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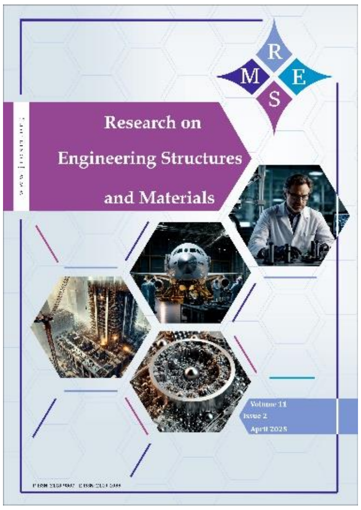

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Research Article

Strength and characterization studies on nano-silica and steel fibre reinforced bacterial concrete: An eco-friendly and sustainable approach

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Abstract

The growing need for environmentally friendly building materials has prompted the creation of creative methods to enhance concrete's mechanical qualities and ecological sustainability. With a focus on its eco-friendliness and sustainability, this research examines the mechanical characteristics and qualities of bacterial concrete augmented with steel fibers (SF) and nano-silica (NS). NS is used at 1%, 2%, 3%, and 4% together with 1% of SF to improve the mechanical strength and durability of concrete. It is well-known for its pozzolanic activity and capacity to refine pore architectures. In this research, tests for compressive, flexural, impact, bond, and splitting-tensile strength are evaluated. Microstructural characterization conducted using techniques such as SEM with EDS on the optimized mix confirms the improved pore structure and calcite ($CaCO_3$) deposition. Comparing the findings of bacterial concrete with the control mix, the addition of 2% NS and 1% SF enhances the compressive strength by 14.17%, the splitting tensile strength by 8.69%, and the flexural strength by 12.16%. This study therefore emphasizes the possibility of combining microbiological, SF, and NS technologies to create cutting-edge green concrete solutions.

1. Introduction

Concrete's strength, versatility, affordability, and durability make it an essential part of modern structures [1-3]. It serves as the cornerstone for the development of infrastructure everywhere. However, since cement manufacturing produces carbon dioxide emissions that make up over 7% of global CO_2 emissions, its widespread usage poses serious environmental difficulties [4]. Furthermore, there are environmental concerns associated with the mining of natural aggregates, which comprise 70–80% of the volume of concrete [5], [6]. Innovative and sustainable methods are required to reduce the environmental effect of concrete manufacturing while preserving structural performance. However, because of things like autogenous shrinkage, freeze-thaw cycles, and mechanical compressive and tensile pressures, concrete is still prone to breaking [7], [8]. The cementitious matrix may be compromised by microcracks, which allow fluids like water and chemical solutions (sulfates, chlorides, and acids) to penetrate the concrete without substantially weakening it. This may lead to the corrosion of embedded steel reinforcing [9]. Cracks affect structural safety by compromising the materials' mechanical strength and durability. Different kinds of bacteria have recently been added to concrete compositions to boost durability and fracture mending [10]. The nutrient composition of culture media and the bacterial species significantly influence urease activity and, consequently, microbial induced calcite precipitation (MICP).

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Three primary techniques are used to introduce bacteria into concrete for self-healing: direct incorporation into the mix, encapsulation to delay activation, and surface application via spraying or injection onto cracked areas [11]. In these approaches, it is essential to supply an organic nutrient, such as yeast extract, along with a urea medium positioned near the bacteria to support cellular growth and activity. Additionally, calcification and biomineralization processes of $CaCO_3$ occur in two primary forms: autotrophic and heterotrophic $CaCO_3$ precipitation [12-15]. The typical pH of concrete mixtures is approximately 12, which limits the suitability of specific strains of alkaliphilic bacteria for $CaCO_3$ production. Bacterial precipitation is influenced by variables that modify the pH of concrete.

The ability of bacterial ureolysis to increase $CaCO_3$ precipitation capacity has been the subject of several investigations. The synthesis of the urease enzyme causes calcium carbonate to precipitate in almost all bacteria. The identification of bacterial species that maximize biomineralization and the immobilization of healing agents, such as bacteria and calcium supplies, has been the main focus of research on self-healing concrete. Rice husk concrete has been treated with Bacillus aerius to increase its durability [16]. Additionally, other bacterial strains such as Bacillus megaterium [17], [18], Bacillus sphaericus [19], and Sporosarcina pasteurii [20] have been used in self-healing concrete, with crack-width healing of around 0.3 to 0.5 mm. Bacterial spore survival is restricted during cement setting by a steady reduction in pore diameter, which falls below 1 µm, which is about the size of Bacillus spores. Because the hole size is too small for the bacteria to survive, they are rendered non-viable after seven days of cure [21]. Bacterial spore survival is restricted during cement setting by a steady reduction in pore diameter, which falls below 1 µm, which is about the size of Bacillus spores. Because the pores are too small for the bacteria to survive, they are rendered non-viable after seven days of cure [22]. By filling micropores, bacteria may increase the mechanical strength and longevity of concrete by decreasing its permeability to water and other substances. Incorporating bacteria into cement-based materials provides an economical and ecologically friendly way to extend the life of structures. Because of the cement industry's substantial carbon emissions, environmentally acceptable substitutes like fly ash and slag are required [23].

Additionally, nanoscale materials, such as NS, may enhance both the environmental sustainability and the quality of concrete [24], [25]. Incorporating fibres, whether natural or synthetic, offers another possibility for enhancing concrete performance [26-28]. SF, in particular, are compelling due to their high tensile strength and ductility, which help to prevent crack propagation and improve behavior after cracking occurs [29]. Certain studies have employed urease-based treatments to enhance concrete surface durability [30-32]. Adding bacteria to concrete has shown promise in enhancing its self-healing qualities, reducing microcracks, and boosting its overall durability [33], [34]. By forming calcium silicate hydrate (C-S-H) gels via a reaction with calcium hydroxide, NS plays a vital function in concrete technology by increasing strength. Its high-water absorption, however, may impact workability; this problem is often addressed by adding fly ash. High-performance and ultrahigh-performance concrete applications benefit greatly from this mixture as it increases flowability and early-age strength [35], [36]. A classic hybrid model (HRL) that uses recycled coarse aggregates has also been created, along with three novel sustainable hybrid deep beam models (CRV, ARC1, ARC2). Improvements in flexural toughness (up to 71%), effective stiffness (1.5–9%), and failure capacity (up to 22%) were reported. Directional cracking was considerably reduced by inclined stirrups, and the proposed models show promise for use in prestressed beams, precast walls, and constructions with numerous focused loads [37]. A new sustainable arching hybrid deep beam model has been shown, which uses recycled coarse aggregate (0%, 50%, 100% RCA) in certain places and steel fiber concrete (1% SFC) in high-stress locations. Testing of seven specimens was conducted using mid-span static loading (a/d = 1.7) with an emphasis on stiffness, ductility, failure load, and cracking behavior. Compared to conventional deep beams, the model showed significant improvements, with peak gains of 100% in toughness, 11% in stiffness, and 46% in ductility [38]. This investigation presents a hybrid sustainable deep beam model that incorporates recycled coarse aggregates (RCA) at replacement levels of 0%, 50%, and 100%. The experimental findings indicated that the introduced arched hybrid model enhanced capacity by as much as 19.7% and flexural toughness by as much as 62.1% when compared to the traditional model. The proposed model also exhibited a flexural failure mode, establishing it as a feasible choice for sustainable precast deep beams [39].

The novelty of this study investigates a sustainable and eco-friendly approach to concrete design that integrates NS, SF, and self-healing technology. The purpose this study is to assess the effect of these components on the mechanical characteristics and self-healing capacities of the material. The research will look at various NS (1, 2, 3, and 4%) concentrations along with bacteria and 1% SF. The outcomes of this research aim to advance the creation of durable and sustainable concrete structures with improved self-healing characteristics, addressing significant challenges related to durability and environmental sustainability.

2. Materials Used and Mix Proportion

Grade 53 Ordinary Portland cement, as per IS 8112 (2013), was utilized for the experimental analysis. Specific gravity, setting time, standard consistency, compressive strength, and soundness tests were conducted following IS: 1727-1967 and IS: 4031-1968 standards. NS functioned as the binder material, improving the economic feasibility of the concrete and decreasing the CO_2 emissions associated with the final product. Table 1 displays the physiochemical characteristics of grade 53 cement and NS. Following the guidelines provided by IS 383:1970, fine aggregate from a nearby M-sand quarry was used in the investigation. In Table 2, the characteristics of the coarse and fine particles utilized in the concrete mix are shown. For mixing all of the concrete ingredients, tap water—which was considered typical and accessible on college property—was used. With their characteristics indicated in Table 3, SF was used as a reinforcing material at a weight ratio of 1% to cement to increase the strength of the concrete.

Table 1. Physiochemical properties of OPC and NS

Physiochemical Properties	OPC	NS
Specific gravity	3.18	2.3
Initial setting time (mins)	38	-
Final setting time (mins)	334	-
Standard consistency	32%	-
Soundness (mm)	0.96	-
MgO	1.31	0.21
Al_2O_3	5.02	0.004
CaO	65.00	0.05
SiO_2	22.02	99.39
SO_3	1.83	-
$CaSO_4$	3.89	-
Chlorides	0.02	0.009
LOI	1.14	0.66
Na_2O	0.20	0.48
Alkalies	0.79	-

Table 2. Properties of fine and coarse aggregates

Properties	Fine Aggregate (M-sand)	Coarse Aggregate (Granite)
Particle size (mm)	4.75	12.5
Fineness modulus	2.52	6.65
Specific gravity	2.64	2.68
Bulk density (g/cm^3)	1.59	1.56
Zone	III	-

Table 3. Properties of SF

Properties	Description
Ult. tensile strength (MPa)	900
Elastic modulus (GPa)	210
Diameter (mm)	0.5
Aspect ratio	60
Elastic modulus (GPa)	210
Length (mm)	30

2.1. Preparation of the Bacteria Culture

The preparation of a sterile and nutrient-rich medium commences with the selection of either Luria-Bertani (LB) broth or nutrient broth as the growth medium. The medium is transferred into sterilized culture bottles, which are sealed to prevent contamination. The prepared medium is autoclaved at 121°C for 15–20 minutes to eliminate unwanted microorganisms. After sterilization, it should be permitted to cool to room temperature prior to advancing to the subsequent step. Bacillus subtilis strips from the HI-media laboratory are introduced into the medium under strict aseptic conditions to initiate bacterial growth. Following inoculation, the medium is placed in a shaking incubator that is kept at 37°C and has a controlled shaking speed of 150–200 rpm to promote enough aeration and ideal bacterial growth. The bacterial culture is continuously incubated for 12 to 24 hours, which expedites its transition to an active growth phase. Bacterial growth is assessed using a spectrophotometer and optical density (OD) measurements at a wavelength of 600 nm. Maximum bacterial activity is an indication that the culture has entered the exponential (log) phase, which is indicated by an OD measurement between 0.6 and 0.8. By dilution with sterile saline or distilled water as needed, the culture is now adjusted to attain the desired concentration of 10^7 CFU/ml. After confirming the concentration by serial dilutions, the plates are spread out on nutritional agar. Bacterial colonies are counted after plates are incubated for 24 hours at 37°C to confirm the CFU/ml accuracy. After confirmation, the bacterial culture is quickly ready to be added to the concrete mixture in order to guarantee its viability. By replacing 10% of the concrete mix's water content, the bacterial solution promotes efficient integration. To make a slurry, water is combined with a 10% bacterial solution that contains 10^7 CFU/ml of Bacillus subtilis spores. The M25 grade requirements outlined in IS 10269 (2009) are met by the concrete mixture. As seen in Table 4, which contrasts the control mix with the alternative mix that incorporates steel fibers (SF), Bacillus subtilis, and nano-silica (NS) to enhance durability and self-healing properties, the mix proportions are carefully determined.

Table 4. Mix proportion

Mix ID	Cement	NS	SF	M-sand	CA	Water	B.Subtilis (10^7 CFU/ml)
N0	391	-	-	574.5	1246	192	-
N1	383.18	1%	1%	574.5	1246	172.8	19.2
N2	379.27	2%	1%	574.5	1246	172.8	19.2
N3	374.36	3%	1%	574.5	1246	172.8	19.2
N4	371.45	4%	1%	574.5	1246	172.8	19.2

3. Experimental Procedure

3.1. Mechanical Properties

This study encompasses the collection of materials, verification of properties, mixing, casting, curing, and testing conducted at 28 days, as illustrated in Figure 1. Conventional concrete and various amounts of NS and SF combined with microorganisms were used to create the specimens. Each mix ID has three samples. The compressive strength, splitting tensile strength, flexural strength, impact strength, and bond strength of a total of 15 specimens were tested. Additionally, SEM with EDS was used to investigate six specimens.

After 28 days of the curing phase, testing was done on a 100 mm³ cube. 100 mm diameter and 200 mm high cylindrical concrete specimens were made and tested in accordance with IS: 5816-2004, which describes how to assess the splitting tensile strength of concrete. Throughout the test, the cylinder's vertical axis received a consistent compressive force. The load was raised progressively until the specimen failed, and the highest load at failure was meticulously documented for further examination.

Prism-shaped specimens measuring 100 mm by 100 mm by 500 mm were created and subjected to four-point loading in accordance with IS: 5816-2004 instructions in order to assess the flexural strength of both conventional concrete and nano silica in steel-reinforced bacterial concrete. Following established methods, the specimens were subjected to a flexural stress until they failed. To assess the impact resistance of the mixes, the methodology recommended by ACI Committee 544.IR-56 was employed. The specimens used for this test had a diameter of 152.4mm and a thickness of 63.5mm. Each specimen underwent impact testing, with the number of blows necessary to initiate and propagate initial and final cracks documented. The test was conducted on a cube specimen measuring 150 x 150 x 150 mm³, which contained a HYSD steel bar positioned centrally. During the test, tensile forces were applied to the steel bars, transferring tensile stress to the concrete across the bonded interface. The embedded length of the specimen was 15 cm. The slip of the bar was monitored for each applied load until failure occurred.

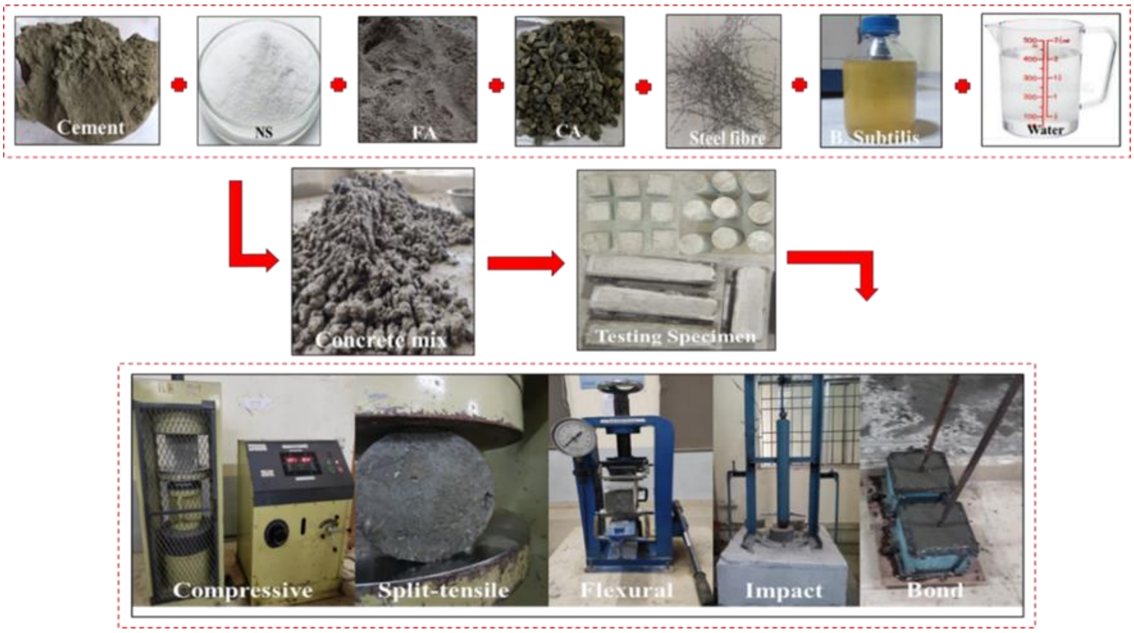

Fig. 1. Experimental procedure

3.2 Characterization Studies

To investigate the microstructure and big pores created in concrete (Optimized mix), a scanning electron microscope (SEM, JSM-IT800, JEOL, Tokyo, Japan) was used. Concrete was broken up into tiny bits using ethanol instead of the original solvent in order to avoid the concrete from hydrating during testing. The samples' conductivity was improved by applying a 20 nm coating of gold.

4. Results and Discussion

4.1. Compressive Strength

After 28 days of curing, the concrete's compressive strength was measured. The findings are shown for specimens N0 (control mix), N1, N2, N3, and N4 in Figure 2. Accordingly, N0, N1, N2, N3, and N4 have compressive strengths of 36.34 N/mm², 39.47 N/mm², 42.34 N/mm², 40.89 N/mm², and

38.9 N/mm^2. The N0 mix demonstrates the lowest compressive strength of the samples tested. Compared to N0, the N2 mix exhibits a significant strength increase of 14.17%. When NS is added, concrete's compressive strength is greatly increased. However, it is crucial to understand that there is an ideal NS concentration of 2%, beyond which the strength may begin to decline [40], [41]. In order to get optimum performance, this emphasizes the need for meticulous testing and cautious mix design. This formulation is the most successful in this series, as shown by the 14.17% improvement seen with 2% NS. Compressive strength is increased when 1% SF is added as a reinforcing agent and 2% NS is used as a cementitious material in bacterial concrete.

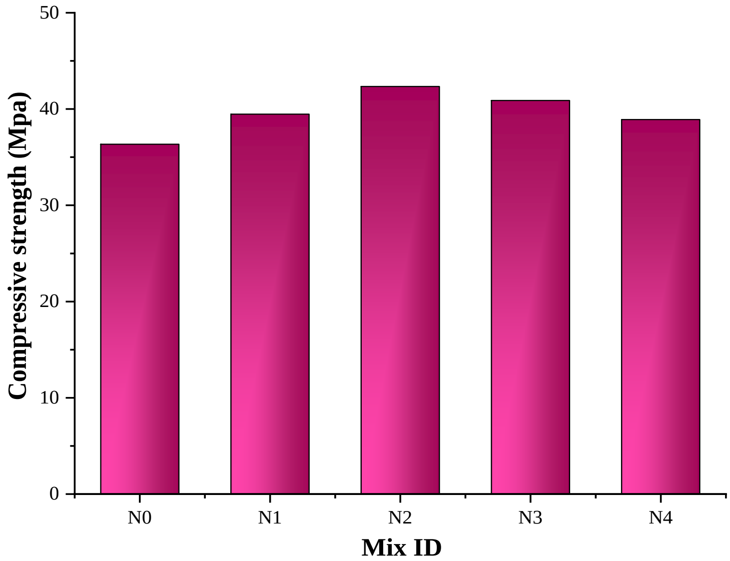

Fig. 2. Compressive strength

4.2. Splitting Tensile Strength Test

Following a 28-day curing period, the concrete's splitting tensile strength test results were acquired. The findings are shown in Figure 3 for specimens N0, N1, N2, N3, and N4. Concrete performance is impacted by NS, SF, and Bacillus subtilis, as shown by the splitting tensile strength tests for mixes N0, N1, N2, N3, and N4. The control mix N0, with a tensile strength of 4.2 N/mm^2, acts as the reference point, demonstrating the lowest strength.

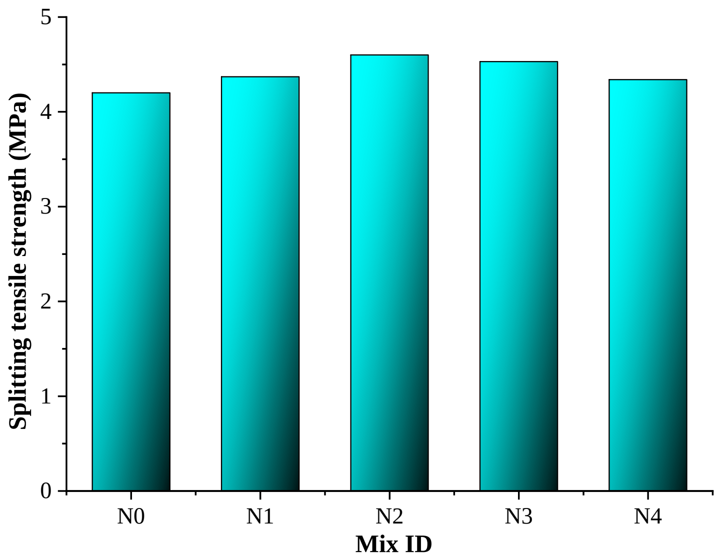

Fig. 3. Splitting tensile strength

The incorporation of 1% NS in mix N1 results in a tensile strength increase to 4.37 N/mm^2, reflecting a 4.05% enhancement due to improved microstructural densification and the crackbridging properties of the SF. The formulation containing N2 achieves a maximum tensile strength of 4.6 N/mm^2, indicating an 8.69% enhancement compared to N0. The enhanced performance results from the synergistic interactions of NS, which refines the concrete matrix; SF, which enhances crack resistance; and Bacillus subtilis, which facilitates biomineralization through calcium carbonate ($CaCO_3$) production, thereby sealing microcracks and increasing material density. Exceeding this threshold of NS content leads to a reduction in tensile strength. The N3 mix, which includes 3% NS, demonstrates a tensile strength of 4.53 N/mm^2, indicating a 7.86% increase; nonetheless, it is still inferior to N2, possibly due to particle agglomeration at higher NS concentrations. The N4 mix, which includes 4% NS, decreases to 4.34 N/mm^2, indicating a 3.33% increase, likely attributed to microstructural inconsistencies and insufficient dispersion of the additional NS. The results suggest that a 2% NS concentration is optimal for enhancing tensile strength, as increased concentrations result in diminishing returns[42]. The integration of NS, SF, and B. Subtilis enhances tensile strength, with mix N2 exhibiting the most effective and balanced performance.

4.3. Flexural Strength Test

After a 28-day curing period, the concrete specimens' flexural strength was evaluated. Figure 4 presents the test findings for samples N0, N1, N2, N3, and N4. Since the N0, without NS, has the lowest flexural strength, adding NS significantly increases the concrete's ability to withstand bending pressures. At 6.34 N/mm^2, N2, which has 2% NS, has the maximum flexural strength and is 12.61% better than N0. The observed increase may be ascribed to NS's capacity to improve particle packing, optimize the microstructure of concrete, and promote the production of calcium silicate hydrate (C-S-H), all of which strengthen the binding within the matrix. Mixes N3 and N4 exhibit enhanced performance compared to N0; however, their flexural strength values are marginally lower than those of N2. This suggests that elevated concentrations of NS may lead to particle aggregation or enhanced brittleness, which could impede efficient stress transfer within the matrix [43]. The findings suggest that a 2% NS dosage and 1% SF in bacterial concrete are optimal for maximizing flexural strength, achieving an effective balance between strength and durability. This highlights the importance of optimizing mix designs to attain enhanced performance in concrete applications.

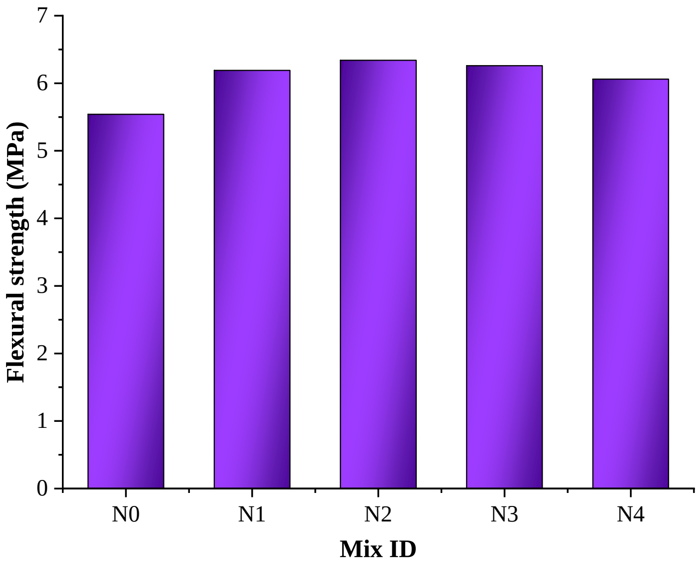

Fig. 4. Flexural strength

4.4. Impact Strength Test

A comparison between the initial and terminal fracture loads for mixes N0, N1, N2, N3, and N4 as determined by impact strength tests is shown in Figure 5. The assessment measured the number of jolts required to achieve the final fracture and to create the first visible crack, and the findings were recorded for every combination. For N0, N1, N2, N3, and N4, the corresponding first crack jolts were 16, 19, 25, 20, and 18. Crack values were 20, 24, 29, 23, and 19 at the end. Findings reveal that using NS instead of cement greatly increases concrete's impact strength, with N2 doing the best. The fact that N2 was found to increase both initial and ultimate fracture loads suggests that NS helps to densify the matrix and improves its resistance to crack propagation. The incorporation of SF in bacterial concrete enhances impact strength. The incorporation of extended, continuous fibres improves the cohesion of concrete, allowing it to endure greater impact loads prior to cracking. The incorporation of fibre reinforcing enhances the material's toughness and ductility [44]. The findings demonstrate that N1, N3, and N4 outperform N0, with N2 showing the most substantial enhancement. This indicates that the integration of 2% NS, SF, and bacterial activity produces the most effective synergy for improving impact resistance in concrete.

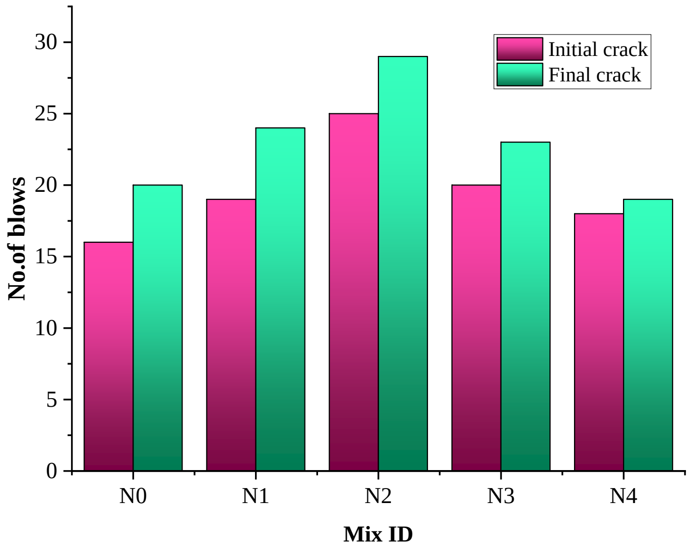

Fig. 5. Impact strength

4.5. Bond Strength Test

In Figure 6, the bond strengths of concrete mixes N0, N1, N2, N3, and N4 are shown. Concrete bond strength was measured using cubes of 150 x 150 x 150 mm^3, to which High Yield Strength Deformed (HYSD) bars were inserted during pouring. Because steel bar adhesion to the concrete matrix is crucial to maintaining structural integrity and facilitating effective load transfer in reinforced concrete, it is investigated in this study. 1.98, 2.0, 2.5, 2.3, and 2.19 N/mm^2 were the reported bond strength values for mixes N0, N1, N2, N3, and N4, respectively.

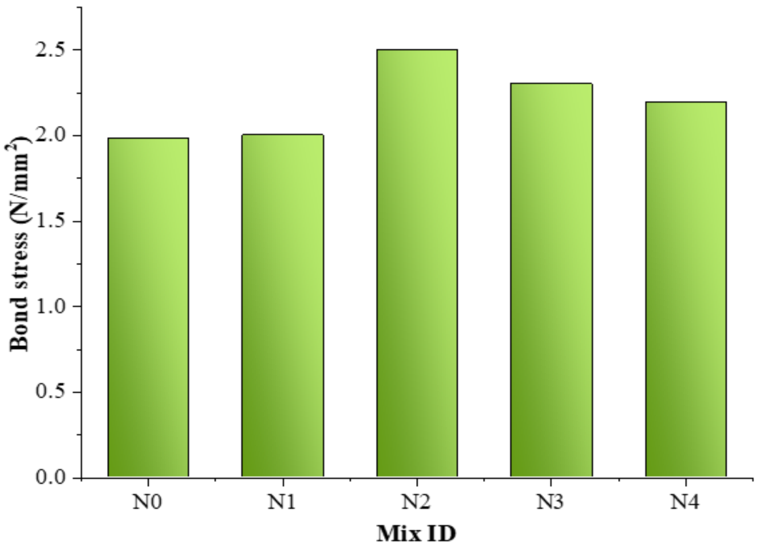

Fig. 6. Bond strength

The lowest bond strength, 1.98 N/mm^2, was shown by the control mix (N0), which was used as a benchmark. Thanks to the bacterial concrete formulation's optimal inclusion of N2 and 1% SF, mix

N2 obtained the greatest bond strength of 2.5 N/mm^2. By filling voids and increasing matrix density, NS improves the microstructure of the concrete and is primarily responsible for the notable increase in bond strength. The use of SF enhances the mechanical interlock between concrete and steel reinforcement because of its ability to bridge cracks. Bacterial agents strengthen the connection between steel bars by forming calcium carbonate deposits around them. In comparison to N0, mixes N3 and N4 demonstrated enhanced binding strength; nonetheless, their values were somewhat less than those of N2. Accordingly, 2% NS and 1% SF seem to provide the best results, while greater doses may cause problems such agglomeration or poor particle dispersion. Based on the results, N2 is the best combination for reinforcing concrete buildings because the combined impacts of NS, SF, and bacterial activity greatly increase the bond strength.

4.6. Scanning Electron Microscope (SEM) with Energy dispersive X-ray spectroscopy (EDS)

The 28-day crushed strength specimen yielded the optimal concrete mix (N2) SEM picture, which is shown in Figure 7. The photograph obtained from the Scanning Electron Microscope (SEM) using electron backscattering shows the concrete sample's microstructure, highlighting its surface shape and hydrated grains. The optimal concrete formulation includes calcium hydroxide, also called portlandite (CH), which is essential to the hydration process, as well as calcium silicate hydrate (C-S-H) particles, which increase strength. Picture 7. (a) shows circular slices at a 200 µm scale, showing the presence of calcium carbonate ($CaCO_3$) precipitation linked to CH and the ideal mix (N2). Furthermore, the optimized mixture displays monosulfo aluminate phases that resemble prismatic needles. At a 20 µm scale, Figure 7(b) shows the ideal composition, highlighting durability and strength. Due to the consumption of CH, the N2 mix displays a fibrous structure of secondary C-S-H. When portlandite is combined with amorphous NS, a secondary C-S-H gel is created [40]. C-S-H gel, CH, and many aluminate and ferrite phases work in concert to raise the density of the cement matrix, which is reflected in the presence of hydrated grains. The addition of a 2% NS matrix to concrete enhances its strength and durability due to its uniform shape.

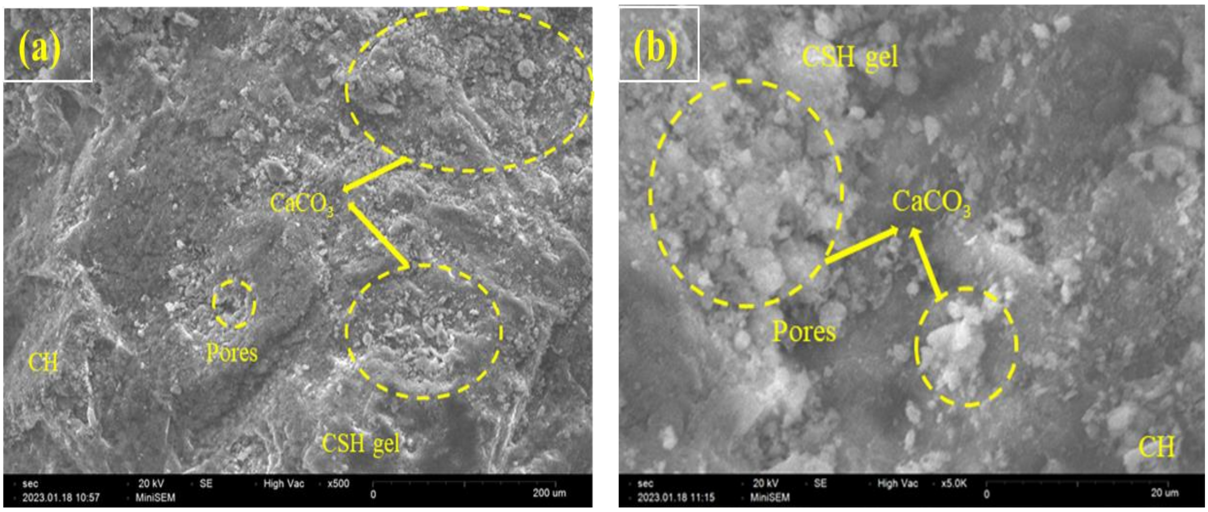

Fig. 7. SEM image of the optimized mix (N2) (a) under 200 µm and (b) under 20 µm

Energy Dispersive X-ray spectroscopy (EDS) is utilized to analyze the structure and composition of magnetic nanoparticles and immobilized enzymes. Figure 8 illustrates the EDS of the optimized mix (N2). EDS testing was conducted on the optimized mixture (N2) to identify the peaks of chemical elements present in the sample and to verify the formation of calcite. The primary elemental components present in concrete mixes include Calcium (Ca), Oxygen (O), Carbon (C), and Silicon dioxide (Si). The EDS results demonstrate that the precipitate is composed of C, Ca, and O atoms, thus confirming its identification as calcium carbonate. The peaks of Silicon (Si) and Oxygen (O) signify the presence of NS in the concrete. The results demonstrate that the optimized mix (N2) displayed calcium peaks, with more significant peaks noted after the incorporation of bacterial spores, which additionally augmented the levels of NS and SF in conjunction with increased bacterial content. The incorporation of 2% NS and 1% SF into bacterial concrete resulted in elevated concentrations of Oxygen (O), Calcium (Ca), and Carbon (C).

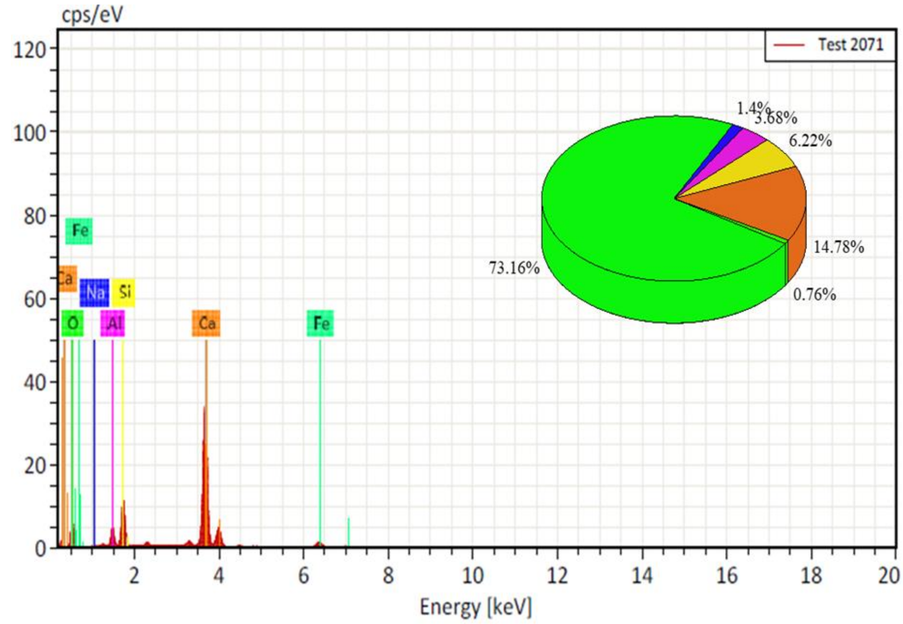

Fig. 8. Element's verification of the optimized mix (N2)

5. Conclusion

This investigation thoroughly examined the effects of Nano Silica (NS) and Steel Fiber (SF) reinforcement in bacterial concrete, emphasizing improvements in mechanical strength and microstructural characteristics. The results highlight the critical contribution of NS to enhancing the structural performance of concrete.

- The addition of NS improved the load-bearing capability by increasing the compressive strength by 14.17% as compared to the control mix.
- Moreover, the bacterial concrete enhanced with NS and SF demonstrated 8.69% enhanced splitting tensile strength, reflecting a higher resistance to tensile stresses.
- The flexural strength of the N2 mix (which included NS) was 12% higher than that of N0, suggesting better performance in bending situations. In order to strengthen the adhesion between the cementitious matrix and aggregates, the combination of NS and SF greatly increased impact and bond strength.
- Compressive, tensile, flexural, impact, and bond strength were significantly improved after a 28-day curing period using the optimal formulation, which included 2% NS, 1% SF, and 10% bacterial solution.
- By confirming the formation of calcium silicate hydrate (C-S-H) gel and a notable increase in calcium carbonate ($CaCO_3$) in NS and SF-modified concrete, the SEM investigation helped to plug cracks and improve the overall densification of the concrete matrix.
- The presence of calcium (Ca), oxygen (O), and carbon (C) in the optimum mix (N2) suggests the creation of calcium carbonate ($CaCO_3$). Concrete containing nanosilica (NS) was verified by the detection of silicon (Si) and oxygen (O). The composition and microstructural integrity of the concrete were improved by the addition of 2% NS and 1% SF, which led to higher levels of Ca, O, and C.
- NS's incorporation greatly increased mechanical strength while also improving sustainability and cost-effectiveness by lowering the carbon footprint associated with the manufacture of concrete.

The combination of NS and SF in bacterial concrete offers a practical and effective method for enhancing mechanical properties and durability, highlighting its promise for high-performance and sustainable construction materials.

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