A REVIEW ON SELF-HEALING AND STRUCTURAL PERFORMANCE OF FIBER-REINFORCED CONCRETE: TOWARD AN EXPERIMENTAL AND ANN-BASED PREDICTIVE FRAMEWORK

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ABSTRACT

Concrete is one of the most widely used materials in the world in terms of volume. Approximately 25 billion tons of concrete production occurs annually around the globe. Despite having superior compressive strength and multifunctionality, concrete is still prone to cracking due to plastic shrinkage, thermal gradients, freeze/thaw cycles, or continuous loads. Once formed, cracks become channels for corrosive elements such as chlorides, sulfates, or CO2 in the air. This results in faster reinforcing bar corrosion and reduces concrete service life, leading to premature failures, much earlier than the initial calculations suggested. Currently employed measures, such as manual patching, chemical injection of epoxy, cathodic protection, are costly, laborious and sometimes simply impossible to implement in confined spaces or underwater constructions.

Self-healing concrete (SHC) is considered a bio-mimetic material that has the ability to autonomously heal its cracks without any external actions. In the last decade, significant interest has emerged in researching SHC in academia and industry. This literature review narrows down the field of studies by considering SHC healing methods in conjunction with steel fiber reinforcement in FRCCs. Specifically, it analyzes the principles behind autogenous and autonomous healing of concrete composites, mechanisms through which steel fibers contribute to fracture healing, carbonate precipitation using microorganisms and enzymes, and Artificial Neural Network (ANN) prediction of the structural behavior of FRCCs. As a result, four knowledge gaps have been identified within the cross-disciplinary approach outlined above. They include the non-optimized interaction between silica fume and steel fibers in HPC, influence of continuous loads on healing efficiency in the FRCC context, need for an accurate engineering-oriented ANN model predicting healing potential based on mix design and load history, as well as lack of repeated crack-heal cycles testing under harsh environmental conditions.

The proposed research project addresses these gaps with an experimental approach and ANN modeling focusing on self-healing of M50 High Performance Concrete with silica fume in a range of 50-100% replacement. Hooked-end steel fibers are introduced in order to reinforce the matrix with fibers and promote crack development under constant loads. Healing efficiency and residual strength prediction are modeled with the help of feedforward backpropagation artificial neural network.

KEYWORDS: Self-Healing Concrete, Steel Fiber-Reinforced Concrete, Silica Fume, Bacterial Concrete, Artificial Neural Network, Autogenous Healing

I. INTRODUCTION

Reinforced concrete (RC) is the primary construction material worldwide, but it suffers from an inherent weakness, i.e., the tendency to develop cracks. As a quasi-brittle matrix, concrete succumbs to plastic shrinkage, thermal stresses, freeze-thaw cycles, and persistent external loads. Although standards, including IS 456:2000 and ACI 318-19, permit controlled cracking up to specific widths, the cracks themselves act as portals for chlorides, CO_2, and sulfates, thereby triggering the corrosion of reinforcing bars and limiting the structure's useful life significantly earlier than anticipated.

Traditional methods, including manual patching, epoxy injection, and cathodic protection, are relatively expensive and impractical when dealing with inaccessible locations such as tunnels, marine structures, and building cores. The inadequacies in conventional repair techniques have catalyzed the development of self-healing concrete (SHC), a class of bio-inspired cementitious materials capable of sealing cracks in an autonomous manner without requiring any human interaction (De Belie et al., 2018; Amoorezaei & Ghanbari-Ghazijahani, 2025).

The recent trend in SHC involves a combination of silica fume (SF), steel fibers with hook-ended morphology, and biological precipitation of calcium carbonate through enzymes or ureolytic bacteria. The steel fibers ensure that the cracks remain sufficiently narrow (<150 μm) to be healed, while the silica fume alters the microstructure of the pores and provides a reservoir of reactive calcium phases. The enzymes or bacteria cause $CaCO_3$ precipitation inside the cracks (Cuenca & Ferrara, 2017; Javeed et al., 2024). However, although each component exhibits promise on its own, their synergistic effects under long-term service loads have been poorly studied, and no artificial neural network (ANN)-based predictive models exist in the literature for design purposes.

II. REVIEW OF LITERATURE

2.1 Self-Healing Mechanisms in Cementitious Materials

Two types of self-healing concrete have been distinguished in the literature. The first type involves the use of autogenous healing, which utilizes intrinsic processes such as the continuing hydration of any unhydrated clinker and the deposition of CaCO3 due to the carbonation reaction of dissolved calcium hydroxide. The process is environmentally friendly but not very broad-spectrum since it is effective only up to crack widths of 100–150 micrometers if there is continuous moisture contact (De Belie et al., 2018). The stimulation of autogenous healing through the addition of crystalline materials, SAPs, and supplementary cementitious materials is expected to increase the upper bound by providing additional reactive components and/or internal water sources.

The second type of self-healing concrete involves autonomous healing, which introduces intentionally added materials that become activated by crack formation, such as encapsulated polymers and mineral precursors, vascular networks, shape-memory alloys, and microorganisms. Amoorezaei and Ghanbari-Ghazijahani (2025) provide a detailed classification system that includes shape-memory materials, which heal larger cracks (>1 mm) but need external heating, encapsulated materials, which are more effective but mostly single-use, and microbial materials, which are sustainable but pH-, temperature-, and nutrient-dependent. According to De Belie et al. (2018), autonomous healing materials are proven to successfully heal cracks of about 300 micrometers, with the optimized systems capable of healing cracks of 1.0–1.8 mm.

2.2 Fiber-Reinforced Concrete: Crack Control and Healing

Steel fibers have a dual function in self-healing concrete. They serve as mechanical protectors by spanning cracks and transmitting loads, while simultaneously controlling the geometry of the cracks to ensure they remain within the autogenous healing zone (Cuenca & Ferrara, 2017). Steel fibers spread the damage over numerous smaller cracks rather than allowing them to coalesce into a single large crack, thereby ensuring that the cracks remain accessible to natural healing processes. This process was investigated by Cuenca & Ferrara (2017) in various FRCCs, HPFRCCs, and ECCs, and there is a recommendation to adopt standardized healing indices that integrate structural integrity and durability.

Experiments conducted by Ferrara et al. (2016) revealed that hooked end fibers provide adequate crack bridging strength to maintain the width of cracks under working conditions within the healable limit. Additionally, Snoeck et al. (2016) proposed that the combination of microfibers and super absorbent polymers could offer a complementary advantage for crack sealing and stiffness recovery. Luhar et al. (2020) discussed the sustainability aspects of fiber-reinforced composite materials, emphasizing the potential use of biological fibers in future concrete formulations.

2.3 Microbial and Enzymatic Healing

The BICP process utilizes the metabolic actions of ureolytic bacteria, wherein they break down the urea in the pore liquid, producing carbonate ions, which combine with soluble calcium to precipitate CaCO3 inside the microcracks of the concrete material. Thus, self-healing occurs internally (De Muynck et al., 2010). In a comprehensive evaluation, Javeed et al. (2024) assessed bacterial viability and implementation methods including direct mixing, surface treatment, bacterial entrapment, and porous media loading and their respective mechanical improvements, concluding that compressive strength increased by up to 42.8% under ideal bacterial density of 10^5-10^8 cells/mL. Healing effectiveness proved to be multidimensional, contingent upon bacterial strain, nutrient composition, humidity during curing, crack characteristics, and pH level.

Nodehi et al.'s (2022) systematic review of bacteria-based SHC revealed advancements in water uptake, chlorides diffusion resistance, carbonation resilience, and crack width reductions. Additionally, Amran et al. (2022) positioned SHC within the context of sustainable construction practices, emphasizing its multidisciplinary character and the need for standardization of life-cycle assessment protocols. Lastly, Kidanemariam et al. (2024) provided an overview of the EICP technique as an eco-friendly and industrially viable approach compared to using living cells and potential synergies with fiber-reinforced composites. Debnath et al. (2024) researched bio-inspired nanocrystals of calcite formation in concrete.

2.4 ANN-Based Prediction of FRC Behaviour

ANNs have gained prominence as prediction tools for structural concrete. Recently, in 2023, Qin and Kaewunruen designed and compared ANN, BNN, and XG Boost models by training them using a comprehensive data set comprising HSFRC beam data. Through their multi-output regression analysis, shear resistance, flexural resistance, stiffness, carbon footprint, and cost were predicted, attaining R^2 values as high as 0.977. Explaining the variables that drive the predictions was achieved using the SHAP technique, which revealed that the volume fraction of fibers, shear span to depth ratio, and concrete grade are the key factors determining structural behavior. The research provides the methodology to be followed in designing the ANN model that will focus on healing efficiency and residual strength, which remain untouched in the literature thus far.

2.5 Silica Fume in Healing Systems

It is a pozzolan with ultra-fine, high-reactivity particles (with average particle size of 0.15 μm) that increases the density of pores and causes a reaction with calcium hydroxide ($Ca(OH)_2$), thereby producing additional C-S-H gel, enhancing compressive strength, and reducing permeability. As a result of this consumption of $Ca(OH)_2$ in pozzolanic reactions in a scenario of self-healing, the concentration of calcium ions, which precipitate as calcium carbonate ($CaCO_3$), might be reduced. The addition of silica fume with crystalline admixtures, according to Sisomphon et al. (2012), increased the density of pores in healed zone, but how the dosages of silica fume influence Ca^{2+} concentration in $CaCO_3$ precipitation is still an open question for experimental investigation.

2.6 Historical Context of Autogenous Healing

Crack self-healing of cement mortars was first discovered by the French Academy of Science in 1836. According to Van Tittelboom and De Belie (2013), the main process behind self-healing of concretes with low water to binder ratio is due to the fact that a large amount of cement clinkers remain unreacted; when water gets into these areas, these clinkers reactivate themselves to form C-S-H and $CaCO_3$ within cracks. The formation of carbonates crystals is what mainly causes permeability recovery, which is how current efficiency indices have been developed.

III. SUMMARY OF RESEARCH GAPS

However, on closer inspection, the synergistic interactions of silica fume, steel fiber, and enzyme-based healing materials under practical conditions have not been established systematically, nor is there any off-the-shelf predictor using ANN for these three materials. The following table gives a brief account of four such gaps along with their expected benefits.

Table 1: Research Gaps and Proposed Contributions

Gap	Research Gap	Proposed Contribution
G1	Silica fume + steel fiber synergy on autogenous healing unoptimized.	Systematic SF variation (50–100%) in M50 HPC mixes.
G2	Healing penalty under sustained loading unquantified.	Spring-loaded frame at 40% load during healing tests.
G3	No ANN model for healing efficiency from mix + load history.	Feed-forward ANN
G4	Scarce data on repeated crack-heal cycles under aggressive exposure.	Wet-dry cyclic curing, RCPT, sorptivity on hybrid FRCC.

The final cross-cutting gap is the lack of standardised healing indices that combine structural performance recovery with durability indicators, hampering cross-study comparability and the generation of ANN training datasets.

IV. PROPOSED RESEARCH FRAMEWORK

4.1 Aim and Objectives

Firstly, it aims to evaluate the structural and self-healing capabilities of M50 high-performance concrete mixed with silica fume, hooked-end steel fibers, and an enzyme-based self-healing technique, providing simultaneously a well-established ANN model which can be directly utilized for engineering applications. Objectives are set as follows:

- To determine the influence of silica fume on the workability and mechanical properties of self-healing concrete.
- To examine the effects of using steel fibers on workability, bending strength, and the ability to bridge cracks.
- To experimentally investigate the self-healing process efficiency by studying crack closure, stiffness recovery, and water tightness properties in reinforced concrete beams subjected to continuous loads.
- To develop mathematical models by means of Artificial Neural Networks (ANN) to estimate self-healing and strength characteristics of concrete.

4.2 Scope, Materials, and Mix Proportions

The scope of work is focused on M50 HPC incorporating OPC 53 Grade cement, commercially available silica fume, and hooked-end steel fibers. Self-healing will be investigated through immersion in water and wet-dry cycles only. Testing is not performed by air curing and dynamic loading tests. Six different proportions of cement substituted by silica fume in amounts of 100%, 90%, 80%, 70%, 60%, and 50% with 0.1%, 0.2%, and 0.3% healing agent are evaluated. Test specimens include 150 mm cubes, 150×300 mm cylinders, and 100×150×1200 mm beams, which are subjected to continuous loading of 40% of ultimate load using a reaction frame spring loading.

Mix ID	Cement	Silica fume	Healing Agent (%)
C-H0.1	100	0	0.1
C-H0.2	100	0	0.2
C-H0.3	100	0	0.3
SF10-H0.1	90	10	0.1
SF10-H0.2	90	10	0.2
SF10-H0.3	90	10	0.3
SF 20-H0.1	80	20	0.1
SF 20-H0.2	80	20	0.2
SF 20-H0.3	80	20	0.3
SF 30-H0.1	70	30	0.1
SF 30-H0.2	70	30	0.2
SF 30-H0.3	70	30	0.3
SF 40-H0.1	60	40	0.1
SF 40-H0.2	60	40	0.2
SF 40-H0.3	60	40	0.3
SF 50-H0.1	50	50	0.1
SF 50-H0.2	50	50	0.2
SF 50-H0.3	50	50	0.3

Now we will assume C-H0.3 and SF 40-H0.3 is critical. Now add fiber percentage here from 0.5%, 1%, 1.5%, 2%

Mix ID	Cement	Silica fume	Healing Agent (%)	Fiber content (%)
C-H0.3-F0.5	100	0	0.3	0.5
C-H0.3-F1.0	100	0	0.3	1
C-H0.3-F1.5	100	0	0.3	1.5
C-H0.3-F2.0	100	0	0.3	2

SF40-H0.3-F0.5	60	40	0.3	0.5
SF40-H0.3-F1.0	60	40	0.3	1
SF40-H0.3-F1.5	60	40	0.3	1.5
SF40-H0.3-F2.0	60	40	0.3	2

4.3 Hypotheses

- H1: The steel fibers will limit crack width development to <150 μm when subjected to service loads, providing geometric crack closure of >60%.
- H2: The ANN-based predictive modeling approach will provide predictions of self-healing and strength recovery with an R^2 value ≥ 0.90.
- H3: The bacterial/enzymatic concrete material system will produce higher crack-width reduction and permeability recovery compared to conventional and autogenous healing concretes for cracks with dimensions between 0.1 mm and 0.6 mm wide.
- H4: The microscopic $CaCO_3$ content (SEM, XRD, and FTIR analysis) will demonstrate positive correlations with the noted mechanical/transport performance improvements.

4.4 Testing Programme

The testing program comprises the following tests:
(i) Mechanical testing—compressive and flexural strengths, as well as stiffness of the beam at critical phases: prior to cracking, post-controlled cracking, and post-healing;

(ii) Durability testing—water permeability, sorptivity, rapid chloride permeability test (RCPT), and optionally freeze–thaw resistance and carbonation;

(iii) Characterization of microstructure—scanning electron microscopy-energy dispersive spectroscopy, x-ray diffraction, Fourier transform infrared spectroscopy, and thermo-gravimetric analysis (to confirm precipitation of $CaCO_3$ crystals and to assess the effect of pore refinement

4.5 ANN Modelling Approach

The multilayer feed-forward back-propagation artificial neural network is going to train with the aid of the Levenberg-Marquardt method based on the experimental data set, tested using k-fold cross validation technique. Input parameters for the model include percentage of silica fume, volume percentage of steel fibers, amount of healing agent used (%), initial crack width (μm), load level (%) and healing time (days). The output results are the residual compressive strength, crack closure (%) and RCPT permeability class.

V. EXPECTED OUTCOMES

- An advanced self-healing M50 HPC formulation that offers a minimum of 60% of crack healing for cracks below 300 μm in length and reduces chloride permeability by 20% relative to the reference sample.
- The first study to quantitatively evaluate the impact of self-healing on service loads in hybrid FRCC.
- A reliable ANN prediction model capable of estimating healing efficiency and residual strength with engineering-level precision.
- An extensive experimental database that contributes to the advancement of machine learning in self-healing FRCC investigations.
- Guidance on bacteria/zyme dosages, crack width limits, and curing humidity requirements for practical application in the field.

VI. CONCLUSION

The review thus emphasizes an exciting but relatively unexplored area in high-performance concrete, which involves the combination of silica fume, self-healing, and fiber-reinforced concrete with hooked end steel fibers. Whereas individually, these components have exhibited significant performance improvements, the overall performance of these materials when subjected to real-world loads over time and their prediction using artificial neural network (ANN) methods remain areas of concern in terms of present-day literature. The methodology adopted in the current study attempts to address the gaps in the research by using a systematic experimentation and modeling process, which will not only provide scientific insights but also serve as a useful design tool for engineers.

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