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Utilization of Industrial Waste as a Sustainable Approach for Enhancing the Properties of Ternary Blended Concrete Prediction with Machine Learning

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ABSTRACT

The utilization of industrial by-products in concrete manufacturing supports environmental sustainability by reducing the consumption of natural resources while simultaneously enhancing concrete performance. In this context, the present investigation examines the behavior of self-compacting concrete (SCC) incorporating supplementary cementitious materials, namely Alccofine and silica fume, along with copper slag as a partial replacement for fine aggregate. In the experimental program, ordinary Portland cement was partially replaced by fixed proportions of 15% Alccofine and 20% silica fume. Copper slag, an industrial waste generated during the copper smelting process, was employed as a fine aggregate substitute at replacement ratios of 0%, 10%, 20%, 30%, and 40%. The study primarily focused on evaluating the fresh-properties and mechanical performance of M40-grade SCC produced with these materials. Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were determined after 7 and 28 days of standard water curing. The results indicated that the most favorable performance was achieved at 30% replacement of fine aggregate with copper slag. At this optimum level, compressive strength increased by 14.95%, split tensile strength by 5.34%, and flexural strength by 83.33% in comparison with the control mix. However, further increases in copper slag content beyond 30% resulted in a reduction in strength, suggesting a limiting threshold for its effective incorporation. In addition, strength values predicted using MATLAB-based modeling showed a strong correlation with the experimental results, thereby confirming the robustness of the computational approach. Overall, the findings demonstrate that copper slag can be effectively used as a sustainable alternative to natural fine aggregate in SCC, leading to enhanced mechanical properties while supporting environmentally responsible construction practices.

1. INTRODUCTION

The construction sector is widely acknowledged as a major source of global carbon dioxide (CO_2) emissions, largely arising from the high energy consumption associated with cement manufacturing and the extensive exploitation of finite natural resources. Mitigating this environmental impact requires a comprehensive strategy that includes reducing material demand, promoting alternative and sustainable materials, and adopting efficient carbon management practices. Consequently, the incorporation of environmentally responsible and sustainable approaches in construction has become imperative, not only to lower the sector's carbon footprint but also to support global efforts toward climate change mitigation. In this context, one of the notable developments in concrete technology in recent years is the emergence and increasing use of self-compacting concrete (SCC). SCC is characterized by its exceptional flowability and resistance to segregation, enabling it to spread and consolidate under its own weight without the need for external vibration [1]. This advanced concrete technology significantly enhances construction efficiency, delivers superior surface finish, and minimizes labor requirements as well as equipment usage. Owing to its ability to uniformly flow through intricate formwork and densely reinforced sections, SCC is particularly well suited for complex structural applications.

However, the workability of SCC can be adversely affected by the inclusion of fibers, which, while beneficial for enhancing mechanical properties and crack resistance, tend to reduce flowability and increase the risk of blocking [2]. Therefore, a balanced mix design is crucial to maintaining the rheological performance of SCC while achieving the desired structural benefits.

To achieve the required performance in the fresh state, SCC must satisfy a set of well-defined rheological and flow-related criteria. Key parameters such as slump flow, V-Funnel flow time, U-box height difference, and L-box blocking ratio are evaluated in accordance with the guidelines established by the European Federation of National Associations Representing Concrete (EFNARC). These standardized tests are essential for verifying the filling ability, passing ability, and resistance to segregation of SCC, thereby confirming its effectiveness for self-compacting applications.

Once hardened, SCC demonstrates mechanical strength and durability characteristics that are comparable to, and in many cases superior to, those of conventionally vibrated concrete. This improved performance is primarily due to the formation of a dense and uniform microstructure, which enhances load-bearing capacity and long-term durability [3]. In addition, the environmental impact of concrete can be significantly reduced by partially substituting Portland cement with pozzolanic industrial byproducts such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS). The incorporation of these supplementary cementitious materials not only conserves natural resources and minimizes industrial waste but also improves durability-related properties of concrete [4, 5]. Such practices align with circular economy concepts and contribute effectively to lowering the carbon footprint associated with cement production.

By substituting a portion of the cement with a substantial quantity of waste material, concrete producers may realistically decrease their industry's adverse ecological impact and boost cost effectiveness. The consideration has been provided to the usage of the unused additives to boost mechanical properties of concrete. It is apparent that fly ash and Alccofine can be used in place of cement in concrete. To achieve zero net carbon emissions by 2050 is one of the objectives of Sustainable Development Goal 13 (climate action) [6]. In accordance with experimental research, adding more copper slag to novel materials strengthened concrete characteristics. At 50%, the industrial waste by product copper slag exhibited increased mechanical qualities for high-strength concrete (HSC) with suitable consistency and would be a viable alternative for sand [7]. Mineral admixtures are essential for overcoming cost constraints in manufacturing. The hardened concrete is dense, and solid and has constant engineering properties and sturdiness as that of conventional concrete [8]. Commuting the fine combination with copper slag associate degree industrial by-product helps with the increase of strength and sturdiness parameters. Inclusion of silica fume refines the pore structure resulting in stronger concrete. Silica fume has an exceedingly specific surface area and functions as a reactive pozzolona. Silica fume is a highly prospective mineral addition, particularly for ensuring high-strength to ultrahigh-strength concrete, with suitable particle dispersion ensured during mixing [9]. The utilization of Alccofine 1203 and silica fume will increase the strength (both in compression and flexure) to very good extent [10, 11]. The incorporation of Alccofine 1203 and silica fume in SCC positively impacts its engineering properties, making it a cost-effective and sustainable option. As the overuse of natural resources like river sand contributes to environmental concerns, this study examines the potential of copper slag as an alternative fine aggregate. Cement was partially replaced with 15% Alccofine and 20% silica fume, while copper slag was used in varying proportions to replace fine aggregate. The fresh and hardened properties of the resulting SCC mixes were evaluated. Results confirm that the use of industrial by-products enhances compressive strength and supports sustainable construction practices [12, 13]. The results derived from the experiments were compared with the predicted values obtained from Support Vector Machine (SVM) modelling [14-16]. The experimental data indicate that the optimal replacement level of fine aggregate with copper slag is 20%, leading to a 15.25% increase in strength [17-19]. Copper slag has attracted significant attention as a sustainable industrial by-product due to its potential for recycling and value-added applications. Adilov et al. [20] analyzed the challenges and opportunities associated with copper slag recycling, emphasizing regulatory barriers, variability in slag composition, and the need for integrated processing routes to enable large-scale sustainable utilization. Their study highlighted copper slag as a promising secondary resource within the circular economy framework. The environmental implications of copper slag reuse have been examined with a focus on heavy metal leaching and construction applications. Rathee and Misra [21] investigated the leaching behavior of copper slag and its feasibility as a replacement for natural fine aggregate in geopolymer concrete, demonstrating acceptable environmental performance and improved sustainability when proper mix design controls are applied. These findings support the safe incorporation of copper slag in cementitious systems. A comprehensive review by Klaffenbach et al. [22] provided a critical analysis of copper slag utilization pathways, including construction materials, metal recovery, and advanced processing techniques. The review emphasized the importance of holistic life-cycle assessment and techno-economic evaluation to ensure environmentally responsible and economically viable applications. Several studies have focused on the optimization of copper slag use in concrete and geotechnical applications. Turkane et al. [23] applied response surface methodology (RSM) to optimize concrete mixes incorporating copper slag as a fine sand replacement, reporting enhanced mechanical properties at optimal replacement levels. Similarly, Yeo et al. [24] demonstrated the effectiveness of RSM in optimizing concrete paving block mixtures, underscoring the robustness of statistical optimization techniques for sustainable material design. Beyond concrete, Zhang et al. [25] explored the use of copper slag combined with plant roots to reinforce soft soils using RSM, reporting significant improvements in soil strength and stability. This study highlighted the versatility of copper slag in geotechnical engineering applications.

This study aims to enhance concrete performance by incorporating industrial by-products—Alccofine, silica fume, and copper slag—into a ternary blended mix. The fine particle size and high reactivity of Alccofine and silica fume improve workability, cohesion, and compressive strength through enhanced calcium silicate hydrate (C-S-H) gel formation. Copper slag, used as a partial sand replacement, boosts strength due to its density and angular shape. These materials also enhance durability by reducing permeability and increasing resistance to abrasion and harsh environments. While beneficial overall, excessive copper slag can reduce workability, and Alccofine may slow early strength development. The experimental results were further validated by comparing them with the predicted values generated through SVM-based modelling, demonstrating close agreement between measured and estimated strengths [14]. The findings indicate that the optimal replacement level of fine aggregate with copper slag is 20%, at which the compressive strength exhibited an improvement of approximately 15.25% over the control mix [15]. The primary objective of this research is to promote the incorporation of industrial by-products into concrete production, thereby enhancing sustainability and reducing environmental burdens. Ternary blended concrete incorporating Alccofine, silica fume, and copper slag has shown superior mechanical and durability performance compared to conventional concrete mixes. The ultrafine particle size of Alccofine and silica fume significantly improves the workability, cohesiveness, and packing density of the cementitious matrix. Alccofine, owing to its high fineness and latent hydraulic activity, contributes to pore refinement and enhances compressive strength by accelerating the formation of additional C-S-H gel. Similarly, silica fume reacts pozzolanically with calcium hydroxide to generate secondary C-S-H gel, leading to substantial improvements in strength and long-term performance. Copper slag, when used as a partial substitute for natural sand, enhances mechanical characteristics due to its higher density, angularity, and superior particle interlocking. In terms of durability, Alccofine and silica fume substantially reduce permeability, thereby increasing resistance against chloride ingress, sulphate attack, and other aggressive environmental exposures. Copper slag further contributes by improving abrasion resistance, making the composite concrete particularly suitable for marine, coastal, and de-icing environments. Overall, the synergistic integration of Alccofine, silica fume, and copper slag in a ternary blend result in concrete with significantly enhanced strength, durability, and sustainability credentials. However, it may be noted that Alccofine can delay early-age strength development due to its slower hydration kinetics, and excessive copper slag content may adversely affect workability because of its angular and dense nature. Despite these limitations, ternary blended concrete presents a promising pathway toward high-performance and eco-efficient construction materials.

2. MATERIALS AND METHOD

The experimental investigation was conducted using a systematic methodology involving the casting, curing, and testing of concrete specimens as shown in Figure 1. The materials selected for this study were chosen based on their mechanical and chemical characteristics to evaluate the synergistic effects of supplementary cementitious materials and industrial byproducts on concrete performance. The constituents used include ordinary Portland cement, silica fume, Alccofine 1203, fine and coarse aggregates, copper slag, and a high-performance chemical admixture.

2.1 Materials

Cement: Cement functions as the principal binding material in concrete, facilitating the hardening and cohesion of the mix components through hydration reactions. The cement utilized in this study conforms to Indian Standard (IS) 12269:1987 specifications, denoting ordinary Portland cement of 53 grade. This grade is known for its early strength development, which is critical in high-performance and rapid-setting applications.

Silica fume: Silica fume is an ultrafine, amorphous silicon dioxide obtained as a byproduct of silicon and ferrosilicon alloy production. Owing to its very high silica content and large specific surface area, it exhibits strong pozzolanic activity. Its incorporation refines the concrete microstructure, enhances strength, and significantly reduces permeability.

GGBS: GGBS is a mineral admixture derived from the steel industry through controlled granulation. It possesses fine particle size, high pozzolanic reactivity, and a specific gravity of about 2.7, contributing to improved durability and long-term strength.

Alccofine 1203: Alccofine 1203 is a highly reactive, micro-fine supplementary cementitious material produced from granulated blast furnace slag. With a specific gravity of 2.7, its high fineness and pozzolanic activity improve particle packing, accelerate hydration, and enhance the strength and durability of concrete.

Fine aggregate: Fine aggregate fills voids between cement and coarse aggregate particles, influencing density and workability. River sand conforming to IS 383:1970, with a specific gravity of 2.55 and free from harmful impurities, was used in this study.

Copper slag: Copper slag is a dense, angular byproduct of copper smelting. Its use as a partial replacement for fine aggregate supports waste utilization and sustainability while potentially improving the mechanical performance of concrete.

Coarse aggregate: Coarse aggregates constitute the major volume of concrete and govern its mechanical behavior. Well-graded crushed stone with a specific gravity of 2.60, free from impurities, was employed to ensure consistent strength and durability.

Admixture: A high-range water-reducing admixture, Conplast SP430, conforming to IS 9103, was used to improve workability without increasing water content. It enhances dispersion of cement particles, resulting in better flowability, reduced segregation, and improved strength.

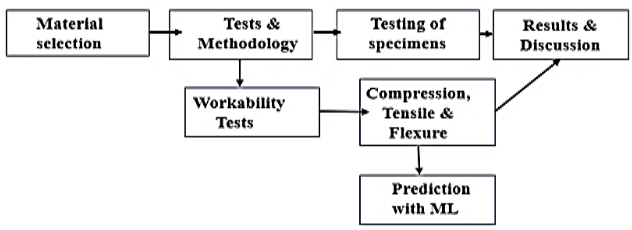


Figure 1. Methodology

2.2 Tests method

J-Ring Test: The purpose of this test is to ascertain the flowing and passing abilities of SCC prepared. Concrete is poured into a slump cone after a specially built J-Ring is set on top of it. The J-Ring aids in preventing excessive concrete flow throughout the test, ensuring that SCC retains its viscosity and does not separate excessively.

L-Box Test: The purpose of this test evaluates the capacity to passing ability and stability of concrete mixes. A concrete sample is poured into an L-shaped box, and the shutter at the bottom of box is lifted, allowing the concrete to flow through the horizontal and vertical sections. In horizontal section of L-box the height at a distance of 200 mm and 400 mm is referred as H_1 and H_2 respectively. This test helps to determine if the concrete mix can maintain a balanced flow without segregation or excessive blocking.

V-Funnel Test: This procedure determines the rate of flow and filling ability of SCC. Concrete is poured into a specifically formed V-Funnel, and the amount of time of the concrete's passage through the funnel is noted. This test ensures the SCC prepared Frictional resistance to flow.

Compressive strength: A digital (Compression Testing Machine) CTM with capacity of 3000 KN was utilized. Formula for determining the strength,

$$F_{ck} = P/(b \times w)$$

where, p = peak load, b = breadth, w = width.

Split tensile: CTM was used for performing this test. Formula utilized,

$$F_{ct} = 2P/(\pi d \times l)$$

where, p = peak load, d = diameter, l = length.

Flexural strength: Test was performed on 4-point load testing machine and formula utilized,

$$F_b = Pl/(b \times d^2)$$

where, p = peak load, l = length, b = breadth, d = depth.

2.3 Methodology

The guidelines for SCC mix design are considered as per IS:10262 and rheological performance tests are based with EFNARC [11-12]. IS 516:1959 (reaffirmed in 2018) standards are used in testing of SCC. These instructions outline the procedures for testing, sampling, and assessing the consistency, strength, and workability of concrete. Furthermore, IS 10262:2019 (Guidelines for Concrete Mix Proportioning) is frequently referenced to identify the suitable SCC mix design, ensuring that the concrete achieves the specified performance parameters including copper slag as an alternate material for river sand. Adherence to these IS criteria is critical for maintaining the quality and reliability of the work ability giving an adequate framework for scientifically rigorous evaluation of SCC with copper slag. In this experimental work, SCC specimens of 150 mm cube for compression testing, cylinders 150 × 300 for tensile-strength and prisms of 100 × 100 × 500 mm with different percentages of copper slag were casted under laboratory conditions and the rheological and mechanical strengths were compared conventional mix.

2.4 Testing procedures

To comprehensively evaluate the rheological and mechanical behavior of the developed SCC incorporating ternary blends and copper slag, both fresh and hardened state tests were systematically conducted. The workability characteristics were assessed through standard tests specifically designed for SCC, while the strength characteristics were determined through compressive, tensile, and flexural strength tests in accordance with relevant IS codes.

2.4.1 Rheological property assessment

The workability and flow characteristics of SCC are critical for ensuring its self-compacting capability, particularly in congested reinforcement zones without external vibration. To evaluate these parameters, the following standard tests were conducted:

- **L-Box Test**: This test was conducted to evaluate the passing ability of SCC through narrow openings or obstructions, simulating congested reinforcement. The apparatus consists of a vertical and horizontal section separated by steel bars. The ratio (H_2/H_1) of the final heights of concrete in the horizontal and vertical sections was measured. A ratio close to 1.0 indicates excellent passing ability.
- **J-Ring Test**: The J-Ring Test assesses both the flowability and passing ability of SCC. It comprises a slump cone surrounded by a ring of evenly spaced steel bars. The difference in flow diameter between the slump flow with and without the J-Ring was measured to evaluate potential blocking effects. A minimal difference suggests good passing ability and compatibility of the mix.
- **V-Funnel Test**: The V-Funnel Test determines the viscosity and filling ability of SCC by measuring the time required for the concrete to flow through a narrow, funnel-shaped apparatus. A shorter flow time indicates lower viscosity and higher flowability, while a moderate flow time suggests an optimal balance between flow and stability.

These tests were conducted immediately after mixing to ensure accurate assessment of the fresh properties. The results provide crucial insights into the mix's suitability for field applications where high flow and minimal segregation are required.

2.4.2 Hardened property assessment

To evaluate the mechanical properties of hardened SCC, standard specimens were cured at room temperature and tested at 7 and 28 days. The compressive strength test was conducted on 150 mm cubes using a 300-tonne CTM, following IS 516:1959, to assess load-bearing capacity. Split tensile strength was measured on 150 × 300 mm cylinders under diametral loading to evaluate crack resistance. Flexural strength was determined using 100 × 100 × 500 mm prisms under four-point bending to assess resistance to bending. These tests confirmed the impact of ternary blends and copper slag on improving both fresh and hardened properties of SCC.

3. RESULTS AND DISCUSSION

3.1 Workability

The rheological behavior of the formulated SCC mixes was evaluated through a detailed set of standardized workability tests, namely the L-Box, J-Ring, and V-Funnel Tests. All assessments were performed in compliance with the recommendations of the EFNARC. The outcomes of these tests are presented in Table 1, which summarizes the flowability and passing ability of the SCC mixtures. The data highlight the effect of incorporating different proportions of crushed sand as a partial substitute for natural river sand, thereby illustrating the role of fine aggregate type in governing the fresh-state performance of SCC.

Table 1. Workability test

Percentage of Copper Slag	L-Box (H_2 / H_1)	J-Ring (650–800 mm)	V-Funnel (Initial) (sec)	V-Funnel (T-5) (sec)
Zero	0.81	612	10.4	13.2
10	0.81	654	10.1	12.3
20	0.83	670	9.8	11.2
30	0.86	692	9.7	10.9
40	0.87	710	9.5	10.7

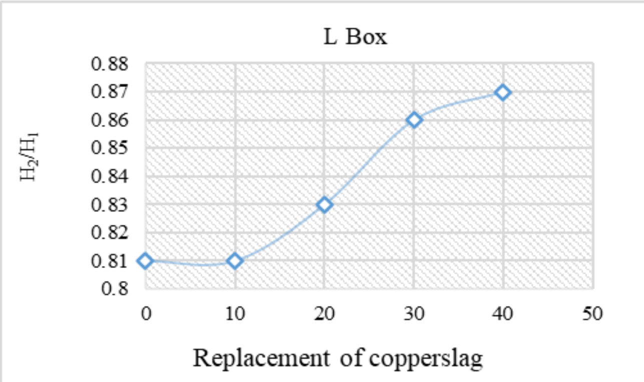


Figure 2. L-Box

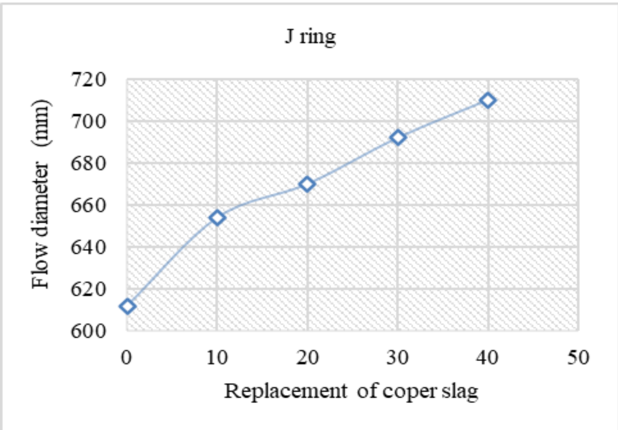


Figure 3. J-Ring

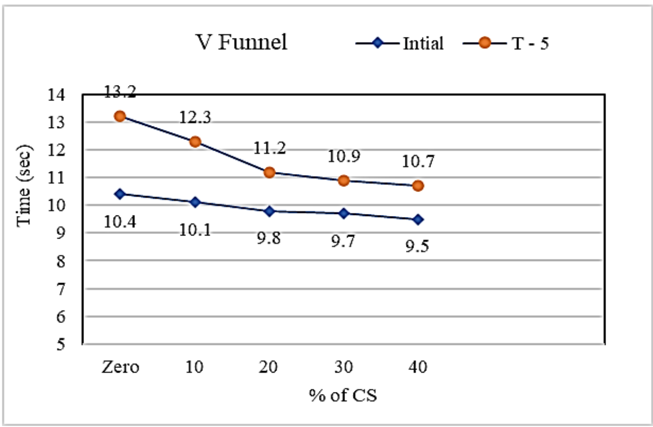


Figure 4. V-Funnel

Figures 2-4 present a graphical comparison of the rheological behavior of the SCC mixes as evaluated through the L-Box, J-Ring, and V-Funnel Tests, respectively. These visual representations clearly demonstrate a consistent trend: as the proportion of crushed sand replacing river sand increases, there is a notable enhancement in workability parameters across all test methods. This improvement in rheological performance is primarily attributed to the lower water absorption capacity of copper slag compared to river sand. Due to its reduced porosity and angular particle shape, copper slag retains less mixing water, thereby increasing the availability of free water within the concrete matrix. The presence of this additional free water effectively reduces inter-particle friction and enhances the lubricating effect among the aggregates, leading to improved flowability and self-compaction characteristics. In the L-Box Test, higher copper slag content corresponded with an increase in the H_2/H_1 ratio, indicating superior passing ability. Similarly, the J-Ring Test showed a reduced difference in flow diameter between the control and the copper slag-modified mixes, reflecting improved obstruction-free flow. The V-Funnel Test results also confirmed reduced flow times with increasing copper slag content, signifying better filling ability and lower viscosity. Furthermore, all measured values for the SCC mixes fall within the permissible limits specified by EFNARC, validating the adequacy of the mixtures in satisfying the fundamental criteria for SCC. These findings confirm that the inclusion of copper slag not only maintains but actively enhances the rheological properties of SCC, making it a viable and sustainable alternative to natural river sand in high-performance concrete applications.

3.2 Compressive strength test

Compressive strength evaluation was carried out on concrete cube specimens measuring 150 mm × 150 mm × 150 mm in accordance with IS 516:1959 (reaffirmed in 2018), using a standard compression testing machine. The test results, presented in Table 2 and illustrated in Figure 5, demonstrate a progressive increase in the compressive strength of SCC with a higher proportion of crushed sand, with the optimum performance observed at 30% replacement of natural river sand. This enhancement can be attributed to improved particle packing density and more efficient load transfer within the concrete matrix. Furthermore, the incorporation of Alccofine 1203 and GGBS contributed to additional strength development by refining the microstructure and promoting secondary hydration reactions.

Table 2. Compressive strength test

Percentage of Copper Slag	7 Days (MPa)	28 Days (MPa)
0	30.59	48.35
10	31.42	49.59
20	31.62	51.84
30	37.57	55.58
40	31.27	50.57

Strength through increased C-S-H gel formation, due to their high silica and calcium content. These materials refine the microstructure and improve the cement–aggregate bond, leading to better overall mechanical performance and sustainability.

The compressive strength test was performed on 150 mm concrete cubes as per IS 516:1959 (reaffirmed in 2018), using a compression testing machine. Results shown in Table 2 and Figure 6 indicate that compressive strength of SCC improved with increasing crushed sand content, peaking at 30%

replacement of river sand. This improvement is linked to better particle packing and mix efficiency. Additionally, the inclusion of Alccofine 1203 and GGBS enhanced strength through increased C-S-H gel formation, due to their high silica and calcium content. These materials refine the microstructure and improve the cement–aggregate bond, leading to better overall mechanical performance and sustainability.

Figure 5. Strength in compression

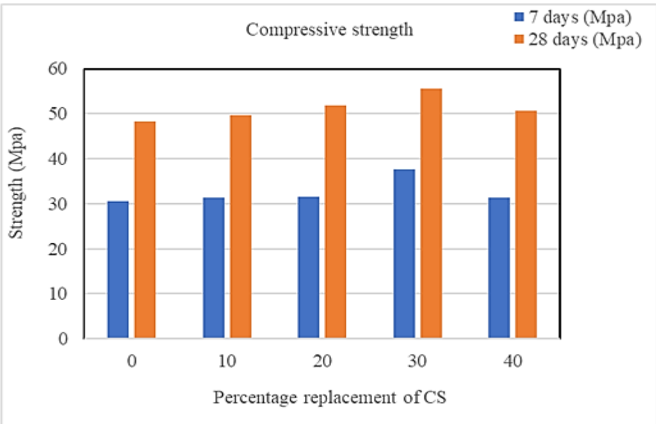


Figure 6. Strength in compression

Table 3. Split tensile strength test

Percentage of Copper Slag	7 Days (MPa)	28 Days (MPa)
0	3.55	5.80
10	3.77	5.45
20	3.79	5.70
30	4.13	6.11
40	4.06	6.06

Figure 7. Split tensile strength

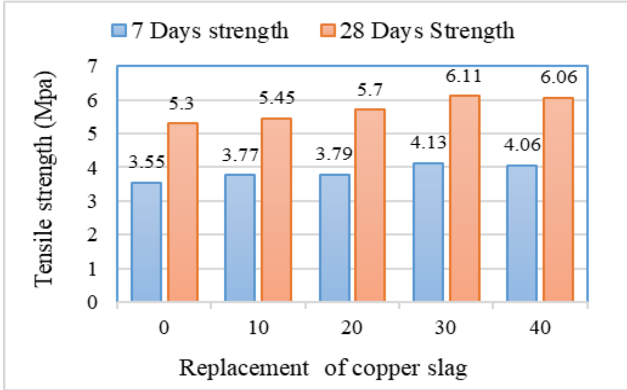


Figure 8. Split tensile strength

3.3 Split tensile strength test

The split tensile strength test was carried out in conformity with IS 516:1959 (reaffirmed in 2018) as shown in Figure 7. This test was performed on specimens of size 150mm diameter and 300 mm length. Table 3 and Figure 8 illustrate the outcome. Tensile strength of SCC has been increased at 30% replacement of copper slag as compared to other resulted output. Secondary cementitious material like Alccofine and GGBS enhance the properties.

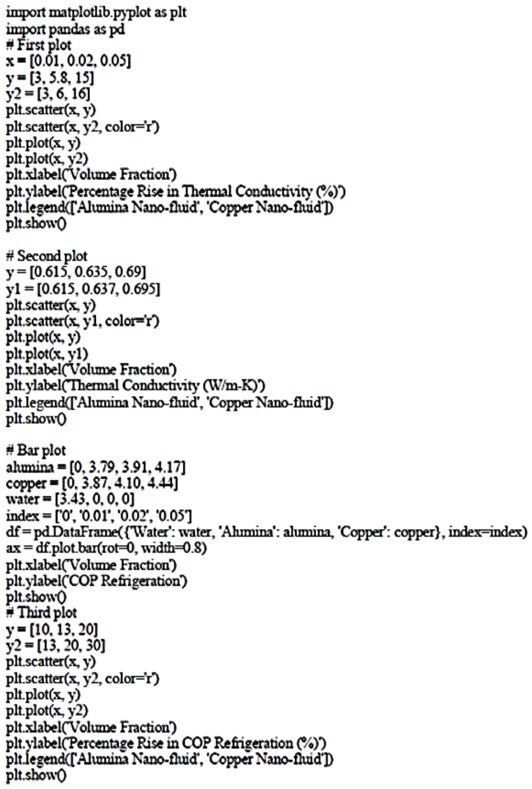
3.4 Flexural strength test

The test was conducted in accordance with the IS 516:1959 standard (reaffirmed in 2018), as detailed in Figure 9. The specimens used were characterized by a cross-sectional dimension of 100 mm and a length of 500 mm. The output results, are presented in Table 4 and Figures 10 to 11. Notably, the bending strength of the SCC was enhanced by up to 30% with a 30% replacement of coarse aggregate, compared to other tested outputs.

Figure 9. Flexural strength test

Table 4. Flexural strength test

Percentage of Copper Slag	7 Days (MPa)	28 Days (MPa)
Zero	3.5	4.5
10	4.75	7.1
20	5	7.5
30	6	8.25
40	5.37	7.75



```
import matplotlib.pyplot as plt
import pandas as pd
# First plot
x = [0.01, 0.02, 0.05]
y = [3, 5.8, 15]
y2 = [3, 6, 16]
plt.scatter(x, y)
plt.scatter(x, y2, color='r')
plt.plot(x, y)
plt.plot(x, y2)
plt.xlabel('Volume Fraction')
plt.ylabel('Percentage Rise in Thermal Conductivity (%)')
plt.legend(['Alumina Nano-fluid', 'Copper Nano-fluid'])
plt.show()

# Second plot
y = [0.615, 0.635, 0.69]
y1 = [0.615, 0.637, 0.695]
plt.scatter(x, y)
plt.scatter(x, y1, color='r')
plt.plot(x, y)
plt.plot(x, y1)
plt.xlabel('Volume Fraction')
plt.ylabel('Thermal Conductivity (W/m-K)')
plt.legend(['Alumina Nano-fluid', 'Copper Nano-fluid'])
plt.show()

# Bar plot
alumina = [0, 3.79, 3.91, 4.17]
copper = [0, 3.87, 4.10, 4.44]
water = [3.43, 0, 0, 0]
index = ['0', '0.01', '0.02', '0.05']
df = pd.DataFrame({'Water': water, 'Alumina': alumina, 'Copper': copper}, index=index)
ax = df.plot.bar(rot=0, width=0.8)
plt.xlabel('Volume Fraction')
plt.ylabel('COP Refrigeration')
plt.show()
# Third plot
y = [10, 13, 20]
y2 = [13, 20, 30]
plt.scatter(x, y)
plt.scatter(x, y2, color='r')
plt.plot(x, y)
plt.plot(x, y2)
plt.xlabel('Volume Fraction')
plt.ylabel('Percentage Rise in COP Refrigeration (%)')
plt.legend(['Alumina Nano-fluid', 'Copper Nano-fluid'])
plt.show()
```

Figure 10. Output of MATLAB

3.5 Prediction of strength values with machine learning

The prediction of strength values has been estimated using MATLAB through experimental values. Figure 10 present developed algorithm for compression strength prediction using MATLAB. Table 5 shows the obtained experimental and predicted compressive strength values. Strength versus the percentage substitution of aggregate is displayed in Figures 12 to 14. From these plots, it was seen that the experimental results are almost similar to the predicted results. The prediction accuracy rates of the six datasets in aspects of the coefficient of determination (R^2), mean squared error (MSE), and root mean square error (RMSE), are found and the readings are demonstrated in Table 5. The R^2 values lies in between 0 to 1 in which more the value of R^2 greater the accuracy of the results obtained. The R^2 value of compressive strength was found to be 0.98 while for Splitting tensile strength the value of R^2 was 0.97 and for flexural strength the value of R^2 was 0.91 which shows that the prediction of SVM model was more accurate.

From Figure 11 and Table 5 it is observed that the experimental and predicted values of model using MATLAB shows a close match. In this model compressive strength values are taken as data set for modelling with Radial Basis Function (RBF) algorithm was used. At 30% replacement getting optimistic strength values. SVM modelling is most reliable too.

Table 5. Experimental and predicted compressive strength

S. No.	% Copper Slag	Compressive Strength Experimental (MPa)	Compressive Strength Predicted (MPa)
1	0%	48.35	48.60
2	10%	49.59	49.84
3	20%	51.84	51.58
4	30%	55.58	53.45
5	40%	50.57	50.82

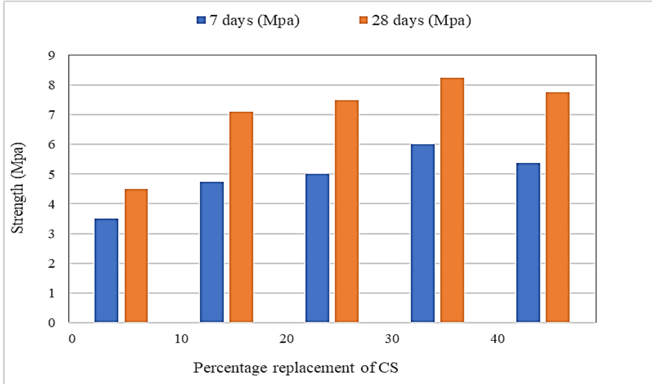


Figure 11. Comparison of flexural strength

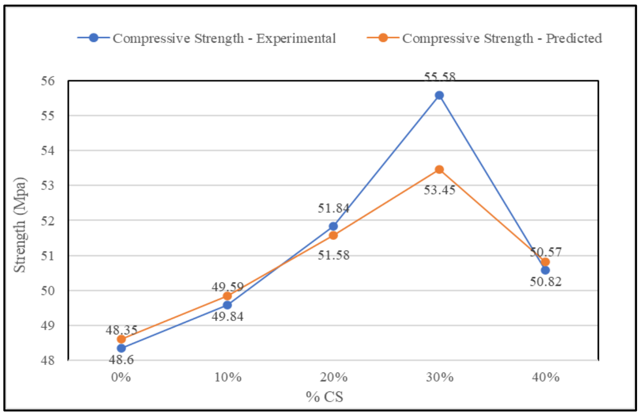


Figure 12. Prediction of compressive strength
Note: R^2 = 0.915, MSE = 0.862, RMSE = 0.8937

3.6 Split tensile strength prediction using MATLAB

The code utilized for both split tensile and compressive strength calculations is the same; the only modifications are in the labels, titles, and legends. Table 6 shows the obtained experimental and predicted split tensile strength values.

Table 6. Experimental and predicted split tensile strength

S. No.	% Copper Slag	Split Tensile Strength Experimental (MPa)	Split Tensile Strength Predicted (MPa)
1	0%	5.80	5.82
2	10%	5.45	5.50
3	20%	5.70	5.73
4	30%	6.11	6.07
5	40%	6.06	6.02

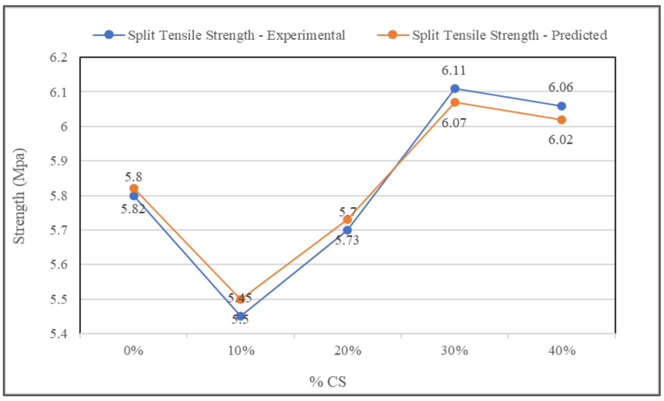


Figure 13. Prediction of split tensile strength
Note: R^2 = 0.9758, MSE = 0.0014, RMSE = 0.0334

It is observed that (Figure 13) the experimental and predicted values of model using MATLAB shows a close match. The SVM model was developed using RBF algorithm for prediction of tensile strength. The graphs showing relatively closer values with the experimental values. In evaluating the results MSE and R^2.

3.7 Flexural strength prediction using MATLAB

The code used for calculating split tensile and compressive strengths is identical, with the sole differences being in the labels, titles, and legends.

From Figure 14 and Table 7 it is observed that the experimental and predicted values of model using MATLAB shows a close match. The values are identical with experimental values.

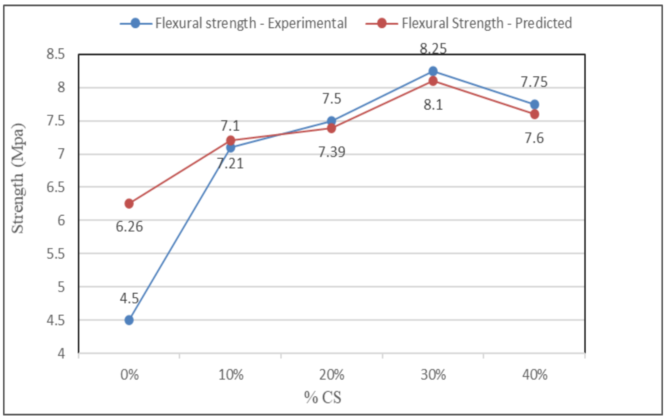


Figure 14. Prediction of flexural strength

Table 7. Experimental and predicted flexural strength

S. No	% Copper Slag	Flexural Strength Experimental (MPa)	Flexural Strength Predicted (MPa)
1	0%	4.50	6.26
2	10%	7.10	7.21
3	20%	7.50	7.39
4	30%	8.25	8.1
5	40%	7.75	7.6

Note: MSE = 0.6382, RMSE = 0.5903, R^2 = 0.91

4. CONCLUSION

The strength improvement in ternary blended SCC using copper slag, silica fume, and Alccofine is due to better particle packing and the pozzolanic activity of the finer materials. Alccofine and GGBS enhance hydration through their reactive silica and calcium content, while copper slag improves packing density and workability, especially up to a 30% replacement level. Beyond this, strength may decline due to copper slag's lower inherent strength. At 30% copper slag, compressive strength increased by 14.95%, tensile by 5.34%, and flexural by 83.33%. MATLAB predictions closely matched experimental outcomes, confirming the mix's reliability and sustainability.

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