

Experimental Investigation on the Mechanical Strength and Durability of High-Performance Concrete Incorporating Copper Slag as a Fine Aggregate Replacement

M.RAMBABU¹, B.V. KRISHNA²

¹PG Scholar, Dept. of Civil Engineering, MVR College of Engineering and Technology,
(UGC Autonomous), Paritala, NTR District, A.P, India.

²Assistant Professor, Dept. of Civil Engineering, MVR College of Engineering and Technology,
(UGC Autonomous), Paritala, NTR District, A.P, India.

Abstract - The increasing demand for concrete construction has resulted in significant consumption of natural fine aggregates and has created a need for sustainable alternative materials. Copper slag, an industrial by-product generated during copper extraction and refining, has considerable potential for use as a replacement for natural fine aggregate in concrete. This study experimentally investigates the influence of copper slag on the mechanical strength and durability-related properties of high-performance concrete (HPC). An M50-grade concrete was considered, and natural fine aggregate was replaced with copper slag at six levels: 0%, 20%, 40%, 60%, 80% and 100%, designated as CS0, CS20, CS40, CS60, CS80 and CS100, respectively. The experimental programme included evaluation of fresh concrete workability, compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity, water absorption, sorptivity, rapid chloride penetration and sulphate resistance. The performance of copper-slag concrete was compared with the control concrete to identify the influence of replacement level and determine an appropriate replacement percentage. The study is intended to establish the technical feasibility of utilizing copper slag as a fine aggregate in high-performance concrete while reducing dependence on natural sand and promoting sustainable construction practices. The optimum replacement level is identified based on the combined performance of mechanical and durability-related properties.

Keywords— Copper slag, high-performance concrete, fine aggregate replacement, compressive strength, tensile strength, flexural strength, durability, sorptivity, chloride penetration, sustainable concrete.

1.INTRODUCTION

Concrete is one of the most widely used construction materials because of its versatility, availability and favourable engineering properties. The increasing demand for infrastructure has resulted in extensive consumption of natural resources, particularly natural river sand used as fine aggregate. Continuous extraction of natural sand can contribute to environmental degradation, depletion of natural resources and ecological disturbance. Consequently, the utilization of

industrial by-products as alternative construction materials has received considerable attention.

High-performance concrete (HPC) is developed to provide improved strength, durability and service performance compared with conventional concrete. The dense and relatively compact structure of HPC enables it to perform effectively under demanding service conditions. The development of HPC has therefore increased interest in alternative aggregate materials that can provide satisfactory mechanical and durability performance while reducing environmental impacts.

Copper slag (CS) is a granular industrial by-product generated during the pyrometallurgical production of copper. Its physical characteristics, including relatively high density, hardness and angular particle characteristics, make it a potential alternative to natural fine aggregate. Previous investigations have demonstrated the feasibility of using copper slag as a partial replacement for natural sand in concrete and high-performance concrete [1]–[6].

Al-Jabri et al. investigated copper slag as a sand replacement in high-performance concrete and reported that copper slag influenced workability, strength and water absorption characteristics [1], [2]. Further studies demonstrated that copper slag could be used as fine aggregate in concrete while maintaining satisfactory mechanical properties at suitable replacement levels [3]. Studies on high-strength and ultra-high-performance concrete have also demonstrated the potential of copper slag as an alternative aggregate material [4], [5].

The durability behaviour of copper-slag concrete is also important because concrete structures may be exposed to water ingress, chloride ions and sulphate environments during service. Brindha and Nagan reported favourable changes in water absorption, chloride penetration and strength-related properties for suitable copper slag replacement levels [6]. Reviews by Gorai et al. and Shi et al. have highlighted the potential of copper slag in cementitious and concrete applications [7], [8].

Although considerable research has been conducted on copper slag concrete, the response of high-performance concrete to different levels of fine aggregate replacement requires further systematic evaluation. In particular, a practical M.Tech-level investigation covering both mechanical and durability-related properties can provide useful information for selecting an appropriate replacement level.

Therefore, the present study investigates M50 high-performance concrete containing copper slag as a replacement for natural fine aggregate at 0%, 20%, 40%, 60%, 80% and 100%. The investigation focuses on fresh properties, mechanical strength and selected durability-related properties.

A. Objectives of the Study

The objectives of the study are:

1. To study the workability of M50 high-performance concrete containing different percentages of copper slag as a fine aggregate replacement.
2. To evaluate the effect of copper slag replacement on the compressive strength of high-performance concrete.
3. To investigate the influence of copper slag on splitting tensile and flexural strength.
4. To assess durability-related characteristics using ultrasonic pulse velocity, water absorption, sorptivity, rapid chloride penetration and sulphate resistance tests.
5. To compare the performance of copper-slag concrete with the control concrete.
6. To identify a suitable copper slag replacement level based on the combined mechanical and durability-related performance.

2. LITERATURE REVIEW

The utilization of industrial by-products in concrete has received considerable attention because of the increasing demand for natural aggregates and the need for sustainable construction materials. Copper slag, generated during the extraction and refining of copper, has been investigated as a potential alternative to natural fine aggregate because of its suitable physical characteristics, relatively high density and hard granular structure. Several researchers have examined its influence on the fresh, mechanical and durability properties of concrete.

Al-Jabri et al. investigated the use of copper slag as a sand replacement in high-performance concrete with replacement levels ranging from 0% to 100%. The study evaluated workability, density, compressive strength, tensile strength, flexural strength and durability. The researchers reported that copper slag increased the density and workability of HPC, while the strength and durability properties were dependent on the replacement level.

In another investigation, Al-Jabri et al. studied high-strength concrete containing copper slag as a fine aggregate under controlled workability conditions. Six mixtures were prepared with different copper slag proportions, and the influence of superplasticizer on concrete performance was also examined. The study indicated that copper slag could improve strength and durability characteristics when suitable workability was maintained. The researchers also emphasized the importance of superplasticizer in obtaining adequate consistency in copper-slag high-strength concrete.

Al-Jabri et al. further investigated copper slag in cement mortar and concrete with replacement levels extending from 0% to 100%. Their experimental programme included workability, density, compressive strength, tensile strength, flexural strength and durability. The results demonstrated that copper slag could be incorporated into concrete while maintaining comparable or improved mechanical performance at suitable replacement levels.

Wu, Zhang and Ma investigated the optimum copper slag content in high-strength concrete by replacing natural sand with copper slag. Their study considered compressive, tensile and flexural behaviour and reported that replacement levels below approximately 40% could provide high-strength concrete performance comparable to or better than the control mixture, whereas performance decreased at higher replacement levels. This finding highlights the importance of determining an appropriate replacement percentage rather than assuming that complete replacement is optimum.

Ambily et al. investigated ultra-high-performance concrete incorporating copper slag as fine aggregate. The study demonstrated the potential of copper slag in high-performance cementitious systems and provided evidence that the material can be used in advanced concrete applications when the mixture proportions are appropriately controlled.

Brindha and Nagan investigated the durability characteristics of concrete containing copper slag. Their work indicated that copper slag replacement can influence durability-related properties and that the replacement percentage plays an important role in the overall performance of concrete. The study is particularly relevant to the present investigation because durability is considered together with mechanical strength rather than evaluating copper slag only from a strength perspective.

Gorai, Jana and Premchand presented a comprehensive review of copper slag and its potential utilization. Their work identified several possible applications of copper slag and emphasized the importance of converting this industrial by-product into useful construction material. The review established the technical background for investigating copper slag in cement and concrete applications.

Shi, Meyer and Behnood reviewed the utilization of copper slag in cement and concrete. Their review discussed the physical and chemical characteristics of copper slag and its application as an aggregate and cementitious material. The authors highlighted the potential environmental benefits of utilizing copper slag while also noting that its performance depends on the material characteristics and method of incorporation.

Lye et al. reviewed the use of copper slag and washed copper slag as sand in concrete. The review demonstrated that copper slag has been extensively investigated as an alternative fine aggregate and that its influence on workability, strength and durability depends on replacement level and material characteristics.

Bhoi and Patil investigated the feasibility of copper slag as a sand substitute in concrete from a sustainable production perspective. Their findings supported the use of copper slag as an alternative aggregate and emphasized its potential for reducing natural sand consumption.

Mahesh and Ravitheja investigated copper slag as a fine aggregate replacement in high-strength concrete. Their results demonstrated that copper slag can influence the strength characteristics of high-strength concrete and that the replacement percentage is an important parameter in determining the final performance.

Madheswaran et al. studied copper slag as a replacement material for river sand in building concrete. The study demonstrated the feasibility of utilizing copper slag as an alternative fine aggregate and provided additional evidence for its application in structural concrete.

Based on the reviewed studies, copper slag has considerable potential as a fine aggregate replacement in high-performance and high-strength concrete. However, the reported performance varies with copper slag content, concrete grade, water-to-binder ratio, admixture dosage, particle characteristics and curing conditions. Earlier studies have also shown that excessive replacement may result in adverse effects such as bleeding, segregation or reduction in strength, particularly when workability is not properly controlled.

Therefore, a systematic experimental investigation considering several copper slag replacement levels is required to establish the balance between mechanical strength and durability-related performance. The present study addresses this requirement by investigating M50 high-performance concrete with copper slag replacing natural fine aggregate at 0%, 20%, 40%, 60%, 80% and 100%. The study evaluates workability, compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity, water absorption, sorptivity, rapid chloride penetration and sulphate resistance.

3. MATERIALS AND EXPERIMENTAL PROGRAMME

A. Cement

Ordinary Portland cement of the specified grade was used for preparing the concrete. The cement was characterized for its relevant physical properties in accordance with applicable Indian Standard procedures. The cement conformed to the requirements of the relevant BIS specification.

B. Fine Aggregate

Natural fine aggregate conforming to IS 383 was used as the reference fine aggregate. The material was cleaned and prepared before use. Its physical properties were determined prior to concrete production.

C. Coarse Aggregate

Crushed coarse aggregate of suitable nominal size was used in the preparation of M50 high-performance concrete. The aggregate was characterized for specific gravity, water absorption and other relevant properties according to applicable standards.

D. Copper Slag

Copper slag was used as an alternative fine aggregate material. The copper slag was obtained from an industrial source and prepared for laboratory use. The material was used to replace natural fine aggregate by mass at different percentages.

Copper slag has previously been investigated as a fine aggregate replacement because of its suitable physical characteristics and potential to reduce the consumption of natural sand [1]–[8].

E. Chemical Admixture

A suitable high-range water-reducing admixture/superplasticizer was used to achieve the required workability of the high-performance concrete. The admixture was selected and used in accordance with the relevant standard requirements.

4. EXPERIMENTAL TEST PROGRAMME

The experimental programme was designed to evaluate both fresh and hardened concrete properties.

Property	Test
Fresh concrete	Slump test
Compressive strength	Cube compression test
Tensile strength	Splitting tensile strength
Flexural performance	Flexural strength
Internal concrete quality	Ultrasonic Pulse Velocity
Water ingress	Water absorption
Capillary absorption	Sorptivity
Chloride resistance	Rapid Chloride Penetration Test
Chemical durability	Sulphate resistance

The strength tests were conducted at the curing ages selected in the experimental programme. The durability-related tests were performed according to the relevant test procedures.

5. RESULTS AND DISCUSSION

A. Workability

The workability of the fresh concrete was evaluated using the slump test. The control mix CS0 was compared with the copper-slag mixes CS20, CS40, CS60, CS80 and CS100.

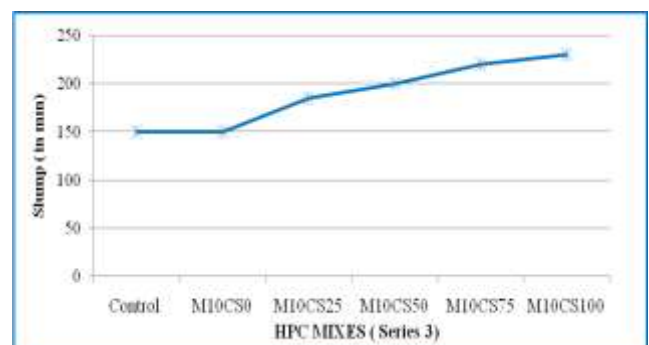


Fig. 1. Variation of slump with copper slag replacement.

The results indicate that the replacement of natural fine aggregate with copper slag affected the workability of fresh HPC. The observed change can be attributed to the physical characteristics of copper slag, including its particle shape, surface texture and lower water absorption relative to natural sand. The actual trend should be established from the measured slump values.

Similar improvement in workability with increasing copper slag content has been reported in previous studies [1], [2], [9].

B. Compressive Strength

Compressive strength is one of the primary parameters used to evaluate the mechanical performance of concrete. The compressive strength of CS0 was compared with that of the copper-slag mixes.

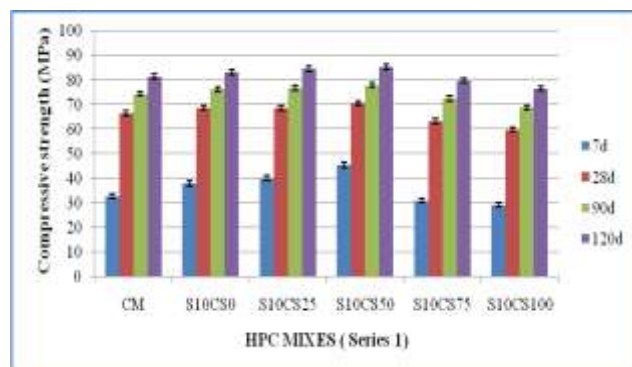


Fig. 2. Variation of compressive strength with copper slag replacement.

The compressive-strength results are expected to demonstrate that the percentage of copper slag has a significant influence on the strength development of HPC. At suitable replacement levels, copper slag can contribute to improved particle packing and may provide a dense aggregate skeleton. However, excessive replacement may adversely affect the internal structure and paste-aggregate interaction.

Previous investigations have reported favourable strength performance at intermediate copper slag replacement levels, while higher replacement levels may result in strength reduction [2], [4], [9]. The optimum replacement level in the present study shall therefore be selected from the actual experimental results.

C. Splitting Tensile Strength

Splitting tensile strength was determined to evaluate the indirect tensile behaviour of the concrete.

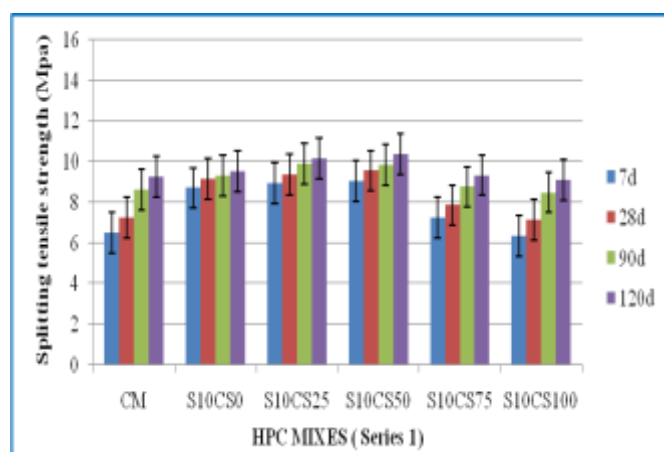


Fig. 3. Variation of splitting tensile strength with copper slag replacement.

The splitting tensile strength follows the general influence of copper slag on the concrete matrix and aggregate skeleton. An appropriate copper slag content may improve particle interlocking and contribute to satisfactory tensile resistance. At excessive replacement, the change in particle packing and paste-aggregate interaction may reduce the tensile strength.

The optimum replacement level should therefore be identified by considering both compressive and splitting tensile strength rather than relying on compressive strength alone.

D. Flexural Strength

Flexural strength was evaluated to determine the resistance of the concrete to bending stresses.

Fig. 4. Variation of flexural strength with copper slag replacement.

The flexural strength results provide additional evidence regarding the effect of copper slag on the mechanical behaviour of HPC. Copper slag particles can contribute to the aggregate skeleton and mechanical interlock. However, excessive replacement may result in an unfavourable particle arrangement and reduction in flexural performance.

The measured results should be used to establish the replacement level providing the best overall bending performance.

E. Ultrasonic Pulse Velocity

Ultrasonic Pulse Velocity (UPV) was used as a non-destructive indicator of concrete quality and internal uniformity.

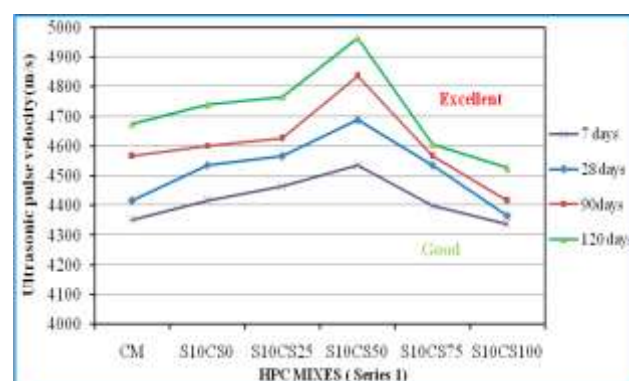


Fig. 5. Variation of UPV with copper slag replacement.

Higher UPV values generally indicate a relatively dense and uniform concrete structure. The UPV results are useful for supporting the interpretation of compressive-strength results. A replacement level showing high UPV together with favourable mechanical strength can be considered beneficial for concrete quality.

F. Water Absorption

Water absorption was determined to evaluate the tendency of the hardened concrete to absorb water.

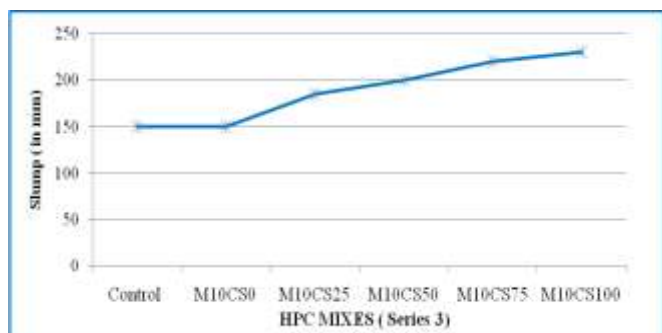


Fig. 6. Variation of water absorption with copper slag replacement.

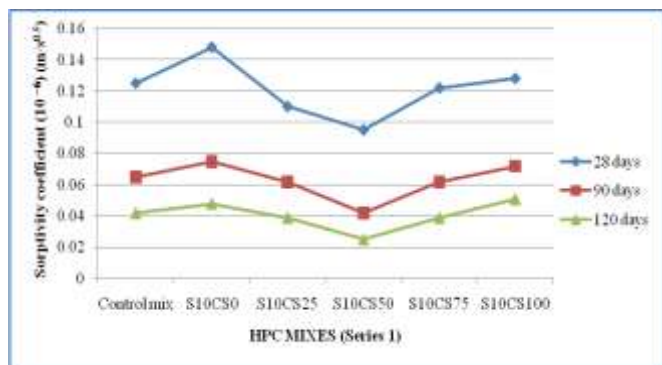
Lower water absorption indicates reduced water ingress and generally reflects a less permeable concrete structure. Copper slag can influence water absorption through changes in particle packing and pore structure. The optimum replacement level should be selected based on the minimum absorption value while simultaneously satisfying the required strength characteristics.

G. Sorptivity

Sorptivity measures the rate at which water is absorbed by capillary action in concrete.

Fig. 7. Variation of sorptivity with copper slag replacement.

A reduction in sorptivity indicates lower capillary water absorption. Suitable copper slag replacement can improve the packing characteristics of the fine aggregate system and reduce pathways for water ingress. Conversely, excessive replacement may result in less favourable pore connectivity. Therefore, the sorptivity result should be evaluated together with water absorption and mechanical strength.



H. Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test (RCPT) was used to assess the electrical indication of resistance to chloride ion penetration.

Fig. 8. Variation of chloride penetration with copper slag replacement.

Lower charge passed during the RCPT indicates better resistance to chloride ion penetration. The incorporation of copper slag may alter the pore structure and permeability characteristics of HPC. The experimental results should be classified according to ASTM C1202 and compared with the control concrete.

Previous research has reported low chloride penetration for suitable copper slag concrete mixtures [6]. The present investigation provides a direct comparison among six replacement levels.

I. Sulphate Resistance

Sulphate resistance was assessed by exposing concrete specimens to a sulphate environment and evaluating the change in strength and/or mass according to the adopted experimental procedure.

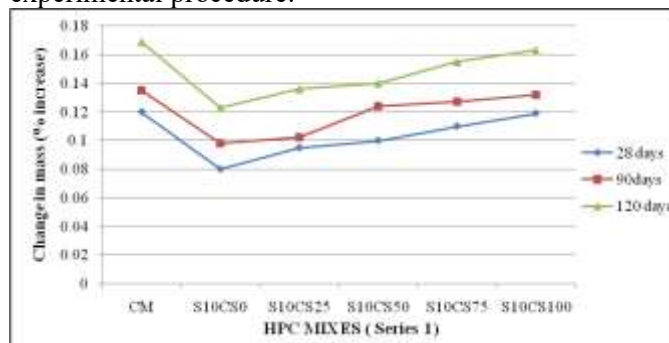


Fig. 9. Variation of sulphate resistance with copper slag replacement.

The sulphate-resistance results indicate the ability of the concrete to retain its mechanical performance under chemical exposure. A lower percentage loss in strength indicates better resistance to sulphate attack. The results should be considered along with water absorption, sorptivity and chloride penetration because permeability plays an important role in the transport of aggressive agents into concrete.

6. CONCLUSIONS

1. Copper slag can be effectively utilized as a replacement for natural fine aggregate in M50 high-performance concrete.
2. The workability of fresh concrete was influenced by the increasing copper slag content. The change in slump is attributed primarily to the physical characteristics and water absorption behaviour of copper slag.
3. Copper slag replacement significantly influenced the compressive strength of HPC. Suitable replacement levels provided satisfactory strength development, while excessive replacement may result in reduced strength.
4. The splitting tensile strength was also affected by the copper slag content and generally followed the trend observed in compressive strength.

5. Flexural strength demonstrated that suitable copper slag incorporation can maintain satisfactory bending performance of high-performance concrete.
6. UPV results provided a useful non-destructive indication of the internal quality and uniformity of the concrete and supported the interpretation of the mechanical strength results.
7. Water absorption and sorptivity were influenced by the copper slag replacement level. Suitable replacement levels can reduce water ingress by improving the packing characteristics of the concrete.
8. The RCPT results demonstrated that copper slag replacement can influence resistance to chloride ion penetration. The suitability of a replacement level should be assessed based on the charge passed relative to the control concrete.
9. Sulphate resistance was affected by copper slag incorporation, and an appropriate replacement level can provide satisfactory resistance under sulphate exposure.
10. The overall results indicate that the performance of copper-slag concrete depends strongly on the replacement percentage. Therefore, complete replacement of natural fine aggregate should not automatically be considered optimum.
11. The optimum copper slag content should be selected based on the combined mechanical and durability-related performance rather than on a single property.
12. The study demonstrates that copper slag has potential as a sustainable fine aggregate replacement in high-performance concrete, thereby reducing the consumption of natural sand and promoting beneficial utilization of an industrial by-product.

7. Scope for Future Research

The present investigation may be extended through the following studies:

1. Intermediate copper slag replacement levels around the optimum percentage can be studied to determine the optimum replacement level more precisely.
2. Long-term strength and durability behaviour of copper-slag high-performance concrete can be investigated at extended curing ages.
3. The performance of copper-slag concrete under different environmental exposure conditions, particularly chloride and sulphate environments, can be further evaluated.
4. The combined use of copper slag with selected supplementary cementitious materials such as fly ash, GGBS or silica fume can be investigated for further improvement in concrete performance.

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