

Article

Properties of Bacterial Copper Slag Concrete

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Abstract: Copper ore processing generates a large amount of copper slag, which has properties that are similar to fine aggregate. Copper slag has a promising future in the construction industry as an alternative to fine aggregate. Up to 50% of fine aggregate substitutions have been successful. The performance of copper slag concrete could be improved by microbiologically induced calcium carbonate precipitation. The impact of micro-organisms on the mechanical properties and flexural behaviour of copper slag concrete was investigated in this study. Five concrete mixtures were created by replacing varying amounts of fine aggregate with copper slag, ranging from 0% to 100%. M30 grade concrete was used, and 1% to 2% of the bacterium *Bacillus subtilis* by weight of cement was added during the concrete casting procedure. Specimens of different shapes, such as cubes, cylinders, and prisms, were cast and examined at 7, 14, and 28 days. When treated with micro-organisms, the test results revealed that replacing 50% to 75% of the sand with copper slag produced concrete with superior mechanical properties and a greater density. With the optimal ratio of copper slag to micro-organisms, a suitable RCC beam was formed. Load–deflection patterns of bacterial copper slag concrete were used to investigate beam flexural behaviour, and the results were compared using ABAQUS modelling. Microbiologically induced calcium carbonate precipitation can alter regular copper slag concrete, resulting in enhanced concrete performance.

Keywords: copper slag; *B. subtilis*; calcium carbonate precipitation; mechanical properties; flexural behaviour; ABAQUS software



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1. Introduction

Copper slag, which is a by-product of the copper smelting process, has a promising future in the construction industry. Copper slag is a viable source of fine aggregate due to its superior mechanical and physical properties. Due to its smooth, glassy surface and low moisture absorption, the fresh concrete properties of copper slag concrete, such as workability, improve as the copper slag content rises [1–5]. When the sand in conventional concrete is replaced with up to 50% copper slag, the concrete is found to have excellent mechanical properties [3–8].

The rate of strength growth is accelerated when copper slag is used to replace 1.5% of hydrated lime by weight of cement [9]. Copper slag combined with ferrous slag produces the greatest compressive strength in comparison to the control mix [10].

In the rebound hammer test, the pulse wave velocity is greater for the 40% fine aggregate replacement, and the compressive strength is exceptional for the 40% fine aggregate substitution with copper slag. The addition of copper slag has no effect on the concrete's stress–strain behaviour [11]. When utilised as a fine aggregate in concrete mixtures, copper slag performs similarly to river sand [12–14]. The primary disadvantage of concrete is its low tensile strength, which results in microcracks that lead to corrosion and the collapse of porous structures. Microbiologically induced calcium carbonate (CaCO_3) precipitation, also known as the MICP method, is the most recent technique developed that can be used to prevent the cracking of concrete [15–21].

When spore-forming bacteria are injected into concrete as part of the bioconcrete strategy for enhancing concrete performance, calcite precipitation occurs. The precursor

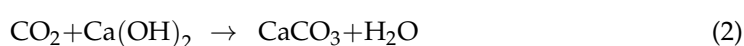
component is activated by the environmental moisture passing through the fracture. The active precursor chemical induces bacteria to produce calcium carbonate crystals. *Bacillus subtilis* bacteria increase the hydrated structure of cement mortar, allowing it to be used safely to enhance the performance of concrete [22–24]. Bioability concrete fills cracks depending on the proportion of micro-organisms present. The increase in compressive strength is proportional to the concentration [25]. In order to achieve a high compressive strength in lightweight aggregate concrete, bacteria may also be utilised [26]. Copper slag concrete's compressive strength and workability can be enhanced by a bacterial admixture [27]. Creating bacterial strains and testing their compatibility with green concrete is an intriguing concept that may change the future of construction technology [28]. Based on a survey of copper slag properties, they are in line with those of fine aggregate and their intrusion in concrete proves to be fruitful when substituted for fine aggregate up to 50%. The technique called microbiologically induced calcium carbonate precipitation is successful with respect to conventional concrete. Copper slag concrete properties can be improved when the concrete is treated with micro-organisms. This research aimed to evaluate the compressive and flexural strength of fractured specimens replaced with micro-organism-remediated copper slag and to compare copper slag to natural fine aggregate in terms of their characteristics. The bacterial action was tested on copper slag concrete, which was the identified research gap in the field, and the novelty of the work was shown.

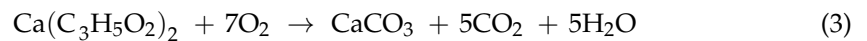
1.1. *Bacillus Subtilis*

Bacillus pasteurii, *Bacillus sphaericus*, *Escherichia coli*, *Bacillus subtilis*, *Bacillus cohnii*, *Bacillus halodurans*, and *Bacillus pseudofirmus* are bacteria that thrive in alkaline environments such as concrete. This study employed the rod-shaped bacterium *Bacillus subtilis*. The outer cell membranes of *B. subtilis* are sufficiently thick to keep the organism alive under unfavourable conditions. The soil-isolated strain of *B. subtilis* possesses extremely high urease activity, in addition to undergoing the constant precipitation of solid, insoluble calcium carbonate crystals and having excellent physical stability. As long as the process of moisture from the atmosphere penetrating the cracks continues, bacteria can inhabit the concrete. The lower the water infiltration, the lower the pH of the concrete, and thus the activation of bacterial life. Calcium lactate is combined with bacteria to produce a nutritional broth that promotes the formation of calcite crystals. According to researchers, neither the initial nor final setting time of concrete will be affected by biomineralisation. During the biomineralisation process, organic compounds are frequently converted into inorganic crystals, which are then utilised to heal fissures [29]. Moisture and nutrient deficiencies in cement can shorten the lifespan of bacteria. *B. subtilis*, on the other hand, regulates hydration processes and can be used to extend the life of structures [30].

1.2. Microbiologically Induced Calcium Carbonate Precipitation

Microbial-induced carbonate precipitation (MICP) via a ureolytic route is a novel technique used in numerous applications because it overcomes significant technical obstacles. Multiple studies have demonstrated that MICP improves the mechanical properties of weak, permeable materials. As shown in Equations (1)–(3), MICP depicts the mechanism by which the metabolites of urease-producing bacteria react with substances in the surrounding atmosphere to form calcium carbonate crystals (CaCO_3) [9]. In the early stages, water seeps through fractures and a limited amount of CO_2 causes calcium carbonate to form. As a result, the formation of limestone effectively seals the interior of the structure by filling the crevices that have formed. MICP is effective for fracture and fissure closures up to 0.5 mm [15]. The microbiological precipitation of calcite crystals is influenced by the concentration of dissolved carbon in the form of locally accessible nutrients, the pH of the surrounding environment, and the calcium ions present in the matrix of the concrete [30].





2. Experimental Program

2.1. Materials

In this study, 53 grade ordinary Portland cement conforming to IS 12269 (1987) [31] was used. The coarse aggregate was manufactured using natural materials and crushed rock. The utilised coarse aggregate conformed to IS 383 (2016) [32]. In this study, 20 mm crushed angular aggregates were utilised. As a fine aggregate, locally accessible river sand from grading zone II of IS 383 (2016) [32] was used. The water is drinkable and of high quality. Copper slag, a by-product of the copper ore smelting process, possesses chemical properties comparable to those of river sand. This study utilised copper slags ranging in size from 0.3 mm to 4.0 mm. Copper slag was imported from Tuticorin, Tamil Nadu, and Sterlite Industries (India) Limited was the importer (SIIL). *Bacillus subtilis*, a bacterium grown in the laboratory, was used to enhance the mechanical properties of copper slag concrete. The proportion of *Bacillus subtilis* adopted in the research was 1% and 2% as compared with 0% bacteria (the controlled concrete). The normal percentage of the admixture used in concrete was 1% to 1.2% by weight of the cement.

Tables 1–3 show the results of the preliminary tests conducted to assess the qualities of the concrete materials. The fundamental qualities of the materials were examined to ensure that they complied with the Indian standard code. Copper slag has a granular consistency and is composed of crystalline particles. Copper has a dark hue and grain size comparable to river sand. Approximately 0.13% of the water that comes into contact with copper slag is absorbed. It has been demonstrated that slag contains less than 0.5% free moisture. Copper slag's chemical makeup was analysed by SGS India Private Limited's general laboratory services in Chennai. The physical and chemical properties of copper slag are displayed in Tables 4 and 5.

Table 1. Properties of cement.

Properties	Value
Specific gravity	3.15
Fineness modulus (%)	1.5
Standard consistency (%)	31.6
Initial setting time (minutes)	100
Final setting time (minutes)	210

Table 2. Properties of coarse aggregate.

Properties	Value
Specific gravity	2.7
Water absorption (%)	0.91
Impact value (%)	10.2
Crushing Value (%)	12.8

Table 3. Properties of fine aggregate.

Properties	Value
Specific gravity	2.65
Zone	II
Fineness modulus	2.82
Water absorption (%)	1.85

Table 4. Physical properties of copper slag.

Properties	Value
Particle size (mm)	0.3 to 4.0
Particle shape	Irregular
Appearance	Black and Glassy
Specific gravity	3.86
Unit weight (Kg/m ³)	3600
Fineness modulus	4.437
Hardness	6–7
Water absorption (%)	0.13
Moisture content (%)	0.1%

Table 5. Chemical properties of copper slag.

Chemical Component	Percentage
Fe	4.087
Fe ₂ O ₃	52
Fe ₃ O ₄	8
SiO ₂	27.85
CaO	3.78
S	0.9
Cu	0.65

2.2. Mix Design

In accordance with IS 60262 (2009) [33], the M30 concrete mix design was employed. The final ratio of ingredients was 1:1.37:2.27:0.45 (Cement:Fine Aggregate:Coarse Aggregate:Water/cement ratio), and the necessary components were investigated. Copper slag was used as a partial replacement for fine aggregate and *Bacillus subtilis* was used as an additive to increase the self-healing properties of concrete. Five concrete mixtures containing varying amounts of copper slag were produced (0%, 25%, 50%, 75%, and 100%). At the time of casting, *Bacillus subtilis* (0%, 1%, and 25% by weight of cement) was added to each concrete in the green stage. The percentage of bacteria to that of cement was mixed with the required quantity of water and poured into the concrete mixture. The amount of cement calculated after employing the mix design was 480 kg/m³. The quantity of bacteria (1%) required for 480 kg/m³ was 4.8 kg/m³. Cube, prism, and cylinder specimens were prepared and tested for their mechanical properties after seven, fourteen, and twenty-eight days, respectively. Table 6 depicts the number of samples prepared to determine the 7-day potency. In total, 135 cube samples were prepared for the compressive strength evaluation, with 45 samples tested on day 7, day 14, and day 28. Tables 7 and 8 indicate the number of prism and cylinder samples prepared to determine the 7-day potency. Similarly, 135 samples were prepared and tested for flexural strength and split strength.

Table 6. Number of cube samples prepared for compressive strength evaluation on day 7.

Compressive Strength (Cube Samples)	0% Copper Slag	25% Copper Slag	50% Copper Slag	75% Copper Slag	100% Copper Slag
0% bacteria	3	3	3	3	3
1% bacteria	3	3	3	3	3
2% bacteria	3	3	3	3	3

Table 7. Number of prism samples prepared for flexural strength evaluation on day 7.

Flexural Strength (Prism Samples)	0% Copper Slag	25% Copper Slag	50% Copper Slag	75% Copper Slag	100% Copper Slag
0% bacteria	3	3	3	3	3
1% bacteria	3	3	3	3	3
2% bacteria	3	3	3	3	3

Table 8. Number of cylinder samples prepared for split tensile strength evaluation on day 7.

Split Tensile Strength (Cylinder Samples)	0% Copper Slag	25% Copper Slag	50% Copper Slag	75% Copper Slag	100% Copper Slag
0% bacteria	3	3	3	3	3
1% bacteria	3	3	3	3	3
2% bacteria	3	3	3	3	3

2.3. Compressive Strength Test

The compressive strength of concrete was determined according to the IS 516 (1959) standards [34]. The cube mould used in the experiment measured 150 mm × 150 mm × 150 mm [35]. After wiping the interior faces of the mould with a waste towel, oil was applied for lubrication. All five compositions of the copper slag received a microbial treatment that was between 1% and 2%. After a 24 h curing period, the specimen was demoulded and cured in water. On days seven, fourteen, and twenty-eight, the compressive strength of the cube specimens was evaluated. The specimen was inserted into a compression testing machine, and Figure 1 illustrates the specimen's failure. The maximum load at the time of failure was determined. The equation recommended by IS 516 (1959) was utilised to calculate the concrete's compressive strength.

**Figure 1.** Compressive strength test.

2.4. Flexural Strength Test

The IS 516 (1959) [34] standard was utilised to evaluate the concrete's flexural strength. The experiment used a 500 mm × 100 mm × 100 mm beam mould [35]. A waste towel was used to dust and lubricate the faces of the beam mould. All of the concrete mixtures that were remediated by bacteria were poured into the mould. After 24 h, the specimens were extracted from the mould and cured in water. The flexural strength of the specimens was evaluated on days 7, 14, and 28. Prior to evaluation with the universal testing machine, the specimens' surfaces were dried. Using a two-point loading method, the specimens were permitted to fail at a progressive rate. Figure 2 illustrates the experimental setup and failure pattern. The IS 516 (1959) specified equation was used to calculate the flexural strength of the concrete.



Figure 2. Flexural strength test.

2.5. Split Tensile Strength

IS 5816 (1999) was utilised to calculate the concrete's split tensile strength [36]. A cylindrical specimen measuring 150 mm in diameter and 300 mm in height was subjected to the test. As shown in Figure 3, concrete mixtures containing and lacking micro-organisms were loaded to failure. The IS 5816 (1999) formula was utilised to calculate the split tensile strength.



Figure 3. Split tensile strength test.

2.6. Optimum Percentage of Copper Slag and Micro-Organisms

Table 9 displays the optimal amount of copper slag at varying bacterial addition levels. The maximum compressive strength was achieved when the copper slag replaced 75% of the fine aggregate. Previous research indicated that up to a 35% copper slag substitution is optimal. However, due to the conversion of applied nutrients into calcite crystals, the compressive strength of copper slag concrete showed a maximum result up to 75% in the replacement of fine aggregate.

Table 9. Optimum percentage of copper slag and micro-organisms.

Sl. No.	Percentage of Bacteria (%)	Optimum Percentage of Copper Slag	Compressive Strength at Optimum Percentage of Copper Slag (N/mm ²)
1	0	75	26.8
2	1	75	40.8
3	2	75	45.6

2.7. Beam Casting

This study's beam had a cross section of 230 mm × 280 mm and was 1500 mm in length. Flexural reinforcement was provided by two rods with a diameter of 10 mm at the

base and two bars with a diameter of 10 mm at the top. Each beam's shear reinforcement consisted of mild steel stirrups with a c/c-space of 200 mm and a diameter of 6 mm. With the use of micro-organisms, it was determined that 75% of copper slag concrete is the optimal amount in the replacement of fine aggregate. The beams were fabricated using M30 concrete. To examine the flexural behaviour of copper slag concrete under the influence of bacteria, twelve beams were constructed. Beam 1 was cast from copper slag and bacteria at a ratio of 0% each. Beam 2 contained 75% copper slag and 1% micro-organisms. Beam 3 contained 75% copper slag and 2% bacteria. The ultimate load and deflection data were averaged over four specimens for each of the four mixtures.

2.8. Experimental Setup

All beams (with a cross section of 230 mm $\times$ 280 mm and a length of 1500 mm) were evaluated as simply supported beams under two-point loads across a 1400 mm effective span. Figure 4 depicts the beam experimental setup. The main reinforcement tied with stirrups is shown in Figure 5a. The mould filled with concrete after the placement of the reinforcement is depicted in Figure 5b. The drying of the beams after demoulding is shown in Figure 5c,d. The loads were gradually applied and monitored using a high-reliability load cell with a 0.1 tonne sensitivity. At midspan and at both ends of the beams, LVDTs of the least count of 0.1 mm were used to measure deflection. Strain gauges were fixed at the top and midspan. Compression strain and tension strain values were determined. The parameters such as the initial cracking load, ultimate load, and the deflected shape of the specimens were examined.

2.9. Strain Measurement Using Strain Gauges

Strain gauges can accurately measure the stress caused by pure bending across the cross section of the beam. A strain gauge was attached with tape to the beam on the simply supported frame arrangement, as depicted in Figure 6. Typically, load cells are used to measure loads in a single direction and are connected to the LVDT via a single channel. On the tension and compression sides of the beam, two strain gauges were installed. Strain gauges coupled to the other two LVDT channels precisely measured the strain value. Weight was gradually added until the first fracture appeared, and then it was gradually increased until failure occurred. Using a strain gauge, the strain values within the channels were recorded.



Figure 4. Beam experimental setup.

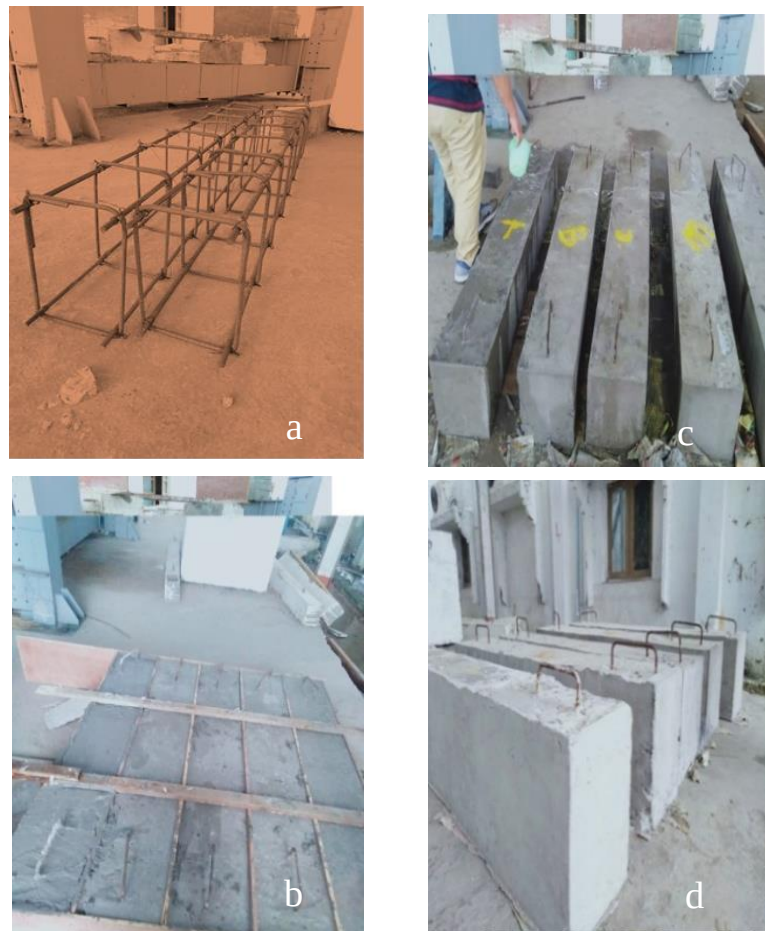


Figure 5. (a) Main reinforcement with Stirrups; (b) Mould filled with concrete. (c,d) Drying of beams.

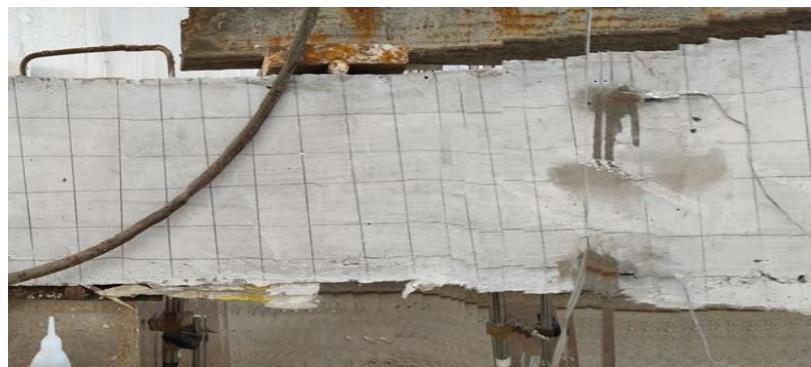


Figure 6. Strain gauge placement.

2.10. Analysis of Beam Modelling Using ABAQUS

Modelling via experiments and solutions obtained via numerical evaluations are both widely accepted techniques for beam analysis. As it is more expensive and time consuming than numerical methods, experimental analysis presents numerous difficulties. ABAQUS has a wide range of applications for finite element analysis as it addresses the shortcomings of existing finite element software packages. This project investigated an RC beam model by utilising ABAQUS's numerical finite element method (student version). To validate the finite element model, the ABAQUS software was used to replicate a recent laboratory experiment on the RC beam and compare the simulation results to the actual values. In accordance with the laboratory experiment, the geometric parameters of the finite element

analysis were determined. The geometric model was subdivided at multiple points to facilitate meshing. Figure 7 depicts the developed beam model for analysis, as well as the reference planes. Figure 8 displays the resulting mesh model. As seen in Figure 9, the concrete model had steel reinforcements. When load scenarios were defined, ultimate load values were assigned to the model. Figure 10 depicts a load placement.

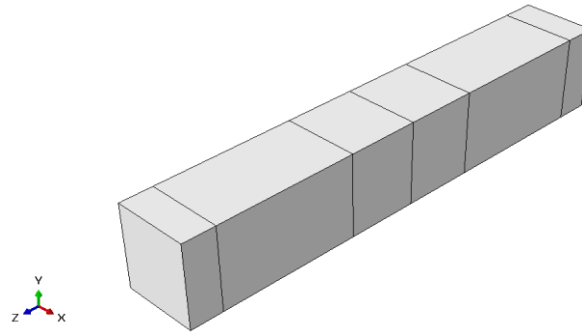


Figure 7. Beam model created for analysis in ABAQUS.

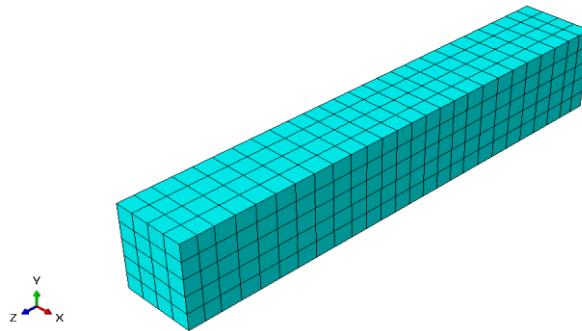


Figure 8. Meshing of beam created in ABAQUS.

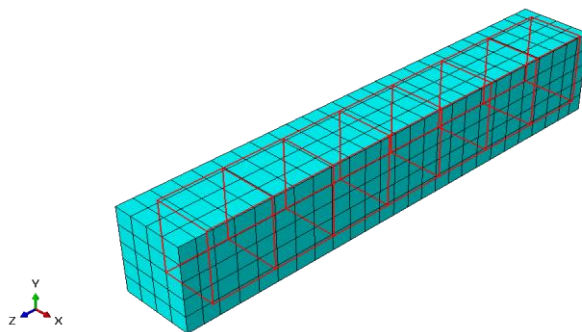


Figure 9. Assembly of concrete and steel reinforcements in a beam.

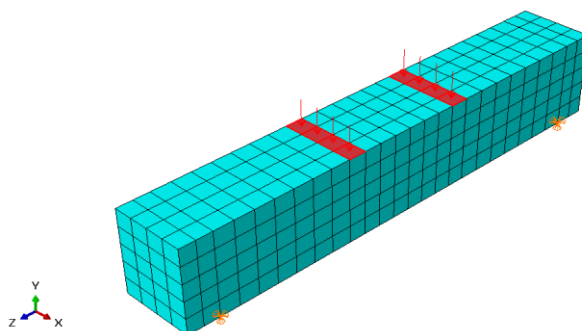


Figure 10. Application of load and support conditions for the beam in ABAQUS.

3. Results and Discussion

3.1. Effect of Copper Slag and Micro-Organisms on the Compressive Strength of Concrete

The compressive strength of the concrete mixtures was measured on days 7, 14, and 28. Figure 11 illustrates the variation in the compressive strength with varying micro-organism concentrations. The compressive strength results indicated that the density and porosity of the copper slag concrete had increased. At the 75% replacement of copper slag treated with 2% micro-organisms, the highest achievable compressive strength was 45.6 N/mm². Nevertheless, the copper slag replacements that were more than 40% resulted in an increase in compressive strength compared to the control concrete. Clearly, the compressive strength of micro-organism concrete exceeded that of conventional concrete. The bacteria-induced increase in compressive strength was likely caused by the deposition of calcium carbonate on the surfaces of the microbe cell and the voids within the concrete, which filled the existing voids in the binder matrix. The increase in compression strength was primarily the result of microbiologically generated concrete mixes filling the voids within the concrete.

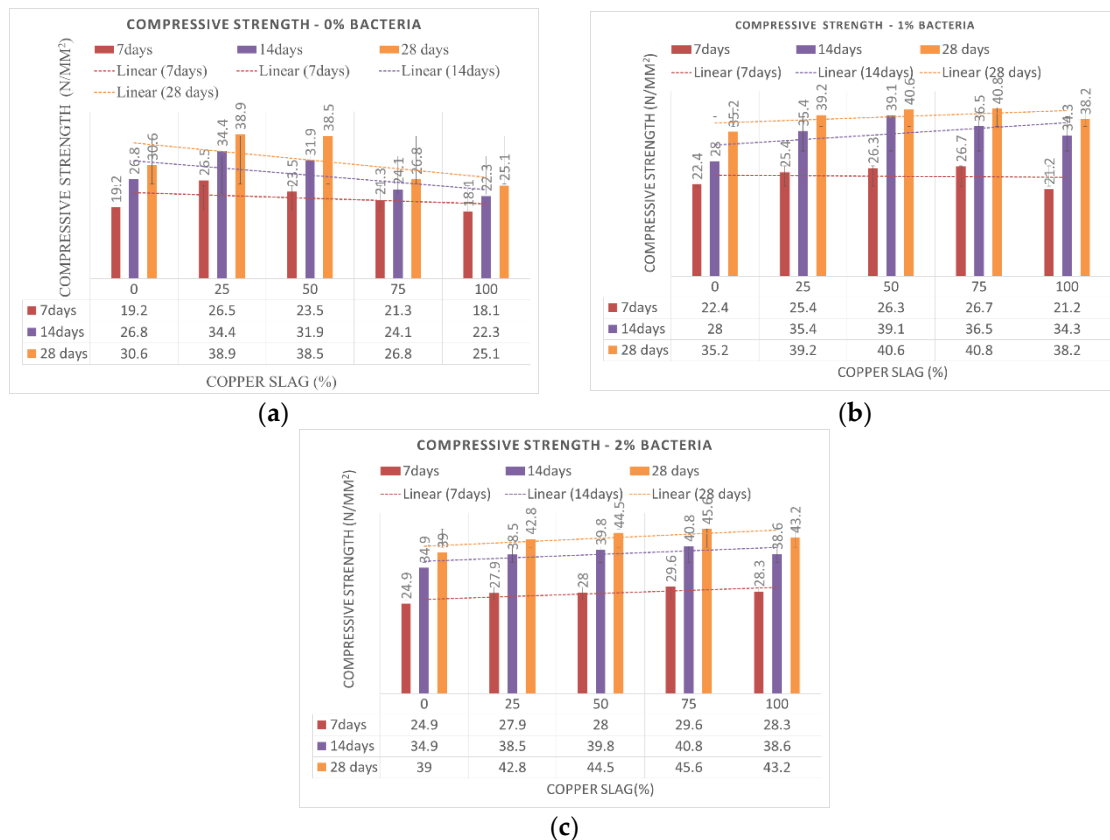


Figure 11. Compressive strength of copper slag concrete with micro-organisms. (a) 0% bacteria. (b) 1% bacteria. (c) 2% bacteria.

3.2. Effect of Copper Slag and Micro-Organisms on the Flexural Strength of Concrete

In the laboratory, prisms measuring 500 mm × 100 mm × 100 mm were cast and tested. The replacement of copper slag was carried out at 0%, 25%, 50%, 75%, and 100%, whereas the addition of 0%, 1%, and 25% of bacteria resulted in flexural prisms. Figure 12 shows the fluctuation in flexural strength due to the varying percentages of bacteria. The flexural strength of bacterial copper slag concrete achieved a maximum value of 10.1 N/mm² with the 50% substitution of copper slag and 10.3 N/mm² with the 75% substitution of copper slag, demonstrating the impact of bacteria on concrete density and, as a result, improving the concrete's flexural strength. The deflection parameter of beams was calculated with and without the action of micro-organisms. The comparative study helps to identify the

reduction in deflection due to microbial action, which adds value to our findings. The factor responsible for the increase in flexural strength is the precipitation of calcium carbonate within the matrix of the concrete which in turn increases the density of concrete and resistance towards the force overcoming the structure. The bacteria serve as nucleating sites for calcite precipitation, which is the principal crystalline healing product.

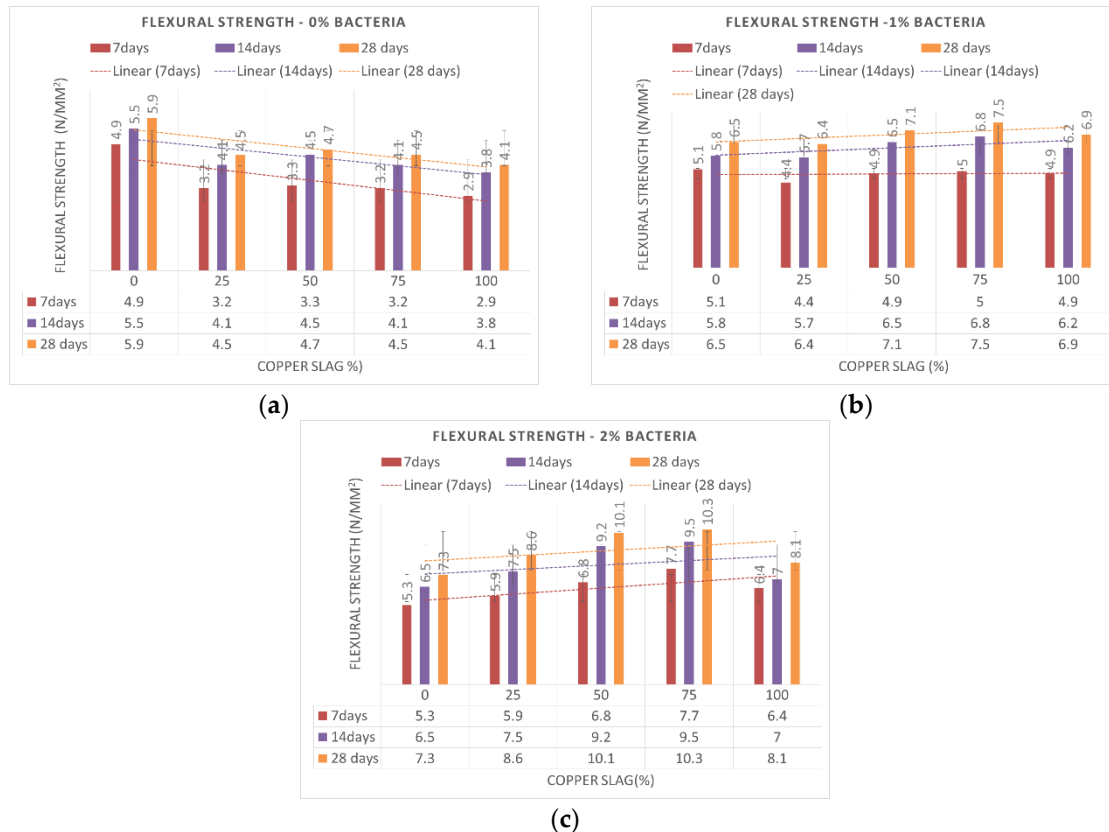


Figure 12. Flexural strength of copper slag concrete with micro-organisms. (a) 0% bacteria. (b) 1% bacteria. (c) 2% bacteria.

3.3. Effect of Copper Slag and Micro-Organisms on the Split Tensile Strength of Concrete

In the laboratory, cylinders with a 150 mm diameter and 300 mm depth were cast using copper slag and micro-organisms (0%, 1%, and 2%) in place of cement (0%, 25%, 50%, 75%, and 100%). Figure 13 depicts the split tensile strength of the specimens evaluated in the laboratory. According to the findings, bacterial activity increased the split tensile strength of copper slag concrete. When 75% copper slag was substituted for the fine aggregate with 2% bacteria by weight of cement, the maximum value of the split tensile strength produced was 8.8 N/mm², whereas regular copper slag concrete produced a split tensile strength of 8 N/mm². Cracks appeared in concrete when tensional forces exceeded its tensile strength. It was observed that the addition of micro-organisms increased the splitting tensile strength. The value increased due to the continuous formation of solid calcite crystals as a result of bacterial action on unhydrated cement particles. Since the tensile strength of the concrete increased, tensional forces could be resisted.

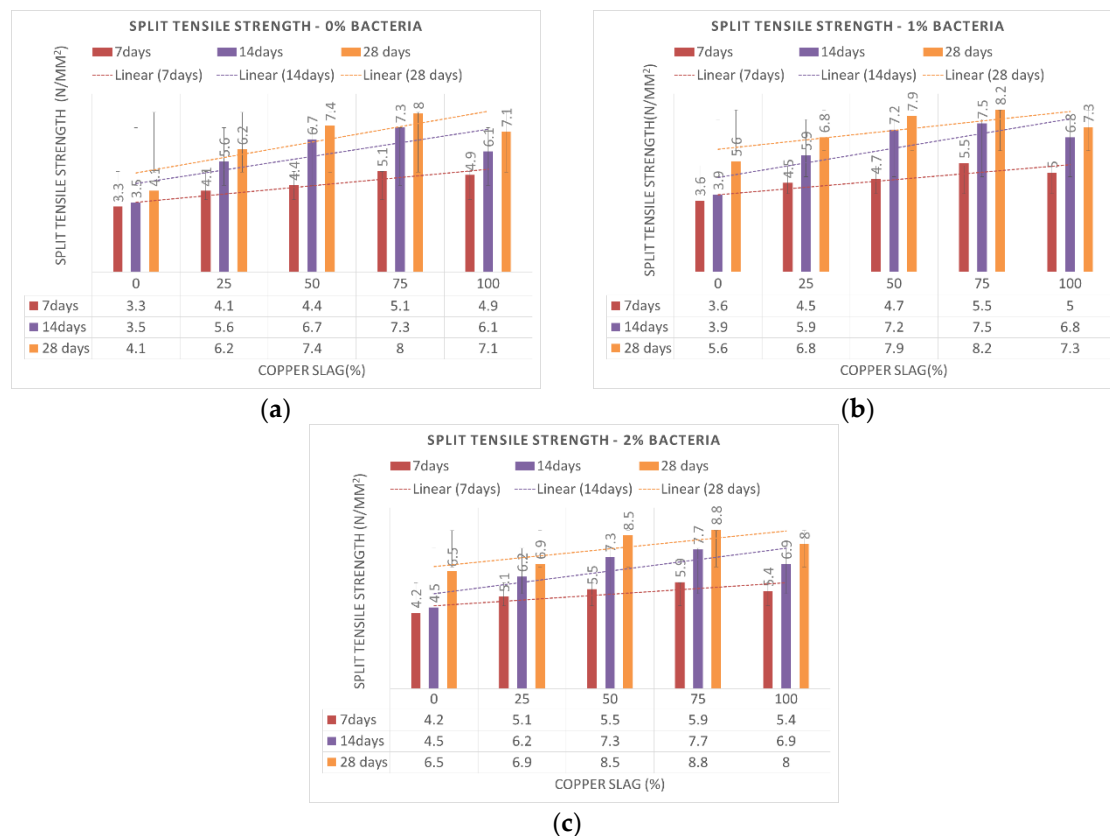


Figure 13. Split tensile strength of copper slag concrete with micro-organisms. (a) 0% bacteria. (b) 1% bacteria. (c) 2% bacteria.

3.4. Effects of Copper Slag and Bacteria on Flexural Behaviour of RCC Beams

The flexural behaviour of RCC beams made from copper slag and sand was tested when treated with an optimum percentage of micro-organisms. After 28 days, the three samples created with varying percentages of copper slag with sand were analysed. Numerous scholars have investigated and reported on the diverse ways in which copper slag affects the performance of concrete. However, these researchers only studied the qualities of fresh and hardened concrete. Using micro-organisms, the mechanical performance of copper-slag-added specimens was extended to reinforced concrete components in this study. As a result, the following parameters were established to meet the objectives of the investigation:

- Beam failure patterns;
- Load–deflection characteristics of RCC beams.

3.4.1. Failure Patterns of Beams

All the beams had flexural failures, indicating that the compressive zone of the concrete reached its maximum capacity. At a force of 24 kN, the controlled concrete began to collapse. Flexural failures associated with copper-slag-replaced specimens (Beam 1 and Beam 2) began with a first fracture at 43 kN and 40 kN, respectively, indicating that micro-organisms enhanced the stiffness of the copper slag specimens. A 45-degree diagonal fracture formed near the supports of the bacterial copper slag specimens, indicating an increase in shear strength relative to shear force. Figures 14–16 illustrate the fracture patterns of three distinct beams. During the experiment, a concentrated load was applied. When the load was applied in the software ABAQUS, it was converted into a rectangular strip load. For the gradual increase in load values, strain gauges were placed at the top and bottom of the beam to calculate deflection values.



Figure 14. Crack pattern for Beam 1 (controlled concrete).



Figure 15. Crack pattern for Beam 2.



Figure 16. Crack pattern for Beam 3.

3.4.2. Load–Deflection Behaviour of the Beam

In RCC beams measuring 230 mm × 280 mm and 1500 mm, the optimal mixture of copper slag and varying bacteria application percentages was evaluated. The beam's deflections were measured at both the compression and tension sides of the midspan. With a 75% substitution of copper slag and 1% bacteria, the crack began at 75 kN, the ultimate load reached 80 kN, and the deflection value was 0.33 mm. With a 75% copper slag replacement and 2% bacteria, the crack began at 75 kN, the ultimate load was 85 kN, and the midspan deflection of the ultimate load was 0.26 mm. For the controlled concrete, the cracks started at 40 kN and the ultimate load was 45 kN. As a result of the micro-organisms' activities, the load–deflection behaviour of copper slag concrete improved. The maximum midspan deflection of a beam with zero percent bacteria was approximately 0.4 mm, and as the proportion of bacteria increased, the deflection decreased. The load–deflection pattern is illustrated in Figure 17.

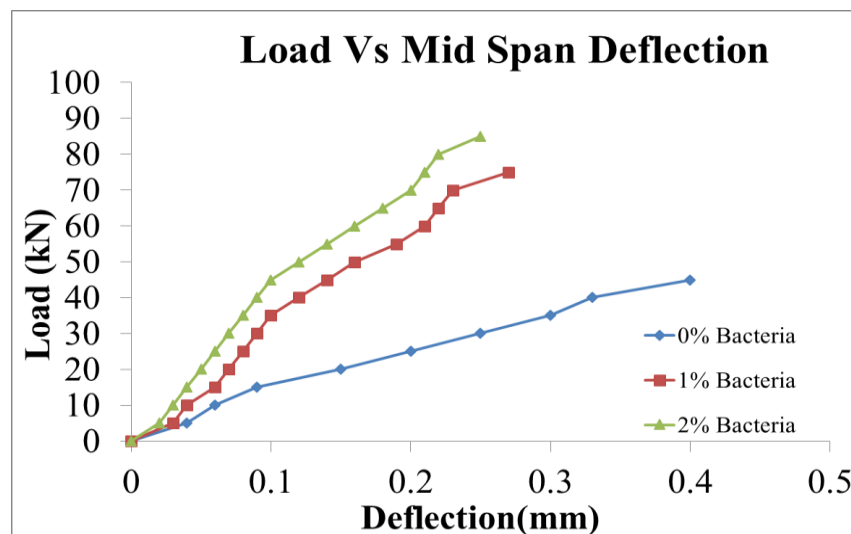


Figure 17. Load–deflection pattern from experiment.

3.4.3. Load–Deflection Pattern from ABAQUS

Figure 18 depicts the horizontal deflection of the beams. The centre span deflection is represented by the output's dark blue hue. Node 105 corresponds to the midspan. The midspan deflection is represented in the table by the blue value. Red indicates the deflection at both ends of the beam, as well as the location where the right and left span deflections were measured. Nodes 75 and 90 represent the point at which the end span deflection was reached. At node 105, the maximum deflection of Beam 1 was 0.37 mm.

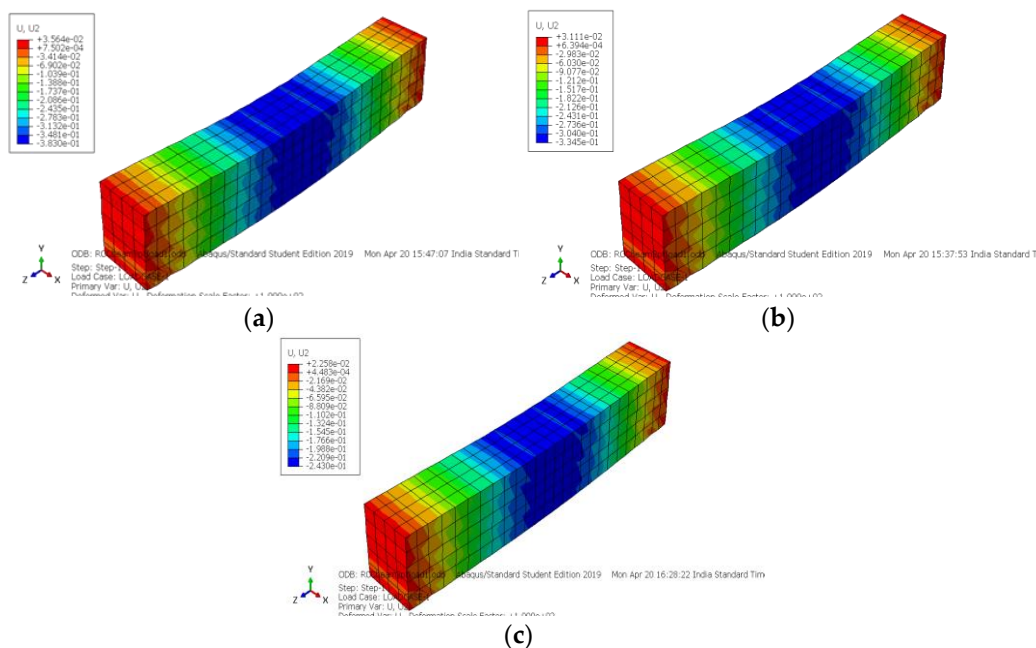


Figure 18. Deflection patterns from ABAQUS. (a) 0% bacteria (conventional concrete). (b) 75% copper slag with 1% bacteria. (c) 75% copper slag with 2% bacteria.

The deflection value of 0.38 mm is represented in the table by the blue value. The maximum deflection of Beam 2 was 0.33 mm, and the blue value in the table corresponds to a deflection of 0.345 mm. The maximum deflection of Beam 3 was 0.26 mm, whereas the blue value in the table indicates a deflection of 0.24 mm.

3.4.4. Comparison of Experimental and Numerical Deflection Parameters

Figure 19 illustrates the outcomes of the current ABAQUS model based on the matching relationships extracted from the selected previous experimental studies. The graphs demonstrate that the beam deflections under normal conditions estimated by the current finite element model and those computed by the previous experimental tests were quite similar. The observed and predicted ultimate deflections for beams B1, B2, and B3 were 1.05, 1.08, and 1.08, respectively. The load deflection predicted by the current numerical model corresponded to the pattern observed in the experiment. Initially, the curve deviated due to microcracks caused by drying shrinkage in the concrete and improper specimen handling. In addition, the numerical model assumed a perfect connection between the concrete and steel reinforcing bars, which was impossible for the tested specimens. The accuracy of the ABAQUS results was within 5% of the experimental study's accuracy. When an external load was gradually applied over a beam, it induced direct and bending stresses, leading to flexural, bond, and diagonal tension fractures. The concrete's tensile stress exceeded its tensile strength, causing the formation of internal microcracks. The deflection increased as the load increased. Once the yield point was reached, the curve began to slope downward.

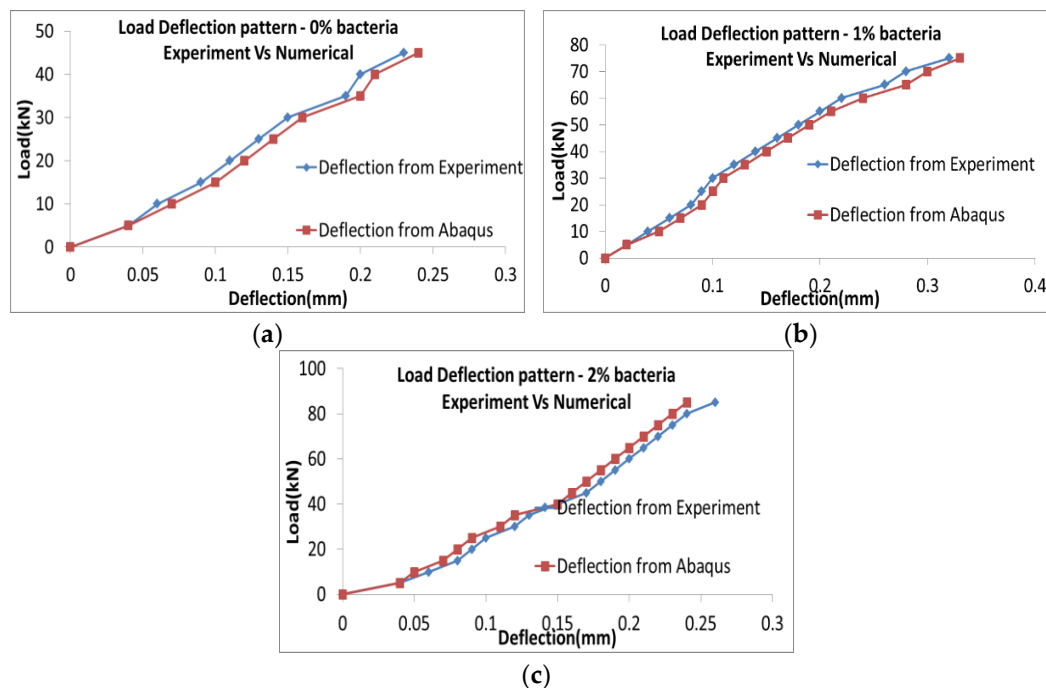


Figure 19. Deflection patterns from ABAQUS. (a) 0% bacteria (conventional concrete). (b) 75% demolition waste with 1% bacteria. (c) 75% copper slag with 2% bacteria.

3.5. SEM Images

Using a scanning electron microscope, the calcium carbonate precipitation caused by the isolation of bacteria in the pores of concrete was analysed. The fragments were collected after the cube specimen was crushed. The specimens were dried in an oven at 1000 degrees Celsius for three days prior to SEM analysis. The SEM images were retrieved in order to identify calcium carbonate crystal formation. In addition, the SEM analysis was utilised as the evidence test for bacterial action on concrete. The images captured with a scanning electron microscope (SEM) revealed the presence of individual crystals, indicating the formation of calcite. In Figure 20, various rectangular and polygonal crystals indicate the formation of calcium carbonate [34], whereas in Figure 21, there are no such formations in the controlled concrete.

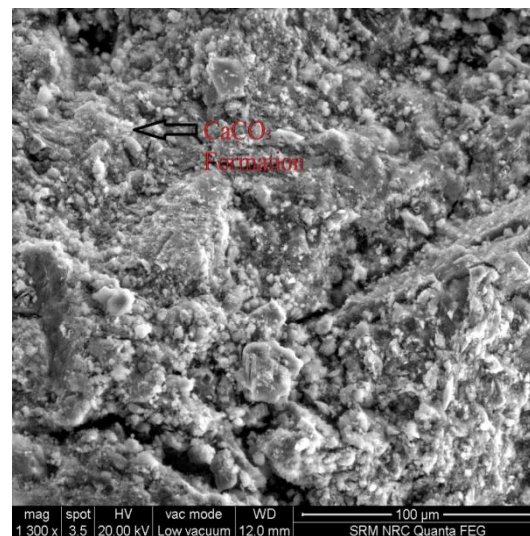


Figure 20. SEM image for copper slag concrete with 75% substitution of copper slag for coarse aggregate and 2% *Bacillus subtilis*.

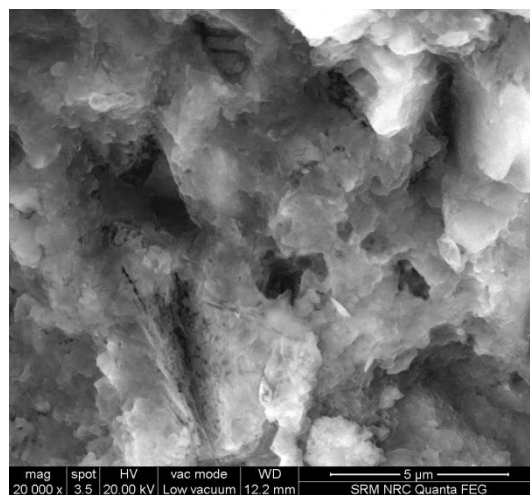


Figure 21. SEM image for controlled concrete.

4. Conclusions

- By substituting copper slag for fine aggregate in concrete, waste disposal can be made more efficient and material costs may be reduced.
- MICP is a new, innovative phenomenon that has the potential to enhance the quality of copper slag concrete.
- The addition of micro-organisms to copper slag concrete enhances its mechanical properties and permits material savings.
- A 75% replacement of copper slag with fine aggregate treated with 1% bacteria by weight of cement produced concrete with better strength as compared to the control mix and regular copper slag concrete.
- A 75% replacement of copper slag with fine aggregate treated with 2% bacteria by weight of cement produced concrete with better strength as compared the control mix.
- In comparison to the strength of the control mix, the strength of the mix containing the 100% copper slag replacement and 2% bacteria was lower.
- The optimum percentage of the combination of waste materials was found to be a 75% replacement of copper slag treated with 2% bacteria.

- According to the load–deflection curves, the initial cracking load and ultimate load of the bacterial copper slag specimens improved by 40% to 45% when compared to the control concrete specimen.
- A comparison between the load–deflection curves generated by the ABAQUS finite element software and those obtained from the experimental data revealed a slight divergence, which may be attributable to shoddy workmanship and improper specimen handling. However, the error percentages between the numerical and experimental results were as small as possible.
- Ultimately, it can be stated that a 75% copper slag replacement treated with 2% bacteria could be a viable alternative to regular conventional concrete, as it results in enhanced concrete performance.
- Based on the scanning electron microscope analysis, it can be concluded that the improvement in the overall performance of copper slag concrete was due to the action of bacteria and the formation of calcite, which was identified by the polygonal crystals.

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