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Research Article

Investigation of Mechanical Strength Recovery and Self-Healing Efficiency of Bio-Mineralized Sustainable Concrete

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Abstract – The current research investigates the self-healing capability of concrete containing steel slag aggregates (SS) by incorporating bacteria into fine aggregates and SS. Using vacuum impregnation, vegetative cells of the Bacillus subtilis bacterium are introduced to enhance the efficiency of the concrete healing mechanism. Concrete specimens are subjected to cracking up to 85% of their strength, followed by evaluations of crack healing widths and strength recovery over different curing periods. The findings of this study revealed that SS serves as an effective medium for bacterial growth, achieving crack healing widths of 0.65 mm and a 74.2% recovery in the strength index. Bacteria immobilized by combining 50% fine aggregates with SS demonstrated optimal healing efficiency, showing a crack width of 1.023 mm at early pre-crack stages and 0.56 mm at later stages. The direct use and combined integration of 50% fine aggregates with SS resulted in compressive strength improvements of 4.3% and 7.8%, respectively. The mix containing 50% fine aggregates and SS exhibited the highest split-tensile strength, with a 41.67% increase compared to the control mix.

Keywords – Steel Slag Aggregate, Sustainability, Autonomous Healing, Bacillus Subtilis, Compressive Strength.

I. INTRODUCTION

In recent years, there has been significant interest in incorporating self-healing technologies into concrete. Numerous studies have demonstrated the effectiveness of integrating microcapsules and bacteria to enhance concrete's durability and serviceability. However, implementing these healing agents on a large scale for practical use poses challenges due to their high demand. This underscores the importance of identifying sustainable, eco-friendly materials that require minimal quantities of such agents while maintaining environmental balance. Concrete is widely favored as a construction material due to its excellent compressive strength, notable fire resistance, and cost-effectiveness [1, 2]. Nonetheless, its low tensile strength makes it prone to cracking under stresses significantly lower than its design capacity [3]. These cracks expose the concrete matrix to potentially harmful agents [4], leading to the corrosion of embedded steel reinforcements, which diminishes the structural strength and longevity of concrete [5-7]. Therefore, addressing these cracks is crucial to prolong the service life of concrete structures.

Several artificial repair techniques have been developed [8-15], but these methods are generally limited to addressing macro-cracks [16]. This limitation has led to the development of self-healing solutions to

repair cracks within the concrete matrix. Self-healing mechanisms are classified into autogenous and autonomous systems [17]. Autogenous healing, commonly used in traditional concrete, relies on physical, mechanical, and chemical processes to mend small cracks [18-21]. To accelerate the healing process, healing agents can be incorporated during the mixing phase of concrete production [13, 22, 23].

In bacterium-based self-healing systems, bacteria and their organic precursors act as healing agents, inducing the precipitation of calcium carbonate [24]. However, protecting the bacteria from the harsh concrete environment, characterized by high alkalinity and mechanical pressure during matrix hydration, is critical [5]. Immobilization techniques are used to safeguard the bacteria during mixing and hydration by embedding them in carriers. For instance, Wiktor and Jonkers [19] used expanded clay to encapsulate bacteria, enhancing crack healing and bacterial survival. Similarly, Khaliq and Ehsan [5] employed lightweight aggregate and Graphite Nanoplatelets (GNPs) as carriers for Bacillus subtilis spores in self-healing concrete. They found that lightweight aggregate enhanced the healing potential by providing greater protection for bacterial spores. Zhang et al. [7] reported a crack healing width of 0.79 mm after 28 days when Bacillus cohnii was immobilized in expanded perlite.

Research suggests that porous macro-carriers like lightweight aggregates and expanded perlite (EP) are effective in prolonging bacterial survival in alkaline cementitious environments. Khaliq and Ehsan [5] compared the effectiveness of GNPs and lightweight aggregates as bacterial carriers, concluding that lightweight aggregates were superior due to their porous structure. This porosity not only shields bacterial spores but also serves as a reservoir for bacterial cells, protecting them from the aggressive concrete environment.

A review of the literature reveals a lack of studies investigating the mechanical properties and self-healing potential of steel slag (SS) aggregates in concrete using bio-mineralization. The present research aims to evaluate the self-healing efficiency of SS when healing agents are incorporated into aggregates during sustainable concrete production. It also seeks to clarify the healing mechanisms in SS concrete. The study examines the strength recovery, crack-healing width, and internal structural behavior of bacteria-infused SS concrete. By employing vacuum impregnation, vegetative cells of Bacillus subtilis are introduced to enhance the self-healing capabilities of the concrete.

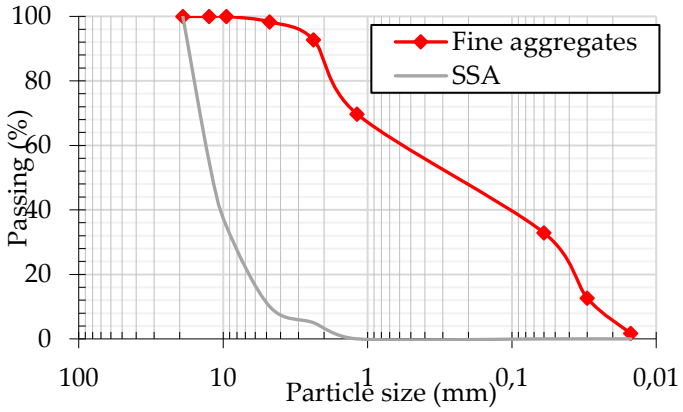
II. EXPERIMENTAL PROGRAM

i. Materials

In this experimental study, Portland cement (grade 43, type-I) with a specific gravity of 3.15 was utilized, conforming to the requirements of ASTM C150 [25]. The initial and final setting times of the cement paste determined according to ASTM C191 [26], were measured as 113 minutes and 177 minutes, respectively. Locally sourced Lawrencepure sand was used as the fine aggregate, exhibiting a fineness modulus of 2.4. The absorption capacity and specific gravity of the fine aggregate in a saturated surface dry condition were 1.5% and 2.9%, respectively.

The primary components of steel slag, including calcium ferrite and calcium silicate, contribute to its potential cementitious and hydraulic properties upon carbonation. Steel slag was therefore employed for aggregate production. When carbonated steel slag fractures, the internal clinker minerals can interact with water to activate self-healing properties. The steel slag particles feature an angular shape, sharp edges, and a porous texture, as shown in Figure 1(a). The particle size distribution of the steel slag is illustrated in Figure 1(b), with a fineness modulus of 6.60 and a specific gravity of 3.65. Before using steel slag as coarse aggregate in concrete production, its mechanical properties were assessed. Various mechanical tests were performed on the steel slag, and the results are summarized in Table 1, in compliance with KS F 2527 [27].

(a)



(b)

Figure 1. Steel slag aggregates (a) image (b) granulometric analysis

Table 1. Physical features of the SS

Type	Specification Value	Testing results	Standard	Standard deviation
Density	3.1 g/cm^3 and above	3.63	KS F 2527 [27]	± 0.03 g/cm^3
Absorption ratio	< 2	2.04%	KS F 2527 [27]	±0.01%
Unit weight volume	1.6 g/cm^3 and above	2.19	KS F 2527 [27]	± 0.01 g/cm^3
Immersion expansion	< 2	0.08%	JIS A 5015 [28]	±0.01%

To employ steel slag as a coarse aggregate in concrete production, expansion testing is essential. The immersion expansion ratio of steel slag must remain below 2% to meet the required standards [28]. Using a direct method, the immersion expansion ratio of steel slag was assessed in accordance with JIS A 5015 [28]. This standard specifies that steel slag is immersed in water at 80 °C for 6 hours, followed by a gradual reduction of the chamber temperature to 20 °C over 18 hours or more. This cycle is repeated for 10 days, after which the volume of the steel slag is measured using a calibrated device with a resolution of 0.01. The immersion expansion is calculated as the average value obtained after performing the procedure multiple times.

Based on the test results, the unit weight, density, and immersion expansion of steel slag satisfied the standard requirements. However, the absorption ratio exceeded the limits defined by KS F 2527 [27] due to the aggregates' porous surface. Despite this deviation, the difference between the standard and measured values was negligible. XRF analysis was conducted to determine the chemical composition of both the cement and steel slag, as detailed in Table 2. The steel slag was found to be abundant in CaO, SiO2, and Fe2O3.

Table 2. Chemical configuration of cement and SS (all values are in percentage)

Material	SiO_2	CaO	MgO	Fe_2O_3	Na_2O	Al_2O_3	SO_3	P_2O_5	MnO	R_2O	MnO	LOI
Cement	25.82	52.65	2.41	3.35	0.35	10.74	2.3	0.22	-	0.64	-	1.52
Steel slag	15.15	47.21	6.74	13.91	-	7.19	-	1.63	2.54	-	2.39	3.24

ii. Fabrication and Testing of Specimens

BS was chosen for this study because of its ability to form endospores under alkaline conditions [29]. Research on the capacity of B. subtilis to precipitate calcium carbonate has shown its potential as an agent for healing cracks and pores in cement-based composites [30]. B. subtilis was cultivated in a liquid medium containing yeast extract (2.0 g/l), lablemco powder (1.0 g/l), sodium chloride (5.0 g/l), peptone (5.0 g/l), and was autoclaved for 20 minutes at 121°C. The liquid medium was then introduced into a laminar flow hood and incubated for 48 hours at 37°C under static conditions. The growth of bacterial cells within the medium was monitored using the same liquid media as a reference. The absorbance at 600 nm (OD600) was measured using a handheld spectrophotometer, HACH DR 2400, and correlated to cell concentration through the Ramachandran equation Y = 8.59 x 107X1.3627 [31], where X represents the optical density at 0.6 µm, and Y represents the microbial concentration per milliliter. Measurements were taken

periodically until the desired concentration was reached. This method ensured the cell concentration was maintained around 1.9 x 107 cells/cm³ of concrete.

To incorporate the bacterial culture into the concrete, the described procedure was followed. In conventional methods, aggregates are fully immersed in the bacterial solution for 24 hours [5], but the absorption rate achieved here was below the desired level. Consequently, the bacterial culture was introduced to the aggregates under vacuum conditions in this study. SS was placed in a vacuum desiccator, where it was degassed to create a vacuum. The bacterial suspension was then introduced into the desiccators from a reservoir above the vacuum level. Bacteria adhered to the SS via absorption and adsorption. Bacteria were absorbed into the porous media of the aggregates [32] and adsorbed onto the solid particles [33]. The SS was allowed to draw in the microbial suspension under vacuum conditions, increasing the absorption capacity from 8% to 11%. To confirm the presence of bacterial cells in the SS, the impregnated aggregate was examined under an optical microscope. For fine aggregates, bacterial cells were impregnated by spraying the microbial culture onto the surface of the dried particles using a pressure nozzle. Simultaneously spraying and rotating the sand particles ensured consistent absorption.

Four distinct mix designs were created and evaluated in this research. SS-BIO-CON-1 served as the control sample with a compressive strength of 27 MPa after 28 days. To achieve the desired compressive strength, several mix trials were conducted. The reference mix (SS-BIO-CON-1) did not contain bacterial cells, while SS-BIO-CON-2 included bacterial cells. In SS-BIO-CON-3, bacteria were immobilized using SS as a carrier medium. For SS-BIO-CON-4, bacteria were incorporated via SS along with 50% fine aggregates (soaked in bacterial suspension), which enhanced the microbial presence at the microstructural level to improve healing. The water-to-cement ratio was kept constant across all mixes. To ensure the necessary workability, an ASTM C494 [34] Type G high-range water-reducing agent was added to the mixture at a rate of up to 1% by weight of cement. Additionally, calcium lactate was used as an organic precursor for bacterial cells at a dosage of 2.5% by weight of cement.

In total, 108 samples, consisting of 27 samples from each mix, were cast for this experimental study. Cylindrical molds with diameters of 100 mm and heights of 200 mm were used for casting. After 24 hours, the samples were demolded and placed in water for curing until the testing age was reached, with the curing water maintained at a constant temperature of 20°C. The experimental program was divided into two phases: the first focused on evaluating fracture healing effectiveness, and the second phase assessed the mechanical properties of the various mixes.

III. DISCUSSION OF RESULTS

i. Recovery of Strength

In samples with pre-existing cracks, the evaluation of the restoration of mechanical properties serves as an indirect method to assess the self-healing capabilities of cement-based materials. Xu and Yao [35] and Wang et al. [22] previously utilized three-point bending tests to measure the recovery of mechanical properties before and after the healing of cracks, while Ref. [36] applied a uniaxial compression test. Similarly, the specimens were pre-cracked until their strength was reduced by 85%, and then they were reassessed after 3, 7, and 28 days. The cracks that appeared on the sample surfaces were smaller compared to those observed in the earlier stage. The pre-cracked specimens were subsequently immersed in water again until they reached the 28-day healing period [29]. Following this, the samples were re-tested under compression to determine the extent of recovery. The compressive strengths for all the tested mix designs are presented in Figure 2. The healing performance was quantified by calculating the percentage of compressive strength recovered, and the recovered compressive strength index (RCSI) was defined using Eq. (1).

$$\text{RCSI}\ (\%) = \left[1 - \frac{C_{max,28} - C_{RC}}{C_{max,28}} \times 100\right] \quad (1)$$

Where C_(max,28) indicates the maximum compressive strength at 28 days and C_RC describes the recovered compressive strength after 28 days of curing.

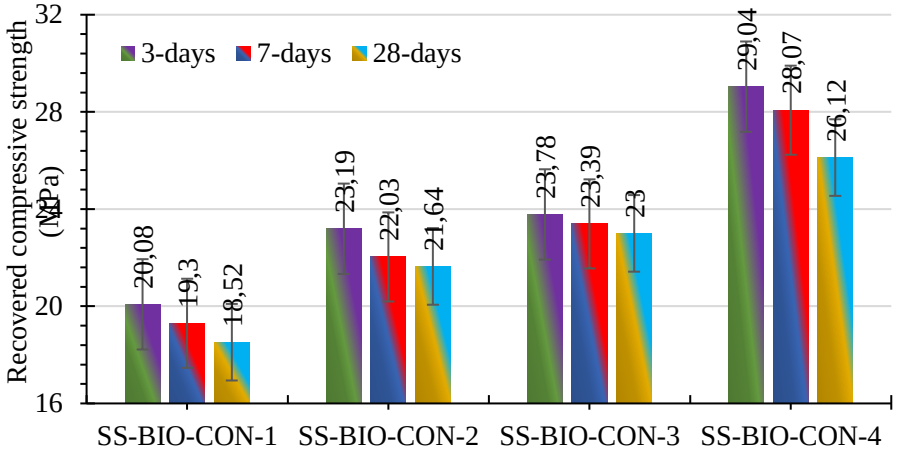


Figure 2. Recovered compressive strength against time at different pre-cracking days

Figure 3 illustrates the strength recovery percentages after 3, 7, and 28 days for the four pre-cracked mixtures. The experimental results show a decline in strength as the pre-cracking age increases. This reduction can be attributed to the gradual decrease in bacterial activity caused by the enhanced density and alkaline conditions in the matrix, resulting from the hydration of the remaining cement [37]. The highest strength recovery was observed in samples with a pre-cracking period of three days, followed by seven and twenty-eight days.

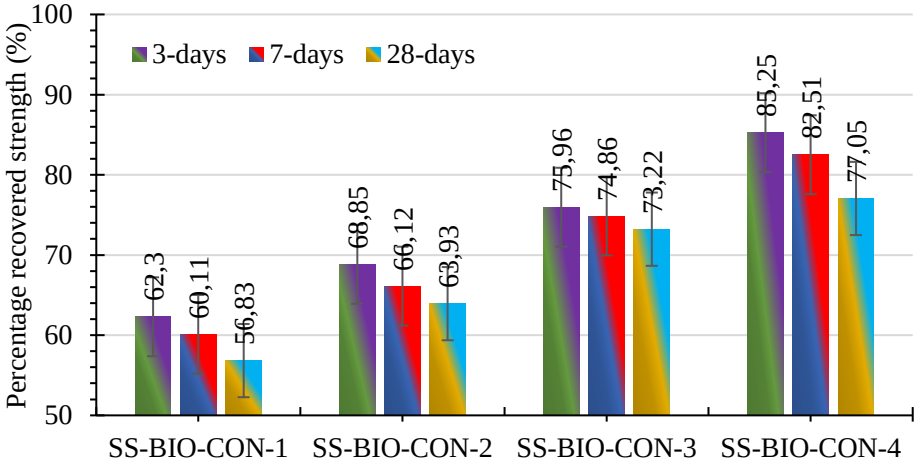


Figure 3. Percent recovery of compressive strength against time at different pre-cracking days

The reference formulation (SS-BIO-CON-1) exhibited the lowest strength recovery among all the mixtures, regaining up to 62.30% of its strength, which declined to 56.83% as the pre-cracking period extended from three to twenty-eight days. The self-healing ability of cementitious materials is responsible for the strength recovery observed in the reference sample, though this process does not produce sufficient precipitates to fully repair cracks created during the pre-cracking phase. SS-BIO-CON-2 achieved a compressive strength recovery of 68.85% after three days of pre-cracking, which then decreased to 63.93% after twenty-eight days. In contrast, SS-BIO-CON-3 recovered 75.96% of its compressive strength after three days of pre-cracking and 73.22% after twenty-eight days. However, SS-BIO-CON-3 demonstrated inconsistent crack healing due to the uneven distribution of microbial cells across the material, leading to relatively poorer compressive strength recovery. The highest strength recovery was seen in SS-BIO-CON-

4, which reached up to 85.25% recovery after three days of pre-cracking, dropping to 82.51% and 77.05% at pre-cracking ages of seven and twenty-eight days, respectively. This outcome is attributed to the uniform distribution of microbial cells during pre-cracking, enabling the healing of most of the micro-cracks that formed.

ii. Crack Healing Study

The crack healing effectiveness resulting from the bacteria's production of calcite precipitates in the cracked regions after 28 days is shown in Figure 4. The samples containing restrained B. subtilis exhibited nearly consistent fracture healing with a significant increase in calcite precipitation. The reference mix displayed minimal healing, likely due to the autogenous healing property of concrete [38]. The healed crack widths, examined using an optical microscope three, seven, and 28 days after pre-cracking, are illustrated in Figures 5a, 5b, and 5c. The largest crack width of 1.023 mm was successfully recovered by using SS and 50% fine aggregates as carriers for B. subtilis.

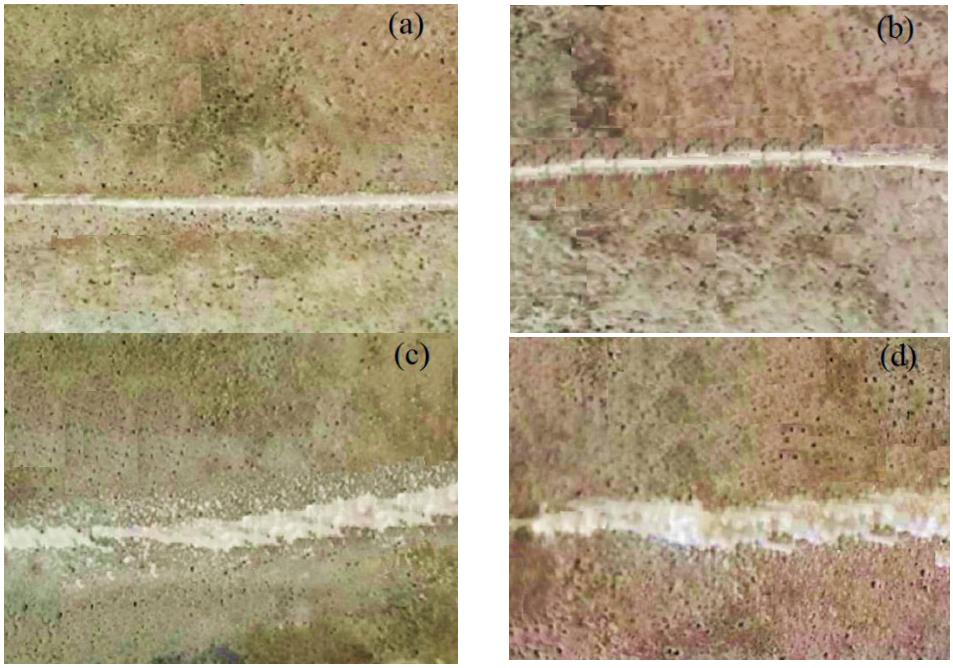


Figure 4. Crack healing in different mixes (a) SS-BIO-CON-1, (b) SS-BIO-CON-2, (c) SS-BIO-CON-3, and (d) SS-BIO-CON-4

Figure 5a presents the maximum recovered crack widths for pre-cracked mixtures after curing durations of 3, 7, and 28 days. As mentioned earlier, incorporating a bio-healing chemical into the concrete has significantly enhanced its self-healing capabilities. SS-BIO-CON-1 exhibited a crack healing width of just 0.098 mm, attributed to autogenous healing. SS-BIO-CON-2 and SS-BIO-CON-3 displayed crack healing widths of 0.563 mm and 0.470 mm, respectively, where bacterial cells were introduced directly and confined by SS. In contrast, SS-BIO-CON-4 demonstrated a more effective fracture healing, reaching a width of 1.023 mm. The combination of microbial cells and SS, along with 50% fine aggregates as a carrier medium, led to faster recovery compared to previous immobilization techniques. The enhanced healing rate of SS-BIO-CON-4 can be attributed to the small size of fine aggregate particles, as shown in previous research using GNPs as a transport medium [5]. The fine aggregate carrier ensures the even distribution of microbial cells within the concrete structure, which promotes the precipitation of healing agents and ensures their presence at every micro-crack. SS-BIO-CON-3 exhibited less healing than SS-BIO-CON-2 and SS-BIO-CON-4. This could be due to the faster bacterial cell growth in SS-BIO-CON-2 and SS-BIO-CON-4

at early ages, leading to more effective crack repair. Moreover, the uniform distribution of microbial cells across the pre-cracked samples contributes to the healing of larger cracks. The larger size of the transport medium, SS, in SS-BIO-CON-3 restricted the presence of healing compounds at the fracture sites, reducing its healing effectiveness. The lack of a healing agent at the crack sites hinders the transport of sealing compounds, thus limiting the healing process. Less fracture healing in reference samples may be due to the formation of calcium carbonate through the carbonation of Ca(OH)2 near the damaged areas or from the hydration of unhydrated cement in the cracks [36]. Traditional concrete crack healing has also been associated with secondary hydration of unhydrated cement and the obstruction of cracks by loose particles [40].

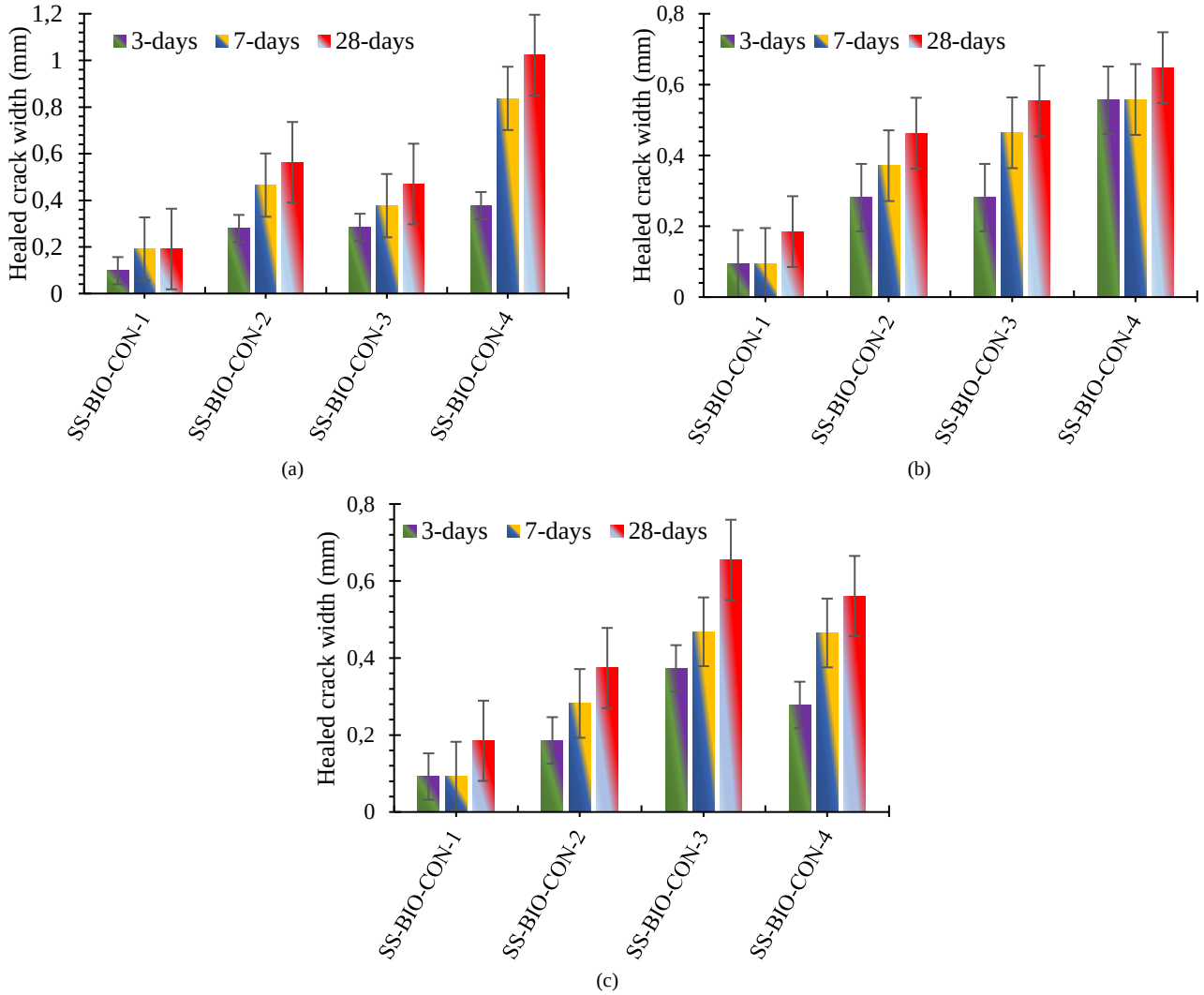


Figure 5. Crack healing widths for the samples pre-cracked at (a) 3-days (b) 7-days (c) 28-days

Figure 5b illustrates the crack healing behavior of pre-cracked samples after a 7-day curing period. Compared to pre-cracked specimens, SS-BIO-CON-2 and SS-BIO-CON-4 exhibited a reduction in self-healing capacity at three days. This reduction in healing ability is attributed to the smaller pore sizes within the concrete structure, which hindered the bacterial spores' movement, both directly and via fine aggregates and filler materials. Similar findings have been reported in previous studies [5]. The superior crack healing potential of SS-BIO-CON-3 is linked to the absorption of bacterial cells into SS, providing effective protection to the microbial cells, thereby improving the concrete mix's density. Figure 5c presents the crack healing widths for pre-cracked samples after 28 days. In comparison to the results from 7-day pre-cracked

samples, SS-BIO-CON-2 and SS-BIO-CON-4 showed a significant decrease in self-healing potential. This further supports the theory, as described in Ref. [5], that the compact microstructure applies forces along various axes, breaking microbial cells and reducing their presence over time. The crack width recovery in SS-BIO-CON-3 increased with the duration of pre-cracking, indicating that its hardened porous matrix offers a refuge for the confined B. subtilis, leading to prolonged bio-mineralization. The healing performance was found to be more effective during the first three days of pre-cracking compared to the later periods of seven and twenty-eight days. This is likely due to the early activation of healing agents near the crack, which prevents their rapid movement away from the fracture. In the bio-restrained formulations, all surface cracks ranging from 0.374 mm to 0.655 mm were effectively repaired. However, the healing efficiency decreased for cracks wider than 0.655 mm, which could be attributed to the depletion of healing agents caused by fluid penetration into the crack area [41].

IV. CONCLUSION

This study aimed to evaluate the effectiveness of bio-mineralization in enhancing the self-healing rate and mechanical performance recovery of concrete containing steel slag aggregates (SS), as assessed through compressive strength testing. The key conclusions from this research are as follows:

1. The inclusion of SS in concrete was found to be an effective medium for fostering bacteria responsible for the self-healing of cracks up to 0.65 mm in width, resulting in a 74.2% recovery in strength. In contrast, direct bacterial incorporation led to a temporary crack healing process for cracks up to 0.56 mm, with a strength recovery of 66.3%.
2. The immobilization of bacteria by incorporating 50% fine aggregates and SS into the concrete mix resulted in the most efficient healing process, with crack widths of 1.023 mm at the initial stages and 0.56 mm at later stages following pre-cracking.
3. A 4.2% reduction in compressive strength was observed when SS was pre-soaked in a bacterial solution. However, direct bacterial incorporation and the combination of 50% fine aggregates with SS resulted in compressive strength improvements of 4.3% and 7.8%, respectively.

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