Review Article

SELF-HEALING BUILDING MATERIALS FOR ENHANCED DURABILITY AND SUSTAINABILITY IN CONSTRUCTION

Abstract:

Herein, we reviewed self-healing materials as a tool for building durable and sustainable construction materials in the industrial sector. It's a known fact that a person spends most of his life in rooms built from various building materials; therefore, the optimization of the human environment is an important and complex task that requires interdisciplinary approaches. The construction industry is continually seeking innovative solutions to address the challenges of durability and sustainability in building materials. This study explores the promising realm of self-healing building materials, presenting a pathway toward revolutionizing the construction landscape. Self-healing materials possess the intrinsic ability to repair damage autonomously, mitigating the impact of wear, weathering, and structural stress. This paper examines the underlying principles and mechanisms of self-healing materials, shedding light on their potential applications in enhancing the lifespan of structures and minimizing maintenance requirements. Furthermore, the various types of self-healing technologies, each offering unique advantages and challenges, are addressed.

Keywords: self-healing materials, durability, sustainability, construction, infrastructure

1.0 INTRODUCTION

The field of Materials Science has transitioned from finding and using natural materials to creating and utilizing artificial materials like self-healing materials, which are more beneficial for our production and daily lives [1,2,3].

Self-healing materials (SHMs) are a kind of material that can automatically repair itself when injured, specifically addressing wear and tear from prolonged mechanical usage. Self-healing materials possess superior mechanical properties, such as insulation, heat resistance, and high molecular weight. They can mimic the self-healing process in organisms by repairing microcracks through chemical bond changes or the release and polymerization of self-healing monomers stored within the materials, thereby preserving the matrix structure's integrity [4,5,6]. Previously, damaged materials had to be disposed of and substituted with new ones, leading to wastage. Regular inspections and maintenance incur substantial expenses, yet self-healing materials may efficiently manage this issue. Self-healing materials outperform typical materials and may be used in a broader range of environments.

The idea of a self-healing material has been around since the mid-20th century, but its first breakthrough occurred in 2001 via experiments using microcapsules [7,8]. The healing agent dispersed and polymerized in the composite due to cracking while embedded in it, interacting with the catalyst. This approach was further advanced to investigate how to prolong the fatigue life of the self-healing characteristics in a uniform system while minimizing the impact on scattered damage. In previous research, the significance of SHMs has been widely recognized.

The improvement of conversion efficiency, mechanical characteristics, energy absorption, and self-healing capacities remain the main areas of research and practical applications [9,10,11,12]. To improve artificial materials' energy efficiency, durability, safety, and environmental impact, scientists and engineers have spent a great deal of time and money developing self-healing materials. Research on materials with the ability to cure itself is still ongoing. Applications for self-healing materials include biomimicry, construction materials, biological materials, medical materials, vehicles, aircraft, electronics, and military gear. Medical hydrogels benefit greatly from self-healing materials [13, 14]. Brain stem cell precursor cells can be cultured in several self-healing hydrogels. Certain hydrogels can respond to changes in pH and temperature, which makes them useful in biological science and related biotechnology fields. Electrical gadget screens on smartphones and tablets may be made of self-healing materials. Many applications, including electronic skin, energy storage devices, sensors, conductive coatings, and supercapacitors, show significant potential for self-healing materials [15]. Previous research has examined composite materials with artificial or natural reinforcement and nanoparticles for a range of applications [16,17, 18].

1.1 Self-healing Materials in Industries

Self-healing materials play a significant role in industries, particularly in construction. These materials are novel and can repair their own harm. It does not imply that they are able to endure significant injury. It is akin to the notion of form Memory Alloys, which possess an elastic feature and retain their original form in memory. When distortion occurs, it results in an uneven form. Upon exposure to heat, cold, or other external stimuli, the objects return to their original form [19,20]. The action of an external agent is not required, and they can endure a somewhat greater impact than Shape Memory Alloys. Trees, animals and human bodies and other natural creations inspired this. Minor accidents may cause scratches or wounds on our skin, resulting in bleeding. Platelets cause blood to clot quickly. This concept was influenced by scientists and led to the development of Self-Healing Materials [21].

Automatic Healing Materials is another name used to refer to SHMs. This notion is mostly applied in concrete use. Cracks less than 0.2 mm will not do any damage. If a crack exceeds a certain size, it might potentially damage the structures. SHMs will play a crucial role in such regions [22,23]. Modifying the preparation technique and material design may enhance the fatigue life of materials. Optimizing the chemical nature of asphalt materials can also extend their lifespan [24]. Recent research has focused on bio-based polymers for self-healing materials, exploring various intrinsic self-healing processes and the depletion of healing chemicals [25]. Strain-induced crystallization at ambient temperature has proven to enhance the mechanical characteristics, including tensile strength and toughness, of self-reinforcement and SHMs, as reported by Li et al. [26]. Self-healing materials have garnered interest in electric cars for energy storage, showing significant improvements in the durability and lifespan of energy storage devices [27]. Many academics, scientists, and engineers are drawn to the notion of S.H.M. because of its benefits. The term "Self-Healing Material" was introduced in the 21st century by [28] in 2011. A worldwide conference on Self-Healing Materials was held in 2007, drawing a large number of scholars.

Self-healing materials are activated by structural impacts. Arkema, a chemical business in 2009, and Autonomic Materials Inc. in 2012 made efforts to bring SHMs to the commercial market [29]. The National Aeronautics and Space Administration (NASA) scientists undertook many research efforts on Structural Health Monitoring (S.H.M.) materials. Scientific literature reveals that scientists have created Self-Healing Materials with excellent ion conduction capabilities. This will lead to the production of electronic components and cables with a long lifespan and self-repairing capabilities. Wires may remain undisturbed and have the ability to self-repair small issues, reducing significant maintenance expenses.

1.2 The Chemistry behind Self-Healing Polymers as well as the mechanism

Self-healing polymers are a category of intelligent materials that can mend internal flaws within any structure, thereby restoring mechanical characteristics like tensile strength, prolonging the longevity of the materials, and improving their performance in various fields such as building, medicine, aerospace, and military. Determining and controlling the polymerization processes are crucial for enabling a polymer's ability to repair itself. Several techniques have been devised to assess the properties of artificial self-repairing polymers, including subjecting them to chemical, physical, or thermal stimuli. Therefore, the healing efficacy of a polymer is influenced by its high chain mobility and glass transition temperature (Tg). The toughness ratio between the original and repaired samples is a standard measure of a material's healing efficiency [30].

1.3 Thermodynamics of self-healing

In the past, welding, gluing, or patching have been the primary methods used to fix broken materials. Allowing a substance to cure itself with little help from outside sources is known as self-healing. According to thermodynamics, a chemical reaction cannot happen spontaneously unless its total energy, dG (=dH-TdS), is less than zero. This means that a positive Gibbs energy shows a spontaneous process. Chain cleavage and chain slippage are the two main processes that occur when macromolecular networks are damaged. While the latter could result in conformational changes, the former generates reactive groups. Chain rearrangements and healing responses must interact for the autonomous repair of damaged networks to occur.

The physical aspects of self-healing have received less attention in recent advances in self-repair, with the majority of the focus being on artificial components. Still, chemical interactions are not as important in network design as physical network properties. The self-repairing process of a fracture is thought to occur in five steps, according to early studies on thermoplastic polymers: segmental surface rearrangements, surface approach, wetting, diffusion, and randomization [31]. In essence, this process resulted in the chain entanglements that restored mechanical properties to the healed region. The primary mechanism responsible for repairs was found to be chain diffusion at the polymer-to-polymer contact. The movement of big molecular segments trapped inside a stationary tube was explained by the reptation model, which was put forth by [32,33,34], quantifying these processes [35]. Only after the entire chain completely separated from the tube and reached equilibrium after a predetermined amount of time Tr—the amount of time required for the chain to disengage from the tube completely—did self-healing take place. When the self-repairing process occurs, each chain leaves the tube cavity within a specific amount of time, resulting in conformational changes that move the chain from a non-Gaussian to an equilibrated Gaussian state. Longer chains required more time to break free, and repair time (Tr) varied with molecular weight (M) following M3. Repair time is, therefore, closely correlated with the molecular weight cube root. This implies that chain diffusion, resulting from a decrease in molecular bond cleavage during damage, was the only factor driving repair, with chain slippage providing the source of loose chain ends.

1.3.1 The Chemical Reactions Involved in Self-Healing

While thermodynamic considerations generally guide the physical requirements of the polymer network, certain reactive groups, such as pendent groups or cleaved chain ends, may help rebonding in order to accomplish self-healing. -CQC-, -COOH, $-NH_2$, -O.H., -S.H., -Si-O, S-S, -C.Q.O., and the creation of cyclic structures are some examples of these. Numerous synthetic attempts that result in self-healing networks have been established using these entities. A few kinds of processes, including covalent bonding [36], supramolecular chemistry [37, 38], H-bonding, ionic interactions, and p–p stacking, have been available in the last ten years that allow polymers to self-heal. Chemo-mechanical repairs [39, 40, 41] concentrated on shape memory-assisted polymers, distant self-healing, and encapsulation on the physical site. Although there are benefits and drawbacks to each of these classes, the ultimate objective is to create materials that can cure themselves on their own.

1.4 Required conditions for self-healing in Cementitious materials

The literature assessment categorizes the self-healing of fractures in cementitious materials into four groups based on processes.

i. autogenous self-healing,
ii. Based on mineral admixtures,
iii. Based on bacteria,
iv. Based on adhesive agents.

The above processes discuss the physio-chemical healing process, the elements that influence it, as well as the benefits and drawbacks of various self-healing categories [42].

1.5 Design Strategies/ Approaches to creating Self-healing materials

Plastics/polymers, paints/coatings, metals/alloys, and ceramics/concrete possess unique self-healing processes. The many approaches to creating self-healing materials are as follows:

i. release of healing agent
ii. reversible crosslinks
iii. miscellaneous technologies – electro hydrodynamics – conductivity – shape memory effect – nanoparticle migration – co-deposition

2.0 RELEASE OF HEALING AGENTS

Polymeric systems incorporate liquid active agents, such as dyes, catalysts, microcapsules, hollow fibers, or channels, in addition to monomers, throughout the production process. The reservoirs are ruptured during a break, which permits reactive substances to enter the gap through capillary force. When pre-dispersed catalysts are present, the agents solidify and successfully mend the crack. This mechanism is primarily driven by crack propagation. However, one major drawback of this method is that it requires the fracture's tension to be released. This process is regarded as autonomic since it functions on its own without the need for human or outside assistance [43].

2.1 Self-healing based on Photo-assisted irradiation

Zheng and associates described a photo-irradiation technique for resin-based self-healing [44]. Using a reaction between hexamethylene diisocyanate and 1,3-bis(eugenyl) glyceroldiether, crosslinked polyurethane films were produced on glass substrates. U.V. light was employed in the study to evaluate a self-healing polymer's characteristics. They showed that the damaged portion of the polymer film could mend itself in just five minutes, proving that the polyurethanes that were created had remarkable self-healing properties and could resist temperatures as high as 1000 °C. When exposed to sunlight, Xu et al.'s crosslinked polyurethanes [45] with a disulfide reactive group in the main chain demonstrated self-healing and re-structuring characteristics. When exposed to heat or light, the reactive groups (C-S or S-S) in the polymer chain can be readily formed and aid in self-healing. Zhao and associates produced photo-healable polymers from epoxidized oil in a single step using a photo-initiated thiol-epoxy addition technique under U.V. light. Epoxidized oil is the main component, while 7-mercapto-4-methyl coumarin, which binds to epoxidized triglycerides through its S.H. groups, is the photo-healing agent. It is anticipated that the thiol-epoxy addition procedure and the dimerization of coumarin reactive groups will result in polymers that are UV-healing and cross-linkable. The grafted coumarin derivative photocleaves into the graft monomer, which causes the polymer film's hardness to decrease after exposure to 255 nm radiation. The hardness of the film may be restored by exposure to light with wavelengths between 300 and 450 nm, suggesting a photoreversible mechanism [46].

2.1.1 Self-healing techniques based on Microcapsule

This type of self-repair is achieved through two mechanisms. The initial approach entails the use of autonomous self-healing polymers that incorporate microscopic microcapsules capable of storing a healing ingredient. Upon the occurrence of damage to the capsule covering, this chemical is discharged into the polymer. This phenomenon is commonly known as the microcapsule-based self-healing mechanism. Multiple external stimuli such as light, pH, redox reactions, thermal heating, additives, catalysts, or solvents are employed to initiate the healing process, which involves the disruption and restoration of chemical bonds [46,47].

In addition, a self-healing approach was employed, which involved the utilization of microcapsules containing epoxy-based healing polymers composed of cyclopentadiene as a healing agent and Grubb catalyst [48]. The adhesion between the liquid curative and the crosslinked thermoset is inadequate. This healing method is suitable only for thermosetting polymers such as epoxy, phenol-formaldehyde (P.F.), and melamine formaldehyde (M.F.). An issue with the capsule-based strategy is its limitation in treating the polymer surface once, whereas healing alternatives based on reversible breakage and restoration of chemical bonds provide a recyclable healing response.

3.0 APPLICATIONS OF SHM

3.1 SHM for Space Applications

Extreme environmental conditions, including heat cycles, UV rays, space debris, mechanical vibrations, atomic oxygen, and more, are exposed to spacecraft when they are in orbit [49]. In 1998, a NASA Research announcement launched the self-healing method. Self-healing materials first attained a high TRL or technological readiness level. The N.R.A. investigated self-healing materials in 2001 by fabricating bladders, testing them for punctures, and confirming their effectiveness in a pressurized test. The study of self-healing for space applications was carried out in 2005. Material qualities, including low mass, thinness, structural endurance, low gas permeability, and flexibility, are necessary for an inflated structure. It also entails fulfilling system-level specifications, such as compatible interfaces with the liner and restraint, as well as guaranteeing the material's lifespan and stopping leaks [50]. For example, a collision with micrometeoroid debris (MMOD), which is composed of small meteoroids and orbital debris, may cause wounds or punctures that eventually cause depressurization and gas leakage [50,51]. Any failure of the current space system would be disastrous because it is incapable of self-repair. In numerous spatial applications, joints, screens, dampening elements, and structures are frequently utilized [52]. To endure impact conditions and recover from damages, materials with good mechanical properties, low weight, heat resistance, and cost-effectiveness have been employed [53, 54]. In space, factors, including temperature fluctuations, pose a threat to spacecraft integrity in addition to orbital debris and micrometeoroids. Self-healing materials in space are intriguing because they offer thermal protection as well as independent repair. Consequently, they could be employed in the production of space mechanisms, rockets, and circuits that follow tight safety guidelines [55].

In space applications, three types of structural materials are essential to the self-healing mechanism. The materials consist of metal alloys used as current conductors, ceramic materials, and composite materials. The composite material's increased specific strength, fatigue resistance, and enhanced corrosion resistance make it a popular choice for self-healing coatings, actuators, compartments, and antennae. It can be utilized in certain engine parts in addition to application parts. Polymer matrix reinforced with fibers, such as carbon fibers in fiber-reinforced plastics (F.R.P.s), glass fibers in GFRPs, and high-performance fibers in carbon-epoxy fiber-reinforced plastic (CFRP) polymer, composites like thermosetting epoxy, are the types of composite materials used in space applications [56]. Metal matrix composites, ceramic matrix composites (C.M.C.s), and E-glass epoxy composites (E.G.C.s) are examples of further composite materials [54].

Ceramic materials can be utilized for hard coating or high-temperature components in thrusters. Electrical circuits and cables are made of metal alloys used as current conductors. Both inherent and external characteristics also influence it. Composite material experiences structural degradation from impact loads. Recent studies have shown that fractures or damages may be healed utilizing heat plates, resin patches, and injection procedures. However, these approaches have drawbacks, including their inability to detect undetectable problems, the need for damage monitors, and lack of utility during building. The use of these materials in aircraft applications is restricted due to the increased maintenance demands [57].

3.2 Applications of self-healing materials for construction

Concrete is a fundamental material in building, with a history dating back to prehistoric times [58]. Because of its special qualities, including its high strength, high fire resistance, ease of casting, and affordability, concrete is the material of choice for building structures. Although concrete has many positive qualities, one major issue is that it has a low tensile strength, which makes it easily fractured. Damage and fractures in concrete may result from design faults, improper selection of construction materials, and environmental factors such as alkali-silica interaction [58]. Cracks in concrete enable corrosive substances like chloride, carbonate, or sulfate to infiltrate the material. The rapid release of microcapsules influences the advancement of self-healing technology in concrete, the flow of healing agents to the cracks, and the interaction with a catalyst [60]. Implementing self-healing technology in road construction is an effective way to enhance the durability and longevity of current and upcoming infrastructure. Asphalt binder is a petroleum-derived substance that produces gasoline, diesel, and several other fuels. The viscoelastic feature enables the material to self-heal by fixing micro-cracks, thereby enhancing its endurance.

Currently, several researchers are exploring the diverse uses of microencapsulation for specific constituents. Utilizing self-healing material in concrete structures might provide an alternative solution to concrete cracking and damage. Zhang and colleagues investigated the self-repairing ability of concrete samples utilizing non-ureolytic bacteria in expanded perlite (E.P.). They observed a reduction in fractures in the concrete specimens containing bacteria over time, particularly when the carriers were immobilized. The research also found that combining process assessment with microstructure is beneficial [61].

3.3 Utilization of self-healing polymers for construction purposes

When it comes to building and construction materials, self-healing polymers offer an improved alternative to binders and binary cement (Portland cement and calcium sulfoaluminate [C.S.A.])

[62]. Various study hypotheses have been used to assess the effectiveness of self-healing polymers in repairing flaws at building sites. Lv et al. [63] show that poly (phenol-formaldehyde) (P.F.) resin may operate as a healing agent by activating resins in crack formation. P.F. microcapsules with a greater volume were created utilizing the in-situ polymerization technique. The microcapsules have been seen to increase in size as the shell thickness decreases. Smaller P.F. microcapsules are more likely to be mechanically triggered by fractures compared to larger microcapsules.

The rapid self-healing and water permeability characteristics of developed sulfur composites using binary cement and superabsorbent polymer (SAP) were studied by Seongwoo et al. [64]. The technique of X-ray diffraction (XRD) was employed to identify the mechanism. After fifteen minutes, the superabsorbent polymer was sealed. By combining particular concentrations of SAP and C.S.A. agents, it may be possible to inhibit water infiltration via cracks in sulfur composites successfully.

Two binders, P.G. 67-22 and P.G. 70-22 M, were chosen by Shirzad et al. [65] in accordance with their viscoelastic characteristics. They also contained 5% of a self-healing substance called OXE-CHI-PUR (Oxetane-substituted Chitosan-Polyurethane), with or without recycled asphalt components. Recycled asphalt shingles use asphalt for waterproofing in roofing, whereas recovered asphalt pavements include the removal or reprocessing of pavement material, including asphalt and aggregates. Tests such as the bending beam rheometer (B.B.R.), multiple stress creep recovery (MSCR), dynamic shear rheometer (D.S.R.), and comparison of the super pave performance grade of the blends were conducted to assess the impact of self-healing material on the binder's rheological capabilities. The fatigue characteristics of binder blends were shown by using the L.A.S. (Linear Amplitude Sweep) test. Asphalt binder is necessary because of heavy traffic. The new self-healing polymer is a kind of polymer that can be mended repeatedly. These recurrent healing processes require alternative methods to produce self-healing polymer at the molecular level rather than being linked to any catalyst or healing agent [66].

3.4 APPLICATIONS OF SELF-HEALING SYSTEMS IN BUILDING

Microcapsules are created by mechanical action or physical processes using physical procedures. Palin et al. [67] documented the effects of excessive seawater on concrete. Kanellopoulos et al. [68] discovered that microcapsules made of acacia gum and gelatin, containing sodium silicate liquid for self-healing concrete, were well-balanced bacterial-based agents. First, micro encapsules were created before incorporating the self-healing microcapsules into concrete. The self-healing microcapsules contained in the concrete are prone to cracking, causing them to rupture and release the healing agents they contain. When the integrated catalyst is present, the healing agent polymerizes and functions to seal and mend fractures [69].

The effective development of a self-healing mechanism relies on three criteria as outlined by Gilaber et al. [60]:

a) rupture of encapsulated microcapsules

b) dispensing healing agent into the fractures

c) catalyzing the polymerization of the self-healing agent

4.0 TYPES OF SELF-HEALING MATERIALS IN CONCRETES

The practical application of Self-Healing Materials can be classified into three main categories:

The three categories of self-healing materials are natural, biological, and chemical SHMs [70]. The Natural SHMs can be classified as Calcium Carbonate type, which helps avoid fractures produced by impurities in water, unreacted cement hydration, and expansion of the hydrated cementitious matrix in crack margins. Biological SHMs can be classified into two distinct types: calcium carbonate formed through precipitation and polymorphic iron-aluminum silicate formed through precipitation. Chemical SHMs can be classified into two distinct categories: active and passive. Every type of SHMs possesses distinct attributes, including corrosive properties, microstructure, conductivity, and low levels of toxicity. The selection of the most adaptable and acceptable kind is determined according to the specified parameters [21,71].

4.1 DEVELOPING ADVANCES IN SELF-HEALING MATERIALS

Scientists are now studying self-healing materials in an effort to create more effective and affordable methods. It is worth noting that very few researchers are working on developing an artificial muscle that resembles a typical human muscle. However, in the event of an accident or fracture, muscles made of materials that can heal themselves will automatically heal. Research on structural health monitoring (S.H.M.) also extends to many medical applications, such as creating artificial human body parts. Novel Bulletproof gear made from self-healing materials is now being developed by researchers [72,73] to repair any damage incurred quickly. Self-healing material suits are used in sky flying to quickly mend scratches caused by trees, restoring them to their previous state and functionality within seconds. Researchers are creating an aircraft that utilizes Structural Health Monitoring (S.H.M.) technology to rapidly regain its form following an accident during flight, potentially saving hundreds of lives.

5.0 CONCLUSION

Self-healing building materials offer a promising avenue for enhancing durability and sustainability in the construction industry. By incorporating self-repair mechanisms, these materials can significantly reduce the need for costly maintenance and repairs, extending the lifespan of structures. This not only leads to economic benefits but also contributes to a more sustainable built environment by minimizing the consumption of resources and reducing waste. They are similar to shape memory alloys and provide a wide range of applications. The emergence of a new age in materials will occur after we successfully develop economically feasible uses of self-healing materials, as previously said. It will enable the development of equipment with higher efficiency and durability at a reduced maintenance cost. As research and development in this field continue to progress, we can expect to see even more innovative and effective self-healing materials emerge. The adoption of these materials represents a crucial step towards building a more resilient and sustainable future.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS
Authors have declared that no competing interests exist.

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