formation of calcium carbonate precipitates. In open water environments, this reaction is sustained due to the continuous availability of CO_2, allowing carbonates to migrate steadily into the cracks, where calcium carbonate crystallization occurs and progressively fills the voids (Wei et al., 2020).

EFFECT OF MINERAL ADDITIVES ON INTRINSIC SELF-HEALING EFFECT

When incorporated into the structure of cement-based materials, mineral additives serve as environmentally friendly alternatives that not only alleviate environmental pressure but also enhance certain properties of conventional cement-based materials. This improvement depends on the mineralogical composition of the additives and occurs without compromising the structural integrity of the concrete. These additives can further promote the self-healing of microcracks. Although powdered mineral additives, when used as admixtures, come into direct contact with water limiting their active period and reducing their effectiveness in later-stage crack repair, they still exhibit self-healing potential for microcracks that form in the early stages due to shrinkage stress or external forces.

Studies from researchers in various countries demonstrate that using mineral additives in cement-based materials can reduce cement content and material costs. Furthermore, due to their micro-filler effect, pozzolanic activity, and particle packing, these additives enhance the pore structure and permeability resistance of concrete. When cracks occur, calcium hydroxide ($Ca(OH)_2$) within the matrix activates the unreacted mineral particles. This promotes further hydration, enabling the healing of microcracks within permissible widths, thereby restoring both the strength and water resistance of the concrete matrix. However, since some mineral additives consume $Ca(OH)_2$ during hydration, they may impact the amount of calcium carbonate precipitation, a key self-healing product. This effect warrants further investigation.

Fly ash is the most widely used mineral admixture in concrete. Yu et al. (2023) found that incorporating fly ash improves the workability and durability of concrete, with performance significantly affected by fly ash quality. Their experimental results showed that, under the same strength grade and water cement ratio, Grade I fly ash yielded slightly higher impact wear strength than Grade II fly ash. Similarly, Yin et al. (2020) observed that increasing fly ash content improved the self-healing ability of cement-based materials, largely by refining the internal microstructure. Zhou et al. (2022) also confirmed that different amounts and qualities of fly ash influence not only mechanical properties but also thermal characteristics and early crack resistance. Zheng et al. (2021) studied the effect of fly ash quality and dosage, concluding that high-quality fly ash significantly enhances compressive strength, thermal insulation, and early crack resistance under equivalent dosages.

In addition to fly ash, mineral powder, commonly derived from blast furnace slag is also effective in improving concrete properties. This slag is produced by quenching molten iron slag and then processing it through drying and grinding. Zhang et al. (2019) reported that when slag content is below 30%, the intensity of the A peak in XRD patterns increases slightly with higher slag content. They concluded that a 30% slag replacement level offers the most effective self-healing performance for concrete microcracks. Yu et al. (2019) compared the effects of fly ash and blast furnace slag, finding that while both enhanced self-healing through continued hydration, they had minimal influence on calcium carbonate formation. Nonetheless, mineral powder demonstrated stronger performance as a cement substitute.

When two or more mineral additives are used in combination, they may interact synergistically, turning individual disadvantages into collective advantages and improving the concrete’s properties. Research has shown that such combinations can significantly improve the mechanical performance of low-strength concrete, especially with age. For instance, compressive strength measured at 90 days was substantially higher than that measured at 28 days. Wang et al. (2022) investigated the effects of “bimineral” admixtures on the early self-healing properties of cement-based materials. They substituted 10% of the cement with combinations of silica fume, metakaolin, quicklime, an expansion agent, and Na_2CO_3. Nine double-admixture specimens were evaluated under immersion and standard curing through crack observation, permeability testing, and compressive strength tests before and after water curing. Results showed that specimens containing quicklime, silica fume, or metakaolin had higher crack repair rates, with the combination of quicklime and metakaolin achieving a 100% crack repair rate at 28 days. Li et al. (2021) similarly found that replacing cement with blast furnace slag and fly ash improved compressive strength and frost resistance. The materials’ pozzolanic characteristics promoted continued hydration of the cement matrix and enhanced self-healing.

CONCLUSION

In summary, the intrinsic self-healing technology of cement-based materials relies on their inherent properties to generate insoluble crystalline precipitates through the continued hydration of unhydrated cement particles in the crack region. This process promotes the autonomous closure of cracks and offers notable advantages, such as simplicity and low cost, when compared to engineering-based self-healing technologies. In the application of cement-based materials, mineral admixtures such as mineral powder, fly ash, silica fume, metakaolin, quicklime, and expansion agents have been shown to influence self-healing performance. These admixtures can reduce early-age strength or cause shrinkage-induced cracking, which in turn can stimulate the self-healing process. However, some mineral additives consume calcium hydroxide Ca $(OH)_2$ during hydration, potentially affecting the formation of calcium carbonate, a key component in crack healing. This interaction requires further investigation.

Experimental studies have demonstrated that, due to the diverse properties of mineral admixtures, multi-component combinations can offer complementary effects. The synergistic interaction between different admixtures can offset the limitations of using a single type and enhance the overall self-healing capacity of cement-based materials. However, the field of crack self-healing remains in its early stages, and the understanding of the underlying mechanisms and governing laws is still incomplete. As such, significant research is needed to address existing challenges and to develop a more systematic and comprehensive understanding of self-healing in cement-based materials.

AUTHORS BIOGRAPHY

Li Mei Ying is conducting research and teaching in the construction courses for undergraduates at Xi'an Siyuan University, China. She is also currently a PhD candidate at Infrastructure University Kuala Lumpur. Her field of expertise are in the construction technology, construction material and concrete technology. *Email: 583955495@qq.com*

Norul Wahida Kamaruzaman, PhD, is an associate professor at Infrastructure University Kuala Lumpur (IUKL). She is conducting research and teaching in the construction courses for undergraduates and postgraduates. Her field of expertise are in the construction technology, construction material and concrete technology. *Email: wahida@iukl.edu.my*

REFERENCES

Eisa, A.S., Elshazli, M.T., Nawar,M.T.(2020). Experimental investigation on the effect of using crumb rubber and steel fibers on the structural behavior of reinforced concrete beams[J]. Construction and Building Materials.

Fernandez,C.A., Correa, M., & Nguyen,M.T.(2021).Progress and challenges in self-healing cementitious materials[J]. Journal of Materials Science.

Gollapudi U.K, Knutson C.L, Bang S. S., et al.（1995）. A new method for controlling leaching through permeable channels [J]. Chemosphere,30(4): 695-705.

Guo,N.L, Guo,R.X, Ma,,Q.M, et al. (2019).The effect of internally doped CCCW on the self- healing and impermeability of concrete is small[J].Non-metallic minerals.

Kong Linjie & Norul Wahida Kamaruzaman. (2023). Study on the Influence of Different Types of Polypropylene Fiber Concrete on Fire Resistance[J]. International Journal of Infrastructure Research and Management, Vol 13(S): pp 29-37

Kong Linjie & Norul Wahida Kamaruzaman. (2025). Application Prospect Analysis of Hybrid Fiber Concrete Subway Shield Segment[J]. International Journal of Infrastructure Research and Management, Vol. 11 (2), December 2023, pp. 63 - 73.

Li Hongyuan & Norul Wahida Kamaruzaman. (2025). A Review of Shrinkage and Crack Resistance of Internal Cured Concrete using SAP as an Internal Curing Agent[J]. International Journal of Infrastructure Research and Management, Vol 13(S): pp 47-55.

Liu,Y.J., Lu,H.X.(2023).Research progress of high ductility cement-based materials[J]. China University of Mining and Technology.

Lin,Z.Y, Liu,R.G, Tang,C, et al. (2020). Repair performance of microencapsulated self-healing concrete encapsulated with sodium silicate under different repair agents[J]. Bulletin of Silicate.

Lv,L.Y., Zhang,X.Y., Dong,B.Q., Wang,X.F., Xie,F.(2024).A review of design methods for trigger mechanism of self-healing concrete.[J]. Materials Herald,1-28.

Liu B F,Wang O F, Yin K,et al.(2020)..An analytical model for crack monitoring of the shape memory alloy intelligent concrete[J].Journal of Intelligent Material Systems and Structures.

Li,J.W., Ma,L.Y., & Li,G.Q.(2021).Research on the influence of fly ash and mineral powder on the mechanical and durability performance of concrete[J]. Contemporary Chemical Industry.

Ren,J, Wang,X.F, Xing,F, et al (2020).Concrete self-healing micro capsules with physical trigger function and preparation method :CN111268937AIP1.

Rong,J,Peng,H,Miao,S.K & Liu,H.X. (2024). A review of permeable crystalline cement-based composites. [J]. Jiangxi Building Materials (08).

Shen,J, Li,H, Zheng,T.X (2020).. Study on the properties of epoxy resin microcapsule self-healing concrete[J]. China Building Materials Science and Technology.

Sun,L.J.(2024),Research and progress of crack self-repair technology of concrete[J].Civil Engineering.

Shang,W.T. (2020), A self-healing micro capsule concrete that can fix carbon dioxide: CN107500589BP1.

Wei,J., Yan,C., Zhao,Y., Zhao,D.G.(2020).Research progress of self-diagnostic composite materials. Composites Science and Engineering (09),111-117.

Wang, K., Chen,F.Y. & Liu,J.(2022).Effect of double-doped mineral additives on self-healing properties of cement-based materials[J]. Material Reports（05）

Wang,B.H, Zhang,J.G, Zhou,M.J, et al., (2020).Experimental study on crack self-healing concrete splitting tensile strength based on expanded perlite immobilized microorganisms[J].Concrete.

Xu,P, Wang,X.Z. (2019). Low-alkali cementitious materials supported by microorganisms are applied to cracking and self-healing of concrete[J]. Journal of Tsinghua University (Natural Science Edition).

Yu, H.D. (2023). Research progress on the influence of tuffaceous rock powder on the properties of cementitious materials. [J]. Acta Sinica Sinica (08), 2090-2097.

Yao,J.C, Yan,Y.D, Xu,P.F, et al. (2020).Study on self-healing properties of cement-based permeable crystalline waterproofing materials and nano-silica modified concrete[J].Bulletin of the Silicate Bulletin.

Yin, S.N., Wu,X.Y.,Yuan, P., & Zhang,Y.(2020).Experimental study on the preparation of fly ash mineral powder composite ultrafine powder and its application in cement.[J].Cement(06).

Yu.Z., Yang, H.Q., Wang,L., & Shi,Y.(2019).Experimental study on the influence of flyash quality on concrete performance [J].Concrete.

Zhang,J.G, Fan,Y.D, Zhou,A.J, et al. (2021), A cheap and efficient method for preparing self-healing concrete with microbial cracks.CN112299767A.

Zhang,L.Q,Yu,J.L,Wang,Y.Y,Han,B.G,Chen,M.C & Xu,K.C. (2024). A review of permeable crystalline cement-based composites. [J]. Materials Reports (13).

Zhou, J.H., Wang, Y.J., Wu,Y.H., & Wang,Y.(2022).The influence of fly ash and mineral powder on the early age mechanical properties of concrete[J].Jiangsu Construction(01).

Zheng, D.X., Li,J.W., & Guo,W.B.(2021).Experimental study on the influence of fly ash quality and dosage on concrete performance.[J]. Contemporary Chemical Industry.

Zhang J., Zhao C., Zhou A., et al. Aragonite formation induced by open cultures ofmicrobial consortia to heal cracks in concrete: Insights into healing mechanisms andcrystal polymorphs [J]. Construction and Building Materials, 2019, 224: 815-822

Zhang, Z., Lv,X.R,Yu,H.L.etc.(2022).Research progress on intelligent self-healing materials[J].Material Review, 36 (7): 20110101.

Zhang,Y.A., Li,J.C.,Wang,Q.F, et al.(2020).Mechanism and experimental study on crack monitoring and repair of intelligent concrete materials[J].Chinese Journal of Solid Mechanics.