FIRE PERFORMANCE OF SELF-HEALING CONCRETE

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ABSTRACT:

Self-healing concrete (SHC) is an innovative material developed to increase the durability and service life of concrete structures by enabling them to autonomously repair cracks. The primary goal of this research was to investigate the behavior of SHC when exposed to elevated temperatures, simulating the effects of fire on its mechanical and self-healing performance. The research observed concrete samples prepared using different bacterial encapsulation techniques, including calcium alginate capsules and direct bacterial incorporation. These samples were subjected to thermal exposure at various temperature levels (ranging from ambient up to 600 °C) to examine how high temperatures influence the self-healing capacity of concrete, particularly its ability to regain compressive strength and elastic modulus, as well as close cracks through biologically induced calcium carbonate precipitation. The review results revealed that SHC exhibits a noticeable decrease in self-healing efficiency and mechanical performance at temperatures above 400°C, primarily due to the degradation of bacterial spores and damage to the microstructure of the concrete. Nevertheless, samples containing encapsulated bacteria, particularly those using calcium alginate as a protective medium, demonstrated a higher level of resistance to thermal damage and retained a partial ability to self-heal cracks at moderately elevated temperatures (up to 300°C). The findings confirm that while SHC has potential for structural applications, its performance under fire conditions is limited by the thermal stability of the healing agents. The encapsulation method plays a crucial role in determining the effectiveness of the healing process after fire exposure. This research contributes to a deeper understanding of the limitations and potential of SHC under extreme conditions and provides a foundation for future improvements in material formulation and encapsulation techniques aimed at enhancing fire resistance.

KEYWORDS:

Concrete, Self-Healing, Encapsulated Bacteria, Mechanical Properties

1 INTRODUCTION

In recent decades, the demand for sustainable, resilient, and low-maintenance construction materials has grown substantially, driven by increasing global urbanization, the effects of climate change, and the rising costs of infrastructure upkeep. Concrete, as one of the most utilized materials in civil engineering, plays a central role in nearly every type of construction, from buildings and bridges to tunnels and dams. However, despite its widespread use and many advantages, concrete has a fundamental vulnerability: its propensity to crack under mechanical loads, environmental influences, and thermal stress.

Cracks in concrete are not only visually concerning—they pose serious structural risks. They allow the ingress of water, carbon dioxide, chlorides, and other aggressive agents that accelerate the corrosion of embedded reinforcement and deteriorate the material's integrity. As a result, service life is reduced, maintenance needs increase, and operational costs escalate. Traditional methods for crack repair are typically reactive, labor-intensive, and often environmentally and economically unsustainable. These challenges have led to the development of innovative solutions aimed at improving the durability and longevity of concrete structures.

Self-healing concrete (SHC) has emerged as one of the most promising materials in the field of advanced construction technologies. It is engineered to autonomously repair cracks without the need for external intervention, restoring not only the material's integrity but also its mechanical and durability properties. Various self-healing mechanisms have been developed and researched, including autogenous healing (continued hydration of unreacted cement), encapsulated chemical healing agents that are released upon cracking, and biologically induced healing—most notably through the use of bacteria. Among these, bacterial self-healing systems have shown excellent potential, particularly through the microbial precipitation of calcium carbonate ($CaCO_3$), which effectively seals cracks and contributes to strength recovery.

While the self-healing behavior of concrete under normal service conditions has been extensively studied, a critical and relatively underexplored question remains: how does self-healing concrete perform under extreme conditions such as fire? Fire exposure is one of the most damaging events for concrete structures, as high temperatures cause severe microstructural degradation, increased porosity, dehydration of hydration products, reduction in mechanical properties, and sometimes explosive spalling. For SHC, especially systems based on living bacteria, this presents a major challenge. Bacteria are highly sensitive to heat, and their survival during and after fire events is uncertain. Therefore, it is essential to investigate whether SHC retains its healing functionality and can contribute to post-fire recovery.

This research focuses on the fire performance and post-fire healing capability of self-healing concrete, with an emphasis on bacterial-based systems using encapsulation techniques. The research explores whether these encapsulated bacteria can survive high-temperature exposure and still initiate healing once conditions become favorable again (e.g., moisture re-entry). The study involves review of a combination of experimental investigations—such as compressive strength tests, thermal exposure of samples, and microstructural analyses using scanning electron microscopy (SEM)—to evaluate the extent of healing and the material's ability to recover its mechanical and structural properties after fire.

2 MATERIALS AND METHODS

The deterioration of concrete structures due to cracking is a significant challenge in civil engineering, leading to reduced durability, increased maintenance costs, and structural failures. Traditional repair methods require human intervention, which can be costly and time-consuming. In response, researchers have explored self-healing concrete (SHC) as a sustainable and innovative solution to enhance the longevity and resilience of concrete structures.

2.1 BACKGROUND AND LITERATURE REVIEW

Self-healing concrete is a material that has the capability to repair its own microcracks autonomously, restoring its mechanical properties without external intervention. The self-healing phenomenon can be classified into two primary mechanisms: autogenous healing, which relies on natural hydration processes, and autonomous healing, which involves the introduction of external healing agents such as bacteria or encapsulated chemicals [1].

Self-healing concrete (SHC) is an advanced material engineered to autonomously repair cracks and mitigate deterioration, thereby improving durability and reducing maintenance costs. The concept of self-healing in cementitious materials was first introduced by Dry in 1994 [2], who explored the idea of incorporating hollow glass tubes filled with healing agents to promote crack closure in concrete. Since then, numerous researchers have investigated various self-healing mechanisms, leading to significant advancements in the field.

One of the most significant contributions to SHC development comes from [3], which introduced the concept of bacterial-induced self-healing. According to Jonkers, SHC is concrete that utilizes bacteria capable of precipitating calcium carbonate to fill cracks and enhance the waterproofing of structures. This definition laid the foundation for numerous subsequent studies in the field of biological self-healing concrete.

Jonkers et al. in 2010 [4] were among the first to introduce bacterial self-healing concrete, incorporating Bacillus bacteria into the cement matrix to promote calcium carbonate precipitation as a means of sealing cracks. Their study demonstrated that this method effectively restores structural strength and improves durability, making it a viable solution for sustainable construction. Similarly, in [5] was investigated the use of microencapsulation, where healing agents like epoxy resins and polymers are enclosed in microcapsules dispersed within the concrete. When cracks develop, these capsules break open, releasing the agents that facilitate repair.

[6] focused on enhancing autogenous self-healing through the addition of mineral admixtures such as silica fume and fly ash. Their findings indicated that these materials significantly boosted the self-healing ability of concrete by increasing the supply of calcium hydroxide, which supports carbonation reactions. Additionally, in [7] was conducted a

comprehensive review of various self-healing strategies, including vascular networks, shape-memory polymers, and microbial healing, discussing their respective benefits and challenges in real-world applications.

The primary characteristics of SHC include its ability to autonomously repair microcracks, improve impermeability, and extend service life. According to [8], the self-healing efficiency of SHC depends on factors such as crack width, environmental conditions, and the type of healing mechanism employed. For instance, bacterial self-healing is highly effective in moist environments where bacteria can thrive, while polymer-based self-healing is more suitable for dry conditions where encapsulated agents can be released upon crack formation.

Recent study [9] emphasized the role of nanotechnology in enhancing self-healing properties, exploring the integration of nanomaterials such as graphene oxide and carbon nanotubes to improve mechanical strength and healing efficiency. Similarly, [10] investigated the influence of fiber reinforcement on self-healing capabilities, demonstrating that engineered cementitious composites (ECCs) with self-healing properties exhibit superior crack control and durability.

Overall, the evolution of self-healing concrete has been driven by interdisciplinary research, incorporating microbiology, chemistry, and material science to develop more efficient and sustainable healing mechanisms. As the demand for durable infrastructure grows, SHC continues to gain attention for its potential to revolutionize the construction industry by reducing maintenance costs and enhancing structural resilience.

It was proposed classification of SHC into autogenous and autonomous self-healing concrete in [11]. Autogenous SHC relies on unhydrated cement particles and natural chemical processes to seal cracks, while autonomous SHC employs special capsules, bacteria, or other additives that actively contribute to material regeneration classification is essential for further research, as it allows for a more precise definition of self-healing mechanisms.

Hanna emphasizes in [12], that SHC is concrete with the ability to naturally and autonomously close cracks, increasing its service life and reducing maintenance costs. This definition encompasses both traditional self-healing methods and newer approaches based on intelligent materials.

Rajczakowska et al. [13] specifically focused on predicting post-fire self-healing of concrete using machine learning. Their definition highlights the ability of concrete to recover its mechanical properties after exposure to high temperatures, considering factors such as concrete age, exposure temperature, and cooling regime. This perspective is significant for the application of SHC in engineering projects where structures are exposed to extreme conditions.

Several researchers have focused on the potential of bacterial self-healing in concrete. Luhar et al. in 2022 [14] provided an extensive review of bacterial healing mechanisms, highlighting the role of Sporosarcina pasteurii in calcium carbonate precipitation, which facilitates crack closure and enhances concrete durability. Jonkers [3] was among the first to demonstrate that bacterial spores embedded in concrete could remain dormant until activated by water ingress, leading to effective self-repair. The results of these studies suggest that bacterial healing not only reduces crack widths but also contributes to improved compressive strength and long-term durability.

An alternative approach to self-healing involves the encapsulation of healing agents within microcapsules. Research [5] examined the efficiency of polyurethane-filled microcapsules in concrete and found that the release of healing agents upon crack formation significantly improved mechanical recovery. Their findings indicate that the type, size, and distribution of microcapsules within the concrete matrix play a crucial role in healing efficiency. Similarly, [15] explored the compatibility of various encapsulated healing agents and noted that polymer-based sealants exhibited superior adhesion and crack-filling capabilities compared to traditional cementitious repair methods.

Another natural mechanism for self-healing in concrete is autogenous healing, which relies on continued hydration and carbonation of calcium hydroxide. In [16] was investigated this process in engineered cementitious composites (ECC) and observed that fine crack widths, typically below 0,2 mm, could be sealed through further hydration. Edvardsen in 1999 [17] also reported similar findings, stating that autogenous healing is more effective in environments with sufficient moisture, where the ongoing hydration of unreacted cement particles can contribute to crack closure. However, these studies suggest that while autogenous healing is beneficial for minor cracks, it may not be as effective for larger structural damage.

Vedrtnam et al. [18] explored the potential for post-fire self-healing in concrete using encapsulated and immobilized bacteria. The key challenges identified in their research include the ability of bacteria to withstand high temperatures during a fire and their activation after thermal damage. The study introduced innovative methods for protecting bacteria within the concrete structure, allowing them to contribute to material regeneration after fire exposure.

The research involved assessing concrete damage through both destructive and non-destructive testing methods, including ultrasonic testing to evaluate crack formation. Scanning electron microscopy (SEM) was used to analyze the concrete microstructure after exposure to high temperatures. By comparing various post-fire self-healing approaches, the researchers identified temperature thresholds at which these methods proved most effective.

Extensive research has established that high temperatures cause notable deterioration in the mechanical properties of concrete. Kodur [19] highlighted that exposure to extreme heat leads to significant physical and chemical changes in concrete, inducing thermal stress, dehydration, and a decline in overall strength. Similarly, [20] analyzed alterations in pore structures and strength loss in both conventional and fiber-reinforced cement pastes, concluding that rising temperatures increase porosity and weaken compressive strength.

Recent studies have explored ways to restore the mechanical properties of concrete following fire damage. [21] investigated the effectiveness of moisture conditioning in recovering strength and found that proper post-fire curing significantly improves strength regain. Additionally, Li et al. in 2019 [22] reviewed various factors affecting the recovery of fire-damaged concrete, emphasizing the role of rehydration and secondary hydration reactions in regaining structural integrity.

The concept of self-healing has also been examined as a potential post-fire recovery method. [13] utilized machine learning techniques to predict the self-healing capabilities of fire-damaged concrete. Their research demonstrated that parameters such as exposure conditions, aggregate type, and curing strategies play a significant role in determining the extent of recovery.

The type of aggregate used in concrete significantly influences its resistance to fire. It was noted in [23] that lightweight aggregates generally offer better fire resistance due to their lower thermal conductivity, while siliceous aggregates undergo phase transitions that lead to structural cracking. [24] studied the impact of re-curing on residual mechanical properties and determined that certain aggregates contribute to enhanced post-fire recovery.

Recent advancements have explored the potential of bacterial self-healing concrete in enhancing fire performance. [25] studied the fire resistance properties of bio-concrete and observed that incorporating Bacillus Subtilis bacteria into the mix resulted in improved mechanical strength and thermal stability due to bio-mineralization. [26] further examined the feasibility of low-carbon self-healing concrete, highlighting its effectiveness in enhancing fire resistance while reducing environmental impact.

International guidelines provide standardized methodologies for assessing the fire resistance of concrete structures. The European standard EN 1992-1-2:2004 [27] establishes general principles for structural fire design, considering variables such as fire duration and material properties. Similarly, the American Concrete Institute’s ACI 216.1-07 [28] presents empirical guidelines for evaluating fire resistance based on experimental data and material testing.

2.1 RESEARCH METHODOLOGY

This research investigates the behavior of self-healing concrete (SHC) at elevated temperatures, with an emphasis on assessing its healing performance after fire exposure. The objective was to examine both mechanical and microstructural responses of SHC, as well as to evaluate the effectiveness of different bacterial encapsulation methods. The research was mainly supported by a detailed literature review and comparative analysis of findings from previous research in this field.

This included analysis of previous studies on SHC behavior at elevated temperatures, bacterial survival, and encapsulation strategies. Comparisons were made between the published experimental results and findings reported in relevant scientific literature. This comparative research helped validate the experimental outcomes and place them within the broader scientific context, showing consistency or divergence in results and helping to explain observed behavior through previously established mechanisms.

The research was designed to answer the following key questions:

RQ1: How do elevated temperatures affect the self-healing capacity of SHC in terms of mechanical property recovery?

RQ2: What microstructural changes occur in SHC after fire exposure, and how do they influence its compressive strength, elastic modulus, and crack-sealing behavior?

By integrating published experimental data, visual and microstructural analyses, and a comparison with existing literature, this research provides a well-rounded understanding of SHC behavior under thermal stress. It contributes to the advancement of fire-resistant and self-healing concrete technologies and highlights the importance of encapsulation method optimization for improving post-fire performance.

3 RESULTS AND DISCUSSION

In modern construction, where structural safety under extreme conditions plays a critical role, the development of materials capable of autonomously responding to damage opens a new chapter in engineering practice. One such material is self-healing concrete (SHC) – a type of concrete capable of healing cracks on its own while maintaining its mechanical and physical properties even after fire exposure. High temperatures present extremely aggressive conditions that cause microstructural degradation of concrete, loss of strength, and crack propagation. However, recent research shows that certain SHC formulations, particularly those incorporating bacteria encapsulated in heat-resistant carriers, have the capacity for partial regeneration even after fire [18].

3.1 THERMAL DEGRADATION OF SHC AND MICROSTRUCTURAL CHANGES

Self-healing concrete (SHC) represents a modern technology in construction that enables the extension of the durability and safety of structures, especially those exposed to extreme conditions such as fire. During a fire, concrete undergoes serious changes in its microstructure. The key hydration products of cement paste, such as calcium-silicate-hydrate (C-S-H) and calcium hydroxide (CH), begin to lose water at temperatures around 200°C. This causes internal stress, microcracks, and a gradual weakening of cohesion between the cement matrix and aggregates. At temperatures exceeding 400°C, dehydration and decomposition of hydration products occur, disrupting the internal structural bond. Furthermore, the porosity of concrete increases significantly, especially above 600°C where C-S-H gel breaks down, and at around 800°C calcium carbonate decomposes, which further compromises the integrity of the concrete [19].

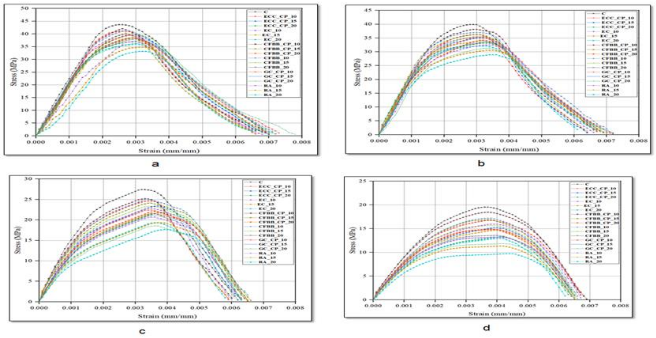

Figure 1: Compressive stress-strain curve under (a) 200°C, (b) 400°C, (c) 600°C, (d) 800°C., Damage in the microstructure, where microcracks and deformations are visible after the fire [18]

Exposure to elevated temperatures initiates a series of progressive degradation processes in the concrete matrix. Between 100°C and 200°C, free and absorbed water within the pores begins to evaporate. As the temperature increases, particularly between 400°C and 800°C, more significant transformations occur:

Calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) undergo dehydration, leading to the collapse of the internal gel structure.

Ettringite decomposes and silicate aggregates (especially quartz) experience polymorphic transformations between 573°C and 650°C, which cause volumetric changes and internal stresses.

These changes result in the formation of microcracks, increased porosity, and reduction in bonding strength between aggregate and paste.

SEM (scanning electron microscopy) images confirm that fire exposure increases the presence of micro voids, disrupts the compactness of the matrix, and leads to disintegration of crystalline phases [19].

Despite this degradation, SHC samples with appropriately encapsulated healing agents show improved post-fire structural continuity due to the ability of the healing system to reactivate after thermal exposure. Advanced encapsulation technologies, such as carbon fiber bacteria balls and cement-coated gelatin capsules, play a vital role in preserving the viability of healing agents (e.g., Bacillus subtilis spores) during fire. These technologies are specifically designed to reduce heat transfer to the encapsulated agents, ensuring their survival up to 70°C. Upon cooling, and in the presence of moisture and CO_2, the bacteria become metabolically active and initiate the precipitation of calcium carbonate ($CaCO_3$), which fills the fire-induced cracks [18].

It shows the formation of calcium carbonate crystals in the cracks, different microstructural deformations and the difference in the distribution of the C-S-H gel depending on the encapsulation method.

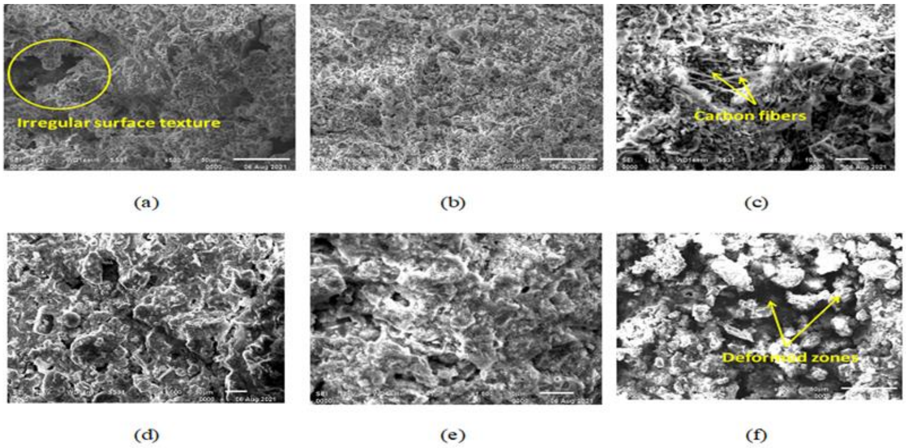

Figure 2: SEM images of (a) ECC_CP_15, (b) EC_15, (c) CFBB_15,(d) CFBB_CP_15, (e) GC_CP_15, and (f) RA_15 [18]

It is especially visible that the samples with carbon-fiber balls show a rougher texture due to the additional protection of the fibers.

3.2 SELF-HEALING MECHANISM AFTER FIRE

To mitigate the effects of these changes and enable concrete to repair itself after fire exposure, researchers have developed self-healing methods using bacteria, most commonly Bacillus subtilis, which can produce calcium carbonate ($CaCO_3$). These bacteria are embedded in concrete in the form of spores, which remain inactive until water and carbon dioxide penetrate the structure. When cracking occurs, water enters the cracks and activates the bacteria, which, using nutrients such as calcium lactate, produces calcium carbonate that precipitates and seals the cracks [18].

However, the greatest challenge in this process is preserving the viability of the bacteria during exposure to high temperatures. To achieve this, different protection strategies have been developed, such as encapsulated bacteria in gelatin capsules coated with a layer of cement or embedding them into carbon fiber balls which are also cement-coated. These formed capsules provide thermal insulation and reduce the direct impact of heat on the bacteria during a fire. In addition, porous aggregates, such as expanded clay, can also be used to immobilize the bacteria, where the bacterial solution is absorbed into the aggregate and then protected with a cement coating (Figure 3) [19].

The key process enabling SHC regeneration after fire is the activation of bacteria (most commonly Bacillus subtilis), which, in the presence of calcium lactate and water, produce calcium carbonate ($CaCO_3$) that fills the cracks. To ensure this process post-fire, bacteria must survive high temperatures. Therefore, research employs various protection strategies:

- Encapsulation of bacteria in carbon fiber balls, gelatin capsules, expanded clay, and other porous aggregates.
- Coating capsules with cement paste.
- Surface treatment of concrete elements (e.g., mixture of plastic ash and cow dung).

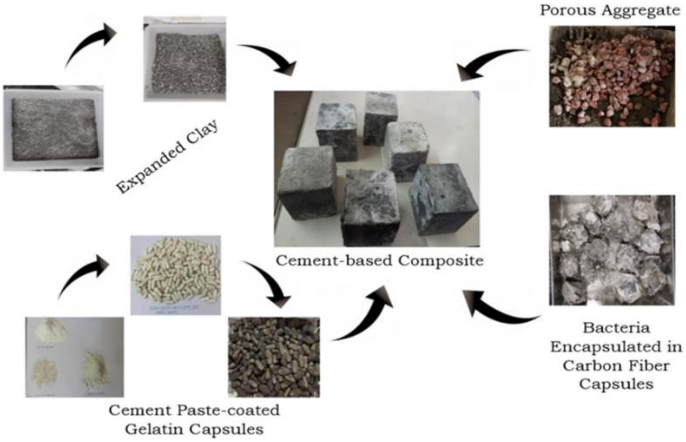

Figure 3: Immobilizing bacteria in expanded clay and porous aggregate, cement paste-coated gelatin capsules, and encapsulating bacteria in carbon fiber capsules for producing CBC samples [18].

These methods help maintain the temperature inside the capsules below 70°C – the survival limit for bacteria. After the fire and cooling, in the presence of moisture, the bacteria reactivate and initiate $CaCO_3$ formation, which fills and seals the cracks.

- Bacteria in expanded clay.
- Gelled capsules with cement coating.
- Carbon fiber balls with bacteria.
- Surface coatings based on cow dung and ash.

3.3 CHANGES IN MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

Experiments have shown that bacteria can survive temperatures up to 600°C if properly protected, and that the self-healing process can be triggered after cooling. At temperatures of 800°C, efficiency decreases significantly due to the irreversible degradation of both the bacteria and the cement matrix. Samples with carbon fiber capsules demonstrated the best performance, as they exhibited the highest resistance to temperature and the greatest retention of compressive strength and self-healing capacity after fire exposure. Compared to conventional concrete, SHC samples showed a smaller reduction in compressive strength at all temperature levels [13].

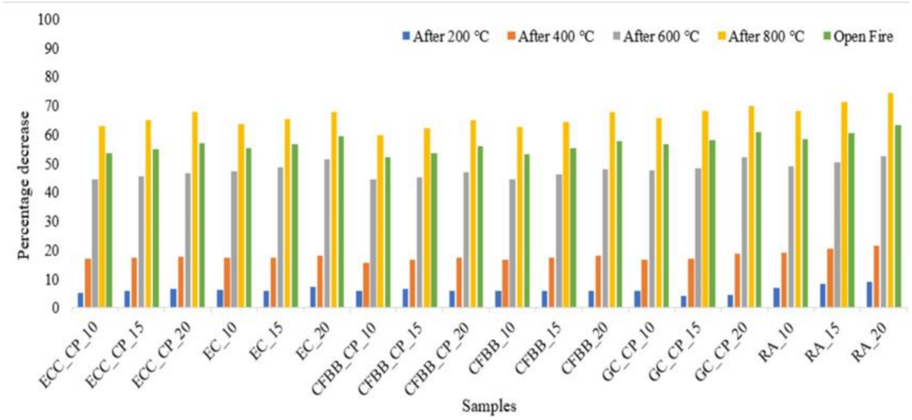

Figure 4: Percentage variations of compressive strength for self-healed samples at 200°C, 400°C, 600°C, 800°C, and open fire [29]

For example, after exposure to 600°C, conventional concrete lost about 44% of its compressive strength, while SHC samples experienced a reduction of around 46–50%. However, thanks to the self-healing process, part of the lost strength recovered up to 4,7% within 28 days. At 200°C, this recovery reached up to 6,7%, while at 800°C, it was less than 3%, confirming that the upper limit for effective self-healing is around 600°C.

It was also observed that samples containing bacteria and fibers developed smaller cracks after fire exposure and demonstrated greater resistance to crack propagation, due to the presence of $CaCO_3$, which acts as a natural “patch.”

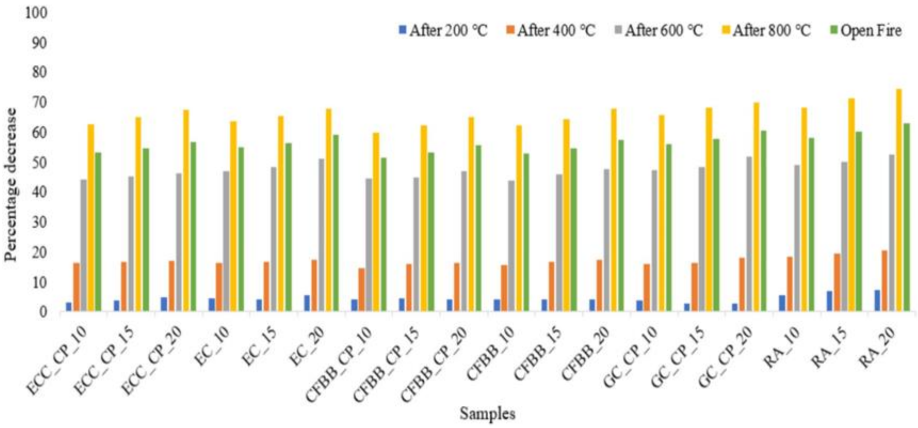

Figure 5: Percentage variations of compressive strength for treated and self-healed samples at 200°C, 400°C, 600°C, 800°C, and open fire [29]

3.3 EFFICIENCY OF SELF-HEALING AFTER FIRE

The effectiveness of post-fire self-healing is influenced by the degree of thermal exposure, type of healing agent, and encapsulation method. Experimental results over a 28-day period after fire exposure showed that SHC samples, particularly those with CFBB encapsulation, achieved measurable gains in residual compressive strength.

Table 1: Increase in strength due to self-healing depending on temperature.

Temperature	Increase in Strength Due to Self-Healing (CFBB_20)
200°C	6,71%
400°C	5,46%
600°C	4,09%
800°C	2,21%

The relatively higher healing efficiency at lower temperatures reflects the improved survival of bacteria and less severe matrix degradation. Even at 800°C, some healing occurred, although to a limited extent, indicating the potential for partial recovery in extreme conditions [18].

In addition to strength recovery, microstructural observations show partial pore filling, crack sealing, and improvement in ultrasonic pulse velocity, further indicating internal densification and structural restoration.

3.4 DISCUSSION

The performance of self-healing concrete (SHC) under elevated temperatures represents a critical and emerging topic in civil engineering, especially considering the increasing demands for resilient infrastructure. Traditional concrete is known to suffer significant degradation when exposed to fire. This includes dehydration of calcium-silicate-hydrate (C-S-H) gel, decomposition of calcium hydroxide (CH), formation of microcracks, and an increase in porosity—all of which compromise the mechanical and structural integrity of concrete [19, 20]. These changes reduce not only the load-bearing capacity of structural elements but also increase permeability, accelerating long-term deterioration [30]. SHC, however, offers a unique ability to mitigate these damages through autonomous or biological crack healing mechanisms, particularly during the cooling phase following fire exposure.

In conventional concrete, exposure to temperatures above 200°C leads to dehydration of the C-S-H gel, while temperatures above 400°C cause decomposition of calcium hydroxide and an increase in porosity. These processes result in microcrack formation and loss of bond between matrix and aggregates, significantly reducing compressive strength [19, 20]. Microscopic analysis (SEM) reveals that such concrete loses compactness and shows micro voids, which further accelerate degradation [19].

In contrast, SHC utilizing Bacillus subtilis bacteria shows partial recovery capabilities. These bacteria, when encapsulated in thermally resistant carriers such as carbon fiber balls coated in cement paste, can survive temperatures up to 600°C and reactivate during the cooling phase when moisture and CO_2 infiltrate the concrete structure [18]. Upon activation, the bacteria initiate the formation of calcium carbonate ($CaCO_3$), which fills cracks and thereby improves the microstructure, reduces porosity, and partially restores lost strength.

The effectiveness of different bacterial protection systems varies significantly. Research has shown that CFBB (carbon fiber ball bacteria) systems are the most resistant to high temperatures and enable the highest level of self-healing, whereas gelatin capsules and aggregates such as expanded clay offer less thermal protection and lower healing efficiency [18]. For instance, at 600°C, SHC with CFBB can recover up to 4,1% of lost strength within 28 days, while other methods achieve lower recovery rates. Notably, healing efficiency is significantly greater at temperatures up to 400°C, where up to 6,7% strength recovery has been recorded [13].

A major difference between biological and chemical SHC systems lies in the number of healing cycles. While chemical microcapsules can respond only once due to irreversible capsule rupture, biological systems allow for multiple reactivations, ensuring more durable resistance [5, 7]. This multi-cycle activation is particularly significant for structures exposed to periodic thermal stress, such as bridges, tunnels, or industrial facilities.

Additionally, the physical characteristics of the composite also play a role. Lightweight aggregates like expanded clay have lower thermal conductivity and help create microclimatic conditions within the concrete that supports bacterial survival.

The presence of microfibers further helps control crack width, thereby enhancing the efficiency of healing as bacteria can more effectively seal smaller cracks [24].

Simulations based on Finite Element Analysis (FEA) have shown that in CFBB capsules, internal temperatures remain below 70°C even during intense fires, enabling bacterial survival and immediate activation of the healing process once the fire subsides. FEA modeling confirms that with proper encapsulation and concrete mix design, SHC can retain functionality even after fire exposure, as evidenced in both laboratory and simulation conditions [31].

Despite these advanced technologies, practical challenges remain. The efficiency of SHC depends on moisture, crack geometry, nutrient availability, and environmental conditions. In real-world scenarios where moisture may be limited and cracks irregular, complete recovery is not always possible. Furthermore, factors such as freeze-thaw cycles and chemically aggressive environments can degrade the formed $CaCO_3$, reducing the longevity of healing effects [21, 22].

A significant challenge is the lack of standardized testing protocols for evaluating SHC performance after fire exposure. Current standards (ISO 834, ASTM E119) do not account for the self-healing phenomenon, which slows down commercial application and integration into building codes [11].

Despite these challenges, SHC offers great potential in terms of economic sustainability and environmental protection. Although the initial installation costs are higher due to the use of specialized agents and encapsulation technologies, the long-term benefits are substantial. These include reduced maintenance needs, extended service life, and fewer repair interventions—particularly in structures that are difficult or costly to access manually, such as tunnels, bridge piers, and nuclear facilities. Furthermore, by reducing the frequency of major repairs, SHC helps lower the carbon footprint associated with cement production and concrete demolition, aligning with sustainable construction goals.

Based on the presented research, SHC, especially in combination with the CFBB system and appropriate aggregates, offers significant advantages in fire resistance. Although complete recovery is not achieved above 600°C, partial regeneration, improved microstructure, and extended lifespan position SHC as a key material for future engineering applications. Continued research in bacterial protection, automated testing, and integration with sustainable construction practices is essential for its widespread application.

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These changes reduce not only the load-bearing capacity of structural elements but also increase permeability, accelerating long-term deterioration. SHC, however, offers a unique ability to mitigate these damages through autonomous or biological crack healing mechanisms, particularly during the cooling phase following fire exposure.

What distinguishes SHC in post-fire conditions is its capacity for partial recovery of properties, particularly when utilizing bacterial healing agents such as Bacillus subtilis. Research confirms that if these bacteria are adequately protected—using encapsulation methods like carbon fiber balls coated in cement paste—they can survive temperatures of up to 600°C and become reactivated in the presence of moisture and CO_2 after the fire [18]. Upon reactivation, the bacteria initiate metabolic processes that lead to the precipitation of calcium carbonate ($CaCO_3$), which fills and seals the cracks. Experimental studies have shown that this self-healing process can recover up to 6,7% of the lost compressive strength within 28 days post-fire [13]. This distinguishes SHC from conventional concrete, which generally requires manual repair or complete replacement after severe thermal exposure [32].

Moreover, microstructural analysis using SEM imaging supports these findings. It has been observed that, post-healing, SHC exhibits reduced porosity, improved compactness, and narrower cracks compared to non-healing concrete. The formation of $CaCO_3$ not only blocks crack pathways but also contributes to the densification of the matrix, reducing ion penetration and enhancing the durability of the structure [19]. This self-generated protection could significantly extend the service life of structures exposed to fire, especially those difficult to access, such as tunnels, nuclear power plant enclosures, or bridge foundations.

However, not all encapsulation strategies perform equally. Studies show that while gelatin capsules coated in cement offer decent protection, carbon fiber balls (CFBB) provide superior insulation and durability, particularly under cyclic thermal loading. Less conventional systems, like expanded clay aggregates or recycled concrete particles used as bacterial carriers, show variable performance and are still under investigation [18, 26].

A critical comparative observation between healing systems reveals that chemically based SHC, such as microcapsules containing polymeric healing agents, lose functionality after a single crack event. In contrast, biological systems, when designed for survivability, may reactivate multiple times, offering long-term sustainability [5, 7]. This positions bacterial SHC as a more adaptable and ecologically favorable solution.

From a material engineering perspective, another factor contributing to SHC's post-fire effectiveness is the use of lightweight aggregates, which reduce internal thermal conductivity and help preserve microclimates within the concrete matrix suitable for bacterial survival [24]. In combination with fiber reinforcement, which controls crack width, these aggregates support the self-healing process and help maintain structural stability even under severe thermal stress [30, 32].

Nevertheless, while laboratory data presents promising results, real-world conditions pose substantial challenges. In practice, cracks may be irregular, moisture may be insufficient, and environmental variables—such as freeze-thaw cycles or sulfate exposure—may diminish the durability of healing products like calcium carbonate. Studies [21, 22] emphasize the importance of proper post-fire curing and environmental conditioning to ensure long-term retention of mechanical properties. These findings suggest that future designs involving SHC should include tailored curing strategies after fire events to maximize healing potential.

Another challenge is the lack of standardized testing procedures for evaluating the performance of SHC under fire exposure. While traditional concrete is assessed according to ISO 834 or ASTM E119 fire curves, no clear protocols exist for determining SHC’s healing efficiency post-fire [11]. The absence of regulatory benchmarks hinders its implementation in structural design codes, limiting broader commercial use.

4 CONCLUSIONS

This research investigated the behavior of self-healing concrete (SHC) under elevated temperature conditions, with a particular emphasis on its ability to recover mechanical and microstructural properties following fire exposure.

SHC exhibits a significant reduction in compressive strength and elastic modulus at temperatures above 400°C. This decline is mainly due to the thermal degradation of bacterial spores and the breakdown of the cement matrix. However, at lower temperatures (up to 300°C), especially in samples with appropriate encapsulation, a partial recovery of mechanical properties was observed, indicating the potential of SHC for partial regeneration after fire.

SEM analysis revealed increased porosity, formation of microcracks, and loss of continuity in crystalline phases within the matrix. Nevertheless, samples with encapsulated bacteria showed calcium carbonate ($CaCO_3$) crystal formation within the cracks after moisture exposure, confirming that self-healing remains at least partially active after fire, particularly at temperatures up to 400°C.

The analysis demonstrated that elevated temperatures above 400°C significantly impair the mechanical properties and self-healing capacity of SHC due to the degradation of bacterial systems and structural damage within the concrete matrix.

This research confirms that although SHC loses some functionality at remarkably high temperatures, through careful selection of encapsulation methods, it is possible to preserve part of the material's healing capability even after fire. This opens new opportunities for its application in structures requiring resistance to extreme conditions, such as tunnels, industrial facilities, and safety-critical infrastructure.

Overall, this paper has provided a comprehensive evaluation of the fire performance and post-fire healing capabilities of self-healing concrete. By combining theoretical knowledge, experimental data, and advanced analysis techniques, the work has demonstrated both the potential and limitations of SHC under thermal stress. The findings offer valuable insights not only for academic research but also for practical engineering applications where durability and safety are critical. This thesis contributes to the growing body of knowledge on smart construction materials and serves as a solid foundation for future innovation in the development of resilient, self-sustaining infrastructure systems.

Future work should prioritize the development of heat-resistant bacterial systems, advancement of encapsulation techniques, and testing under real-world conditions. Enhancing the fire resistance of SHC is essential for broadening its application in durable, self-sustaining, and resilient construction systems.

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