

REVIEW ON POTENTIAL OF INCORPORATING NANOMATERIALS TO ENHANCE SELF-HEALING CAPABILITIES IN CONCRETE STRUCTURES

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ABSTRACT

Cracks threaten the durability of concrete structures, as the ingress of the aggressive substances into the matrix through these cracks can cause concrete degradation. Thus, cracks may propagate and result in the exposure of the reinforcement to environments. Total or partial failure of the structure may happen after the embedded steel begins to corrode or oxidize, leading to a reduction of the in-service durability of concrete.

For that reason, different measures have been undertaken to minimize the size and number of cracks in concrete. Developing an appropriate concrete mix design, carefully selecting raw materials, choosing a proper curing regime and having an appropriate structural management of operation are among these measures. Despite the fact that it is virtually impossible to make cracks disappear, cracks can be controlled or significantly reduced. Despite of this, it is difficult to repair the invisible or inaccessible cracks. Consequently, the self-healing of cracks in concrete is indispensable and would contribute to a longer service life of concrete structures..

Keywords: Coarse Aggregate, Design Mix, Sand, Slump value, workability.

1. INTRODUCTION

1.1 GENERAL

According to Mamalis et al. today there are three primary approaches taken to produce CNTs. The first process is electric arc-discharge, where an electrical arch is passed through an inert gas such as argon or helium between two carbon electrodes. The high temperatures caused by the arc (upwards of 3000o C) cause the carbon to sublimate and re-solidify into the highly organized CNT structure . Electric arc-discharge produces CNT with purity around 30 % by wt and can produce both SWNT and MWCNT. The second method, called chemical vapor deposition (CVD), uses a carbon based gas (such as acetylene, ethanol, or methane) along with a metal catalyst to initiate the growth of the CNT. CVD is the most widely used method to produce CNTs on an industrial scale due to its low cost/unit ratio. However, CVD also contain higher amounts of defects when compared to other production methods. The sizes and lengths can be changed depending on the size of the 6 metal catalyst and the atmosphere within the reaction chamber. CVD can be used to produce large quantities of CNTs with minimum cost and high purity. The final method is the laser ablation (LA) process. This method uses a pulsing laser to vaporize a piece of graphite within an inert gas within a furnace at temperature around 1200o C. The vaporized graphite solidifies onto the cooler walls of the reaction chamber and forms the CNT. This method produces purity around 70 % by wt of mostly SWCNT with a diameter controlled by the temperature of the chamber . CNTs produced by LA are very pure and highly uniform; however, it is very expensive to produce due to the cost of the laser.

CNTs are quickly becoming one of the most promising nano-materials due to their unique mechanical properties. Experimental tests on CNFs have shown them to have a Young's Modulus as high as 400 GPa, with a tensile strength of 7 GPa . Alternatively, CNTs have an average Young's modulus around 1 TPa, an average tensile strength of 60 GPa, and an average ultimate strain of 12%. When compared to the strongest steel, CNTs have a modulus of elasticity of approximately 5 times higher, a tensile strength 100 times larger, and can reach elastic strain capacities 60 times greater than steel, and yet a specific gravity one sixth that of steel.

2. REVIEW OF LITERATURE SURVEY

John Hanna (2024) The main weakest point of concrete is its exposure to cracks, and concrete structure repair is expensive, especially for infrastructure maintenance, which is difficult to access. The ability of self-healing concrete (SHC) to successfully heal fractures without the assistance of humans has received much attention since it increases operational life and lowers maintenance expenses. This paper reviews various techniques and technologies of autogenous and autonomous self-healing concrete. Much more attention is given to the autonomous SHC, including the encapsulation materials, capsule geometries, and healing agents. This is due to its accuracy for healing locations and better healing capabilities compared to the uniform hydration of autogenous SHC. Polymeric materials have shown great potential in both capsules and healing agents. Because they can meet the unusual demands of capsules, which include being flexible when mixing concrete and becoming brittle when cracks develop, the healing agent's viscosity must be

low enough to allow it to flow out of the capsules and fill tiny cracks. In contrast, if the viscosity is too low, the healing agent will either seep out of the fracture or be absorbed by the pores of the concrete matrix.

Kashyap et.al. (2023) A detailed investigation was conducted to analyse the mechanical and durability features of a mixture of binary cement concrete modified with nanomaterials. In the context of the concrete matrix, the substitution of fractional cement content was carried out using Nano silica (NS) at concentrations of 1%, 2%, and 3%. Four distinct cementitious blends were subjected to a comprehensive match of tests, which encompassed compressive strength, flexural strength, split tensile strength, static modulus of elasticity, bulk density, water absorption, permeability, carbonation resistance, acid attack resistance, and rapid chloride penetration. The compositions of the mixes were investigated through the use of various microstructural analysis techniques, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (SEM-EDS), thermogravimetric analysis (TGA), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR). The research revealed significant improvements in the mechanical and durability characteristics of the material. An increment in the mechanical and durability properties of mixtures were seen due to inclusion of marble powder and Nano silica due to enhanced pozzolanic activities of composite and its filling effect. It is worth mentioning that Nano silica has shown the potential to mitigate the degradation caused by exposure to sulfuric acid. The SEM-EDX analysis demonstrated a decrease in the Ca/Si ratio when compared to the reference combination, suggesting an increase in the consumption of calcium hydroxide (CH) and the creation of a more compact calcium-silicate-hydrate (C-S-H) gel. The X-ray diffraction (XRD) findings indicate that NS has the ability to act as an accelerator for pozzolanic processes. This is achieved by consuming calcium hydroxide (CH) and promoting the creation of extra calcium silicate hydrate (C-S-H), which ultimately enhances the overall performance of the concrete mixture.

Huseien et.al. (2023), this paper presents a state-of-the-art review involving the uses of different nanomaterials for production of high-performance cementitious, geopolymer, and alkaliactivated concrete composites. The effects of nanomaterials on the fresh properties, mechanical properties, and durability of diverse nanoparticle-modified concrete composites are analyzed. The past developments, recent trends, environmental impact, sustainability, notable benefits, and demerits of various nanomaterial-based concrete production are emphasized. It is demonstrated that nanomaterials including SiO_2 , Al_2O_3 , TiO_2 , and Fe_2O_3 , etc., can be used effectively to enhance the microstructures and mechanical characteristics (such as compressive strength, flexural, and splitting tensile strengths) of the modified concrete composites, thus improving their anti-erosion, anti-chloride penetration, and other durability traits. In short, this communication may provide deep insight into the role of diverse nanoparticle inclusion in concrete composites to improve their overall attributes.

This critical overview on NP-based concrete composites enabled the following conclusions: Inclusion of NPs into the mix can reduce its flowability as well as both initial and final setting times. Significant improvement in the hydration rate with the inclusion of NPs can lead to the reduction of the setting times of the concrete. Mixes prepared with nanomaterials show excellent improvement in the strength performance. Inclusion NPs in the cement/cement-free binders can cause significant development in the dense gels and dense surface morphology. Nanosilica is widely used in concrete technology and recommended for several applications. It can improve the early strength, reduce the porosity, and enhance the corrosion resistance of modified concrete composites. An optimum dosage of nano SiO_2 between 1 to 6% was suggested depending on the nature of concrete and mix design which could enhance the early and late strength up to 28% and 10%, respectively. The durability traits (porosity and chloride penetration) of NP-modified concrete composites can be enhanced via the inclusion of NPs into the concrete matrix.

Anita Gojevi et.al. (2023) presented a comprehensive review of current knowledge regarding the methods of self-healing in concrete, ranging from autogenic and improved autogenic self-healing to the autonomous self-healing of concrete. Particular emphasis is placed on the methods of autonomous concrete self-healing: the bacterial healing method, the crystalline hydrophilic additives healing method, and the capsule-based self-healing method.

The hypothesis is that applying these self-healing methods could potentially prevent damages or cracks in concrete caused by freeze-thaw cycles, thereby extending the lifespan of concrete structures. The mechanism of action and current achievements in the field are provided for each method.

This study systematically presents the state of the art of methods for concrete self-healing while emphasizing autonomous self-healing (healing by bacteria, healing through crystalline hydrophilic additives, and healing via capsules). It evaluates the diverse properties of concrete both before and after the self-healing process. The mentioned methods could serve as an intelligent approach to enhance the concrete's resistance to freeze-thaw cycles and extend the lifespan of structures. Taking action during concrete mix preparation for incorporation into structures makes it possible to minimize damages/cracks resulting from freeze-thaw cycles, thereby significantly reducing the inspection labour and maintenance costs of such structures. The application of these self-healing concretes is foreseen in structures

that are challenging to access for repairs, such as bridges, water reservoirs, structures prone to chemical reactions, pre-fabricated tunnel sections, tunnel connections, nuclear facilities, dams, concrete roadways, pylons, and airstrips.

Ayesha Kausar (2023) The self-healing behavior of the nanocomposites depends on factors such as microphase separation, matrix–nanofiller interactions and inter-diffusion of polymer–nanofiller. Moreover, self-healing can be achieved through healing agents such as nano capsules and nanocarbon nanoparticles. The mechanism of self-healing has been found to operate via physical or chemical interactions. Self-healing nanocomposites have been used to design structural components, panels, laminates, membranes, coatings, etc., to recover the damage to space materials. Future research must emphasize the design of new high-performance self-healing polymeric nanocomposites for aerospace structures. In short, this review article highlights the fundamentals and potential of self-healing composites/nanocomposites for aerospace structural components. The self-healing effect can be produced intrinsically or by using nano capsules, nanotubes, nanofibers, vesicles or nanocarbon nanoparticles. Literature studies have shown that self-healing polymers are promising materials for repairing structural damage, cracks and defects.

These materials have remarkable mechanical, thermal and other physical features for industrial applications. Self-healing nanocomposites have also been used to recover damage related to the strength, impact, fatigue, cracks, corrosion and environment.

This overview particularly covers self-healing materials for aeronautical applications. Investigations have been carried out to analyze the improvements in crack properties of space structures. Consequently, self-healing nanocomposites have been utilized for various aerospace structures, engines, fuselage, coatings and adhesives. The mechanisms involved in self-healing also enhance the healing efficiency and life cycle of these materials. During different phases of self-healing, materials have been scrutinized to achieve long-time service life. The performance properties of self-healing materials have been improved by the inclusion of nanoparticles. More advanced healing techniques have been proposed in literature studies to extend beyond the intrinsic and extrinsic mechanisms and overcome the challenges involved in fabrication and performance of self-healing materials. More emerging polymeric nanomaterials must also be explored for the aerospace sector. However, studies on aerospace materials are still in progress and further novel developments are needed.

J. Feng and S. Qian (2022) Microbially induced calcium carbonate precipitation is effective in achieving self-healing of concrete cracks when the bacteria are well protected in concrete with a high pH and dense microstructure. Calcium alginate hydrogels are appropriate for encapsulating bacteria in concrete due to the mild environment with rich moisture in the hydrogels. Nevertheless, the low alkaline tolerance and breakage ratios of the hydrogels after concrete cracking restrict their applications in concrete.

To address these problems, nanosilica was doped into calcium alginate hydrogels with encapsulated bacterial spores to react with the $\text{Ca}(\text{OH})_2$ surrounding hydrogels in concrete. Due to the modification by nanosilica, the bond of the hydrogels with cement matrix was enhanced as needle-like C–S–H was generated at the interface after hydration for 7 days. Moreover, the urease activity of the encapsulated spores in the modified hydrogels was higher than that in plain hydrogels after submersion in saturated $\text{Ca}(\text{OH})_2$ solution or simulated concrete solution for 7 days. Therefore, it can be concluded that nanosilica holds promise for modifying hydrogels to improve the effectiveness of encapsulated bacterial spores for self-healing of concrete.

Xiaohong He (2022) This study performed a scient metric evaluation of the bibliometric data on self-healing concrete (SHC) in order to determine its major components. Manual review articles are inadequate in their capability to connect diverse areas of the literature in a systematic and ordered manner. Current research's most difficult parts include scientific mapping, co-occurrence, and co-citation. The Scopus search engine was utilized to locate and collect the necessary information for the investigation.

During the data review, the important publishing sources, assessment of keywords, prolific authors based on citations and publications, most-cited articles, and areas actively engaged in SHC research are identified. VOS viewer was used to examine the literature records from 1294 relevant publications, which comprised abstract, citation, bibliographic, funding, keyword, and other data. In addition, the limitations associated with the use of SHC in the building industry were investigated, as well as potential solutions to these limitations. Due to the quantitative and graphical description of participating nations and researchers, this study can aid academics in developing joint projects and disseminating new ideas and approaches.

Mugahed Amran et.al. (2022) This paper also gives an overview of self-healing concrete. This literature review also provides critical synopses on the properties, performance, and evaluation of the self-healing efficiency of SHC composites. In addition, we review trends of development in research toward a broad understanding of the potential application of SHC as a superior concrete candidate and a turning point for developing sustainable and durable concrete composites for modern construction today. Further, it can be imagined that SHC will enable builders to construct

buildings without fear of damage or extensive maintenance. Based on this comprehensive review, it is evident that SHC is a truly interdisciplinary hotspot research topic integrating chemistry, microbiology, civil engineering, material science, etc. Furthermore, limitations and future prospects of SHC, as well as the hotspot research topics for future investigations, are also successfully highlighted.

Daniel Lahmann, Carola Edvardsen and Sylvia Kessler (2022) In general, autogenous self-healing is based on the reaction of water and concrete in the restricted space of a separating crack of a certain width. Water, concrete, and crack geometry are influenced by various variables that could affect the efficiency of autogenous self-healing.

Based on the findings of this study, the following conclusions can be drawn:

A lot of research has been carried out on autogenous self-healing of cracked concrete in the last decades. The influence of crack width, roughness, and tortuosity, the presence of liquid water, water pressure, water chemistry, and temperature, as well as the aggregate size, gradation curve, W/C ratio and cement content are examples of well-established influencing factors on the healing efficiency of cracked concrete. Calcite precipitation has been identified as the main cause of autogenous self-healing in freshwater environments under atmospheric conditions that could seal cracks up to 200 μm in width.

Studies on the influence of the cement type or Ca^{2+} availability on the healing efficiency come to contradictory results. Some studies reported that the amount of portlandite and CSH affects the amount of CaCO_3 formed during the experiments and hence the healing efficiency, while other studies reported no effect. This indicates a need for further research regarding the diffusion of relevant ions from the concrete into the permeating water and the precipitation reactions at the crack-water interface as a function of composition and time. Reliable diffusion data could lead to a comprehensive chemical and transport-based modeling of autogenous self-healing, for example, with the PHREEQC modeling tool. In addition, a fingerprint of the change in water chemistry during specific phases of the autogenous self-healing process could be generated. Seawater has been identified to impact the chemical causes and the healing efficiency of autogenous self-healing. Typically, brucite precipitates first and is overlayed by aragonite. However, the extend of healing and the influence of the cement type remains controversial and should be investigated in future studies. Instead of using synthetic seawater, experiments with real seawater are desirable. The lack of standardized testing makes it difficult to compare literature data. Improvements are proposed at several points within this study. For instance, special care should be taken to conserve the crack geometry when permeability experiments are planned.

Nikhil Sanjay Gaikwad and Sakshi Chetan Bhalerao (2021) Addition of bacteria into a concrete makes it beneficial. Selfhealing concrete can be a great concrete sealant. It improves durability of concrete, life of the structure. It reduces need of regular maintenance and inspection. It produces calcium carbonate which blocks and seals the crack which reduces water permeability. It increases compressive strength tensile strength and decreases water absorption and acid attacks. From above study, bacterial concrete increases approximately at least 10% of compressive strength and reduces water permeability up to 0.45%.

Maria Stefanidou, Eirini-Chrysanthi Tsardaka and Aspasia Karozou (2020) The present study proposes nano-calcium oxide (NC) and nano-silica (NS) particles as healing agents in cement pastes, taking into account the curing conditions. Two series of specimens were treated in water and under wetting-drying cycles. The addition of NC (1.5% wt of binder) triggered early healing since cracks were healed within 14 days in underwater immersion and before 28 days at wetting-drying cycles. Attenuated Total Reflectance (ATR) spectroscopy and SEM analysis revealed that the healing products were mainly aragonite and calcite in water conditions and more amorphous carbonates under wetting-drying cycles. The combination of NS and NC (3.0% wt in total) healing under both curing conditions before 28 days. The presence of NS assisted toward porosity refinement and NC increased the carbonates' content. The newly formed material was dense, and its elemental analysis by SEM revealed the C-S-H compounds that were also verified by ATR.

Changjiang Liu et.al. (2020) The effects of nano-silica, nano- CaCO_3 , carbon-based nanomaterials, nano- TiO_2 , and nano- MgO on the properties of UHPC were reviewed. It can be seen that the manufacturing of UHPC with nanomaterials instead of cement has broad prospects. The impact of these materials on UHPC is summarized as follows: When these nanomaterials were added to UHPC, the water absorption rate of large specific surface area and filling effect became the key factors affecting the fluidity of UHPC. Except that CNFs and CNTs had little effect on fluidity at low dosage, other materials showed that the water absorption effect of large surface area was more obvious, which reduces the fluidity of UHPC. The modification of nanomaterials by admixture is one of the reliable options to solve this problem. CNTs and CNFs mainly improved the performance of UHPC by their own mechanical properties. Other nanomaterials improved the pore structure through seeding effect, filling effect, and reaction with hydration products. These effects have played a positive role in improving the toughness, impermeability, and bending strength of UHPC.

Ishraq Mohammad Ali Khattab and Hazhar Shekha (2019) The study reviews various methods and techniques for self-healing concrete design. There has been different assortments, but this research proposed a complete classification

and assortments to include crucial methods and techniques for the design. These methods are chemical, biological, and Natural self-healing processes. Chemical techniques were the customary technique that has been utilized as a sole method to structure “self-healing concrete”. This study although focuses mainly on promising biological method especially using bacteria. These methods attracted the attention of researchers intensively. The suggested assortment in this study clarify the roadmap of self-healing concrete for the researchers. The insight enable researchers to conduct future researches on designing biological methods for self-healing concrete.

Bharanedharan G et.al. (2018) Concrete is weak in tension. As a matter of fact, the concrete tends to crack. These cracks progress in time and make concrete vulnerable to environmental effects. Thus self-healing of cracks can be helpful in mitigation of development of cracks. In this study, the self-healing of cracks by bacterial carbonate precipitation and the efficiency of bacterial deposition on compressive strength between *Bacillus subtilis* and *Bacillus cohnii* were compared. Bacteria were introduced into concrete using light weight aggregate i.e. LECA (light weight expansive clay aggregate). Calcium Lactate is used as nutrient (i.e. organic precursor) for the bacteria. Specimens were made for each type of bacteria and compared for changes in crack healing and compressive strength. Results showed that the concrete incorporated with *Bacillus subtilis* were more effective in crack healing than *Bacillus cohnii*. The specimens were also studied under Scanning Electron Microscopy to identify the self-healing effect on the cracked portion of concrete.

3. CONCLUSION

The relationship between the w/c ratio and compressive strength is essential for the preliminary estimation of compressive strength. Indian standard recommends such relationship for natural aggregate concrete. This relationship may be different for RCA concrete depending on the aspects such as age of recycled aggregate and number of recycling. Many studies are reported in literature that focus on the behaviour, properties, and functional uses of RCA. However, no study reported on the behaviour of RCA concrete with regard to above aspects. The present work is an attempt to study the relationship of w/c ratio with compressive strength considering age and successive recycling of RCA. Further, the properties like capillary water absorption, drying shrinkage, air content, flexural strength and tensile splitting strength of RCA concrete are also investigated considering the age and successive recycling of RCA.

It is found from an extensive review of literature that there is hardly any research on the use of bacteria to improve the properties of RCA concrete. Therefore, the present study focus on the improvement of RCA concrete (made by 100% replacement of natural coarse aggregates) by adding two bacteria, *Bacillus subtilis* and *Bacillus sphaericus* bacteria, which are widely available and most efficient in calcite production in an alkaline environment.

An extensive literature review revealed that majority of the published literatures, if not all, present studies on Portland cement. However, production of Portland cement in the recent times is reduced considerably and the construction industry uses slag cement mostly. This is the motivation for a detailed study on the concrete made with slag cement partially replaced by SF or FA. Most of the previous studies on SF concrete considered the partial replacement of cement keeping the total weight of cementitious material, fine and coarse aggregate as constant. The main purpose of these studies was to evaluate the effect of SF on the behaviour of concrete. However, in practical constructions, SF concrete is prepared as per relevant codes and standards. Many international design codes recommend extra cement of 10% while mineral admixture is used as partial replacement of cement. The behaviour of SF concrete prepared with the above practical aspects is not investigated yet. Also, almost all the previous studies on SF concrete are concentrated in high-strength concrete. No attempt has been carried out using SF as a replacement of cement for low/medium grade concretes.

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