

Experiment on Ultra High Performance Concrete using Copper Slag

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Abstract – This research presents an experimental investigation on Ultra-High Performance Concrete (UHPC) of grade M150 developed by incorporating copper slag as a partial substitute for fine aggregate. The study aims to enhance mechanical performance while promoting sustainable material usage through the utilization of industrial by-products. Various proportions of copper slag were introduced to evaluate their influence on strength and durability characteristics. Test results demonstrate that controlled inclusion of copper slag improves compressive and tensile strength due to better particle arrangement and reduced internal porosity. Maximum performance was observed at a replacement level of 20%, beyond which a gradual decline in strength occurred. The study confirms that copper slag can be effectively utilized in UHPC to produce high-strength and durable concrete with reduced environmental impact.

Keywords: Ultra-High Performance Concrete, Copper Slag, Sustainable Materials, Mechanical Properties, Fine Aggregate Replacement, Compressive Strength, Durability, Industrial By-products

1. Introduction

1.1 Background

Modern construction requires materials that can provide high strength, durability, and long service life under demanding conditions. Ultra-High Performance Concrete (UHPC) is an advanced material designed to meet these requirements. It is characterized by a dense internal structure, low water-to-binder ratio, and optimized particle distribution, which together result in very high compressive strength and durability. Due to these properties, UHPC is increasingly used in structures such as bridges, high-rise buildings, and rehabilitation works.

1.2 Problem Statement

Despite its advantages, UHPC production involves a large quantity of cement and expensive mineral admixtures. This increases both the cost and environmental impact, particularly due to carbon emissions associated with cement manufacturing. These challenges limit the large-scale use of UHPC in practical construction.

1.3 Need for Study

To make UHPC more sustainable and economical, it is necessary to explore alternative materials that can partially replace cement. Industrial by-products such as copper slag offer a promising solution. These materials not only reduce waste disposal issues but also have the potential to improve the internal structure of concrete through filler and pozzolanic effects.

1.4 Objectives of the Study

The primary objectives of this investigation are:

- To develop M150 grade UHPC using copper slag as a partial replacement material
- To evaluate the effect of copper slag on workability and mechanical properties
- To determine the optimum replacement level for maximum strength
- To study the durability performance under different conditions
- To analyse the changes in microstructure contributing to strength development.

2. Literature Review

The review is the summary of the previously published article:

Srinivasan et al. (2015) This study aims to assess the possibility of replacing cement with Bagasse Ash in order to reduce carbon emissions and agricultural waste in Ultra High Strength Concrete. The results showed that it enhances workability, chemical resistance, and compressive strength.[1]

Marvila et al. (2021) This review supports the use of alkali-activated cement and supplementary reactive materials such as silica fume to reduce the high cost and environmental effects of UHPC. It highlights the use of industrial waste materials to attain higher durability with comparable strength to conventional materials.[2]

He et al. (2023) The research is focused on the performance of the bond between UHPC and normal concrete, where the roughness of the interface and curing are considered to be the key factors in the reinforcement of the structure. Additionally, the research has emphasized the importance of polypropylene fibers in the enhancement of the anti-burst performance of UHPC at high temperatures.[3]

Liu et al. (2024) In this paper, the superior properties of UHPC in terms of dynamic response and mechanical properties in protecting structures against blast events and progressive collapse are discussed. Future developments in eco-friendly materials, 3D printing, and machine learning-aided design are expected in UHPC.[4]

Kravanja et al. (2024) This literature review focuses on the evolution of UHPC. The material has a high packing density and is reinforced with fibers. This means that it is now ductile rather than brittle. Although it is durable, it is still in its early stages of research, and it is trying to combat its expensive production and environmental impact through sustainable industrial by-products.[5]

Suresh et al. (2024) The comprehensive research assesses the UHPC with strength in excess of 150 MPa with respect to the stress-strain relationship and fracture energy of the mix designs. The research proves that the toughness and post-peak behavior are greatly improved by varying the volume of steel fibers and that it is ready for commercialization in India.[6]

Mohd Zahid et al. (2025) The review of this article discusses green UHPC for on-site rehabilitation, incorporating waste materials such as sugarcane bagasse ash to minimize the effects of CO₂ footprint and energy consumption. The waste-based mixes are reported to decrease autogenously shrinkage, increasing the bond strength with existing concrete. [7]

Patil et al. (2015) This study investigates the effect of replacing natural sand with Copper Slag (CS) in M-30 grade concrete to address the scarcity of natural aggregates and reduce industrial waste. The results indicate that increasing the percentage of Copper Slag enhances the workability and density of the concrete, with a maximum increase in

compressive strength of 34% observed at a 20% replacement level.[8]

Prasanna and Kishore et al. (2020) The research focuses on the performance of High-Performance Concrete (HPC) by replacing cement with Silica Fume (5%–15%) and sand with Copper Slag (20%–100%). The study concludes that a combination of 10% Silica Fume and 40% Copper Slag provides the optimal mechanical properties for HPC. [9]

Mehetre et al. (2016) The research focuses on the feasibility of using Copper Slag as a partial and full replacement for fine aggregates in concrete to promote sustainability and reduce environmental waste. Experimental results demonstrate that the compressive strength increases with the addition of Copper Slag up to a 40% replacement level, after which a slight decrease is observed. [10]

G. S. Kumar et al. (2018) This study investigates Class-F fly ash (30%) and 10% silica fume and partial replacement of sand by 20% of copper slag for all specimen are used in part to substitute cement in the preparation of the specimens. The sample specimens consist of concrete cubes, cylinders and prisms.[11]

Venkataraman et al. (2022) This study investigates the partial replacement of fine aggregate with copper slag in M25 concrete, finding that strength increases up to 40% substitution. The results indicate that a 60% replacement level yields the highest compressive strength, though workability increases while further additions eventually reduce strength.[12]

Tomar and Malviya et al. (2019) This research explores the simultaneous partial replacement of sand and cement with copper slag and rice husk ash in M30 grade concrete. The findings show that while copper slag improves resistance to sulphate attack and reduces production costs, it increases the self-weight of the concrete by up to 18%.[13]

Kamble and Shete et al. (2025) This experimental work evaluates the mechanical properties of M30 concrete by replacing fine aggregate with copper slag at low proportions of 0% to 16%. The study concludes that the optimum replacement level is 12%, which enhances compressive, tensile, and flexural strength compared to conventional concrete.[14]

Gandhare and Yedage et al. (2020) This paper examines the effect of copper slag replacement on M25 concrete, focusing on hardened properties and ultrasonic pulse velocity. Results demonstrate that a 40% replacement level maximizes mechanical strength, while workability and density increase significantly with higher slag content.[15]

Nair et al. (2025) The study focuses on developing Reactive Powder Concrete (RPC) using copper slag and pozzolanic materials to achieve ultra-high compressive strengths exceeding 100 MPa. It highlights that the combination of micro steel fibers and fumed silica optimizes

particle packing and durability, providing an eco-efficient alternative for high-performance construction.[16]

Magarade and Joshi et al. (2022) This investigation focuses on M25 grade concrete with 5% to 20% copper slag replacement to improve mechanical strength and reduce environmental pollution. The results indicate that while compressive strength remains comparable to conventional concrete up to 20% replacement, the material shows better resistance to sulphate attack but low resistance to acid.[17]

Bhosale et al. (2020) This research evaluates the use of copper slag as an alternative to river sand due to mining restrictions and high costs. The study concludes that a 50% replacement level is the optimum proportion for achieving high-performance concrete while gradually increasing the unit weight.[18]

Karthikeyan et al. (2025) The study assesses replacing M-Sand with copper slag in M30 concrete at ratios between 10% and 50% to address sand scarcity. Findings reveal that maximum strength is achieved at 30% to 40% replacement, as higher levels deteriorate bonding and lead to insufficient interlocking.[19]

Fantu et al. (2021) investigated the properties of high-strength concrete (HSC) by replacing cement with varying amounts of Fly Ash (FA). Motivated by the dual goals of reducing CO₂ emissions and utilizing industrial by-products, the study performed a detailed experimental program. It was found that a 10% replacement of cement with fly ash was the optimum amount, as it increased the compressive strength of the concrete and, notably, also improved the workability (slump) of the fresh mix.[20]

Ahmad et al. (2021) carried out an experimental investigation on High-Performance Concrete (HPC) using Rice Husk Ash (RHA) as a partial cement replacement. The primary motivation was to utilize this highly pozzolanic agricultural waste to create a more sustainable and durable concrete. The findings indicated that a 10% replacement with RHA yielded the best results, recording the highest compressive strength, splitting tensile strength, and flexural strength at all curing ages, while also refining the microstructure.[21]

Arivalagan (2022) conducted an experimental study on High-Performance Concrete (HPC) by partially replacing cement with Waste Marble Powder (WMP), a by-product of the marble processing industry. The research was motivated by the need to find a sustainable use for the vast quantities of WMP that pose an environmental disposal problem. The results showed that a 10% replacement of cement with WMP was optimal,

leading to an increase in compressive strength, split tensile strength, and flexural strength compared to the control mix, due to the fine powder's filler effect and pozzolanic activity.[22]

Wang et al. (2018) evaluated the mechanical enhancements of Ultra-High-Performance Concrete (UHPC) by using Steel Slag Powder (SSP) as a partial cement replacement. The study was driven by the goal of reducing the high binder cost and CO₂ footprint of UHPC, while valorizing a major by-product from steel manufacturing. It was found that replacing up to 20% of the cement with SSP could produce UHPC with a denser microstructure and comparable compressive strength to the reference mix after 28 days, while significantly improving its long-term strength.[23]

Pacheco-Torgal et al. (2010) investigated the use of Waste Ceramic Powder (WCP) from sanitary ware and tile production as a partial cement replacement in high-strength concrete. The motivation was to find a solution for the non-biodegradable ceramic waste accumulating in landfills. The results indicated that WCP acts as a highly reactive pozzolan, leading to a significant refinement of the concrete's pore structure. This resulted in a notable increase in durability, particularly a high resistance to chloride ion penetration and chemical attack.[24]

Ganesan et al. (2007) performed an experimental study on High-Performance Concrete using finely ground Waste Glass Powder (WGP) as a pozzolanic replacement for cement. Driven by the dual challenge of waste glass disposal and the high energy consumption of cement production, the study tested various replacement levels. The results concluded that a 20% replacement with WGP showed the best performance, exhibiting higher compressive strength than the control concrete at later ages (90 days) and demonstrating significantly better durability in terms of chloride resistance.[25]

Zhao et al. (2021) investigated the feasibility of using Iron Ore Tailings (IOT) as a complete replacement for fine aggregate in Ultra-High-Performance Concrete (UHPC). The research was motivated by the environmental burden and dam-failure risks associated with the massive stockpiling of IOT, a waste product of mining. The experimental results demonstrated that UHPC prepared with IOT exhibited superior mechanical properties, including higher compressive and flexural strength, due to the high angularity and pozzolanic activity of the fine tailings, proving it a viable and sustainable solution.[26]

Taфраoui et al. (2017) investigated studied of the effect of substituting cement with Metakaolin (MK) on the properties of Ultra-High-Performance Concrete (UHPC). The study was driven by the need to enhance the mechanical properties and durability of UHPC beyond what silica fume alone can provide. The results indicated that the high pozzolanic reactivity of MK significantly accelerated the hydration process, leading to a much higher early-age compressive strength and a refined pore structure, which greatly improved the concrete's resistance to chloride ion penetration.[27]

3. SCMs used in UHPC

Most popular types of SCMs used are (as indicated in Table 1): fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume, metkaolin, limestone powder, steel slag powder and rice husk ash.

Table 1: SCMs used in UHPC

SCM Type	Properties	Applications	Advantages	Limitations	Challenges
Fly Ash	Fine spherical particles; available in Type F (pozzolanic) and Type C (cementations + pozzolanic); improves packing density and workability	UHPC structural members, bridge decks, precast panels	Reduces water demand, improves workability, enhances long-term strength and durability	Slow early strength development; variability in composition	Ensuring consistent quality and supply; compatibility with super plasticizers
Ground Granulated Blast-Furnace Slag (GGBS)	Latent hydraulic SCM with high CaO and SiO ₂ contents; can replace 30–60% of cement content	Durable UHPC infrastructure, marine/bridge construction	Improves sulphate resistance, lowers heat of hydration, enhances durability	May reduce early-age strength; requires activation	Controlled curing needed for reactivity activation; cost of fine grinding
Silica Fume	Extremely fine amorphous SiO ₂ (0.1 μm); highly reactive	Fibre-reinforced UHPC, thin precast elements	Increases strength in compression and tension, impermeability, and refine pore structure.	Decreases workability due to increased surface area; need for high-range admixtures	Uniform dispersion; mitigating autogenous shrinkage
Rice Husk	Agricultural by-	Sustainable	Substitute	High water	Burning must be

Ash (RHA)	product; high amorphous silica (70–80% SiO ₂)	UHPC, rural infrastructure projects	silica fume; makes it impermeable and durable; autogenous shrinkage is decreased.	absorption; reduced workability	controlled so amorphous; consistency must be adjusted.
Metkaolin	Calcined clay (Al ₂ O ₃ ·2SiO ₂); highly pozzolanic	Eco-friendly UHPC, sustainable architectural concrete	Accelerates the early strength development of the concrete and reduces the porosity and increases durability and uniformity of color	Expensive in comparison to fly ash/slag, uses more water	Maintaining uniform fineness; limited large-scale supply
Steel Slag Powder	By-product of steel industry; rich in CaO and Fe ₂ O ₃	Structural UHPC, eco-efficient concrete	Reduces CO ₂ footprint, improves modulus and microstructure	Free lime: free lime could cause potential volume instability; free lime composition varies with conditions;	Stabilisation of slag necessitated a pre-treatment and inconsistencies in supply
Limestone Powder	Finely ground CaCO ₃ ; acts as filler and accelerant	UHPC pavements, precast blocks, lightweight structures	Improves packing density, accelerates hydration, reduces shrinkage	Limited chemical reactivity; possible reduction in later strength	Optimization of replacement level to balance strength and durability

Ultra-high-performance concrete (concrete with compressive strength higher than 150 MPa) has very high durability due to the use of SCM in the production of such concrete. Each type of SCM has some special properties that benefit concrete; for example, silica fume and GGBS increase the durability of concrete, whereas fly ash and met kaolin increase the workability and strength of concrete.

4. Material & Methodology

4.1 Materials

The materials used in making M150 grade Ultra High-Performance Concrete (UHPC) are stated as follows:

Cement: Ordinary Portland cement (OPC) of 53 grade was used as a main binding agent.

Silica Fume: Silica fume, an industrial by-product from silicon and ferrosilicon industries was used to make the concrete stronger and minimize porosity because silica fume has high reactivity and very fine particles.

Fine Aggregates: Fine aggregates that included quartz sand were locally available. These were used to ensure the appropriate gradation and high packing density necessary in making UHPC.

Super plasticizer: A Polycarboxylate Ether (PCE)-based super plasticizer was added to make concrete more workable at very low water binder ratio.

Copper slag: Industrial waste materials were used to replace fine aggregates partially. It helped in increasing the density and workability of concrete and also made it strong.

Fly ash: The addition of fly ash improved workability and performance of concrete in the long term as well as reduced the amount of cement.

GGBS: GGBS was used as an additive cement to improve the performance and make the concrete durable.

Water: Potable water was used in making the concrete.

4.2 Mix Proportion

The mix design was developed based on particle packing theory for the purpose of obtaining maximum density and strength. The water-cement ratio remained constant for all the trials performed during this study.

Details of Mix Design (as per IS 10262:2019):

- Grade: M150
- Quantity of cement: 812 kg/m³

- Amount of fly ash: 166 kg/m³
- Quantity of silica fume: 92 kg/m³
- Quantity of fine aggregates: 1168 kg/m³
- Amount of water: 178 kg/m³
- Quantity of superplasticiser: 13 kg/m³
- Steel fibres used: 2% by volume

4.3 Experimental Methodology

The following tests are to be carried out at different intervals of time post formulation of Ultra High Performance concrete:

1. Compressive Strength Test [IS 10262:2019]
2. Split Tensile Strength Test [IS 10262:2019]
3. Acid Attack Test [IS 10262: 2019]

1. Compressive Strength Test (IS 10262:2019)

Cubes of concrete having dimensions of 150mm x 150mm x 150mm were cast to conduct the tests on compressive strength. After casting, the cubes remained untouched for 24 hours before being demoulded. The specimens were then placed in water for 7 days and 28 days respectively.

Upon being cured, the specimens were tested in the compression test machine following IS guidelines. Uniform loading on the specimen up to its failure point gave the maximum load value which was used to calculate the compressive strength of the concrete specimen.

2. Split Tensile Strength Test (IS 10262:2019)

Specimens of 150 mm diameter and 300 mm height in cylindrical form were made to assess the tensile strength of concrete. Just like the cubic specimens, the cylindrical specimens were stripped from the mould after 24 hours and cured in water for 7 and 28 days.

For the split tensile strength test, the specimen was placed in a compression testing machine where load was applied longitudinally on the specimen.

3. Acid Attack Test

Testing of UHPC Grade M150 with Acid Attack Test is done for evaluating the durability of the concrete against harsh acidic surroundings, with weight loss and compressive strength being the criteria for assessment. In the case of M150 UHPC, cubes of size 150 mm x 150 mm x 150 mm are normally utilized; however, because of the high strength of this concrete, smaller cubes (for example, 100 mm) have been used by researchers because of their high strength.

4.4 Result & Discussion

1. Compressive Strength Test (IS 10262:2019)

Concrete cubes sized 150mm × 150mm × 150mm were produced using grade M150 concrete. Concrete cubes that use OPC. After 24 hours, the samples were then taken out of the mold and cured in water for 7 and 28 days. After curing, the samples were evaluated for their compressive strength using a compression test machine. Compression test was done on the top of the cube at 7 and 28 days of curing.

Table: 3 Results of Compressive Strength in 7 & 28 days

Concrete Mix	Fine Aggregate Replacement (%) By Copper Slag	Compressive Strength 7 Days (N/mm ²)	% Change (7 Days)	Compressive Strength 28 Days (N/mm ²)	% Change (28 Days)
A0%	0%	120.5	0.00%	150.8	0.00%
A10%	10%	129	(+)7.05%	157.07	(+)4.16%
A20%	20%	135.47	(+)12.42%	166.8	(+)10.61%
A30%	30%	130.73	(+)8.49%	161.13	(+)6.85%
A40%	40%	124.8	(+)3.57%	155.2	(+)2.92%
A50%	50%	119.5	(+)0.83%	149.5	(+)0.86%
A60%	60%	114.2	(+)5.23%	142.5	(+)5.31%
A70%	70%	108.6	(+)9.88%	136.2	(+)9.68%
A80%	80%	102.1	(+)15.27%	128.5	(+)14.79%
A90%	90%	95.4	(+)20.83%	121.3	(+)19.56%
A100%	100%	88.5	(+)26.56%	114	(+)24.40%

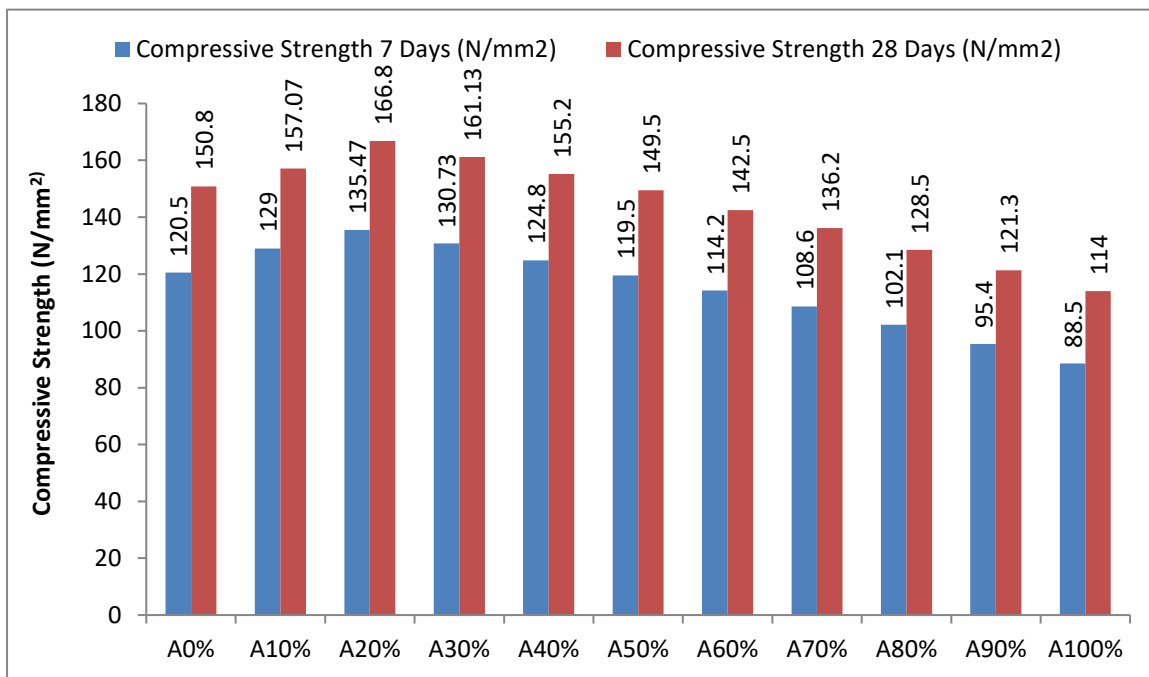


Figure: 1 Comparison of Compressive strength

Discussion: Clearly, it can be seen that the change in strength is characterized by a positive trend in the performance of the material up to an optimal value of the replacement and then a decrease in performance at that point, where the introduction of copper slag improves the density of the matrix material. In the control mixture (A0%), the 28-day strength was recorded at 150.8 N/mm², whereas the optimal replacement of the slag was calculated to be 20% (A20%), giving a peak strength of 166.8 N/mm². The reason for this 10.61% increase in strength is the tough and angular nature of the copper slag, contributing to an optimal packing density in the UHPC.

2. Split Tensile Strength Test (IS 10262:2019)

Concrete cylinder specimens having dimensions 150 mm × 300 mm diameter are prepared with the use of M150 grade concrete. Concrete cylinder specimen with Ordinary Portland Cement (OPC) is referred to as Standard Concrete. Specimens are taken out of moulds after 24 hours and cured in water for 7 days and 28 days. Test for Split Tensile Strength of the Concrete cylinder specimen is performed with the help of a testing machine by placing it lengthwise. Split tensile test on Concrete cylinder specimen is done at 7 days and 28 days curing period.

Table: 4 Results of Spilt Tensile Test in 7 & 28 days

Concrete Mix	Replacement (%)	Split Tensile Strength 7 Days (N/mm ²)	%Change (7 Days)	Split Tensile Strength 28 Days (N/mm ²)	% Change (28 Days)
A0%	0%	12.05	0.00%	15.08	0.00%
A10%	10%	12.9	(+)7.05%	15.71	(+)4.18%
A20%	20%	13.55	(+)12.45%	16.68	(+)10.61%
A30%	30%	13.07	(+)8.46%	16.11	(+)6.83%
A40%	40%	12.45	(+)3.32%	15.45	(+)2.45%
A50%	50%	11.9	(+)1.24%	14.85	(+)1.53%
A60%	60%	11.35	(+)5.81%	14.1	(+)6.50%
A70%	70%	10.8	(+)10.37%	13.35	(+)11.47%
A80%	80%	10.15	(+)15.77%	12.5	(+)17.11%
A90%	90%	9.4	(+)21.99%	11.65	(+)22.75%
A100%	100%	8.7	(+)27.80%	10.8	(+)28.38%

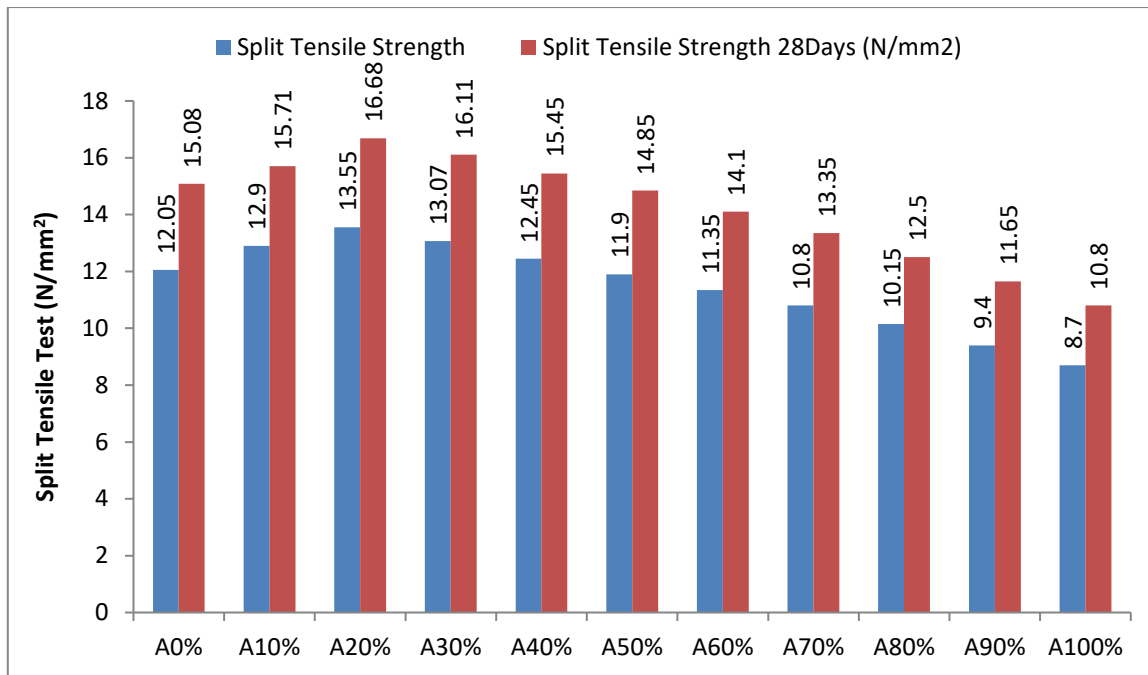


Figure: 2 Comparison Split Tensile Test

Discussion: The split tensile strength almost reflects the compressive pattern, which validates the interaction impact of the copper slag on the tensile behaviour of the M150 cement matrix. The highest tensile strength value attained is 16.68 N/mm² at 20% slag ratio, and this can be attributed to the significant improvement compared to the control. It can be deduced that within the concentration range of 10-30%, copper slag becomes a good micro-filler for the paste-aggregate interface bond improvement. However, when the slag amount is above 60%, the tensile strength starts decreasing, meaning there might be internal voids resulting from slag excess.

3. Acid Attack Test

Acid attack test for Ultra-High Performance Concrete (UHPC) of grade M150 is aimed at the measurement of durability and capability of concrete to withstand aggressive acidic conditions in terms of weight loss and compressive strength of concrete. In case of grade M150 UHPC, usually specimens sized 150 mm x 150 mm x 150 mm are used; however, owing to high strength of this type of concrete, small-sized specimens of up to 100 mm can be tested at universities. The results are shown in Table 5.

Table: 5 Acid Attack Test in 28 days

Concrete Mix	Replacement (%)	Initial Weight (Kg)	Final Weight (Kg)	% Weight Loss	Compressive Strength Before (N/mm ²)	Compressive Strength After (N/mm ²)	% Strength Loss
A0%	0%	8.25	7.879	4.50%	150.8	122.9	18.50%
A10%	10%	8.23	7.9	4.10%	157.07	130.68	16.80%
A20%	20%	8.22	7.925	3.65%	166.8	141.95	14.90%
A30%	30%	8.12	7.949	3.20%	161.13	139.22	13.60%
A40%	40%	8.19	7.192	3.45%	155.2	132.7	14.50%
A50%	50%	8.18	7.869	3.80%	149.5	125.28	16.20%
A60%	60%	8.16	7.814	4.30%	142.8	116.52	18.40%
A70%	70%	8.14	7.741	4.90%	136.2	107.19	21.30%
A80%	80%	8.11	7.661	5.60%	128.5	96.63	24.80%
A90%	90%	8.09	7.572	6.40%	121.3	86.73	28.50%
A100%	100%	8.06	7.484	7.20%	114	77.29	32.20%

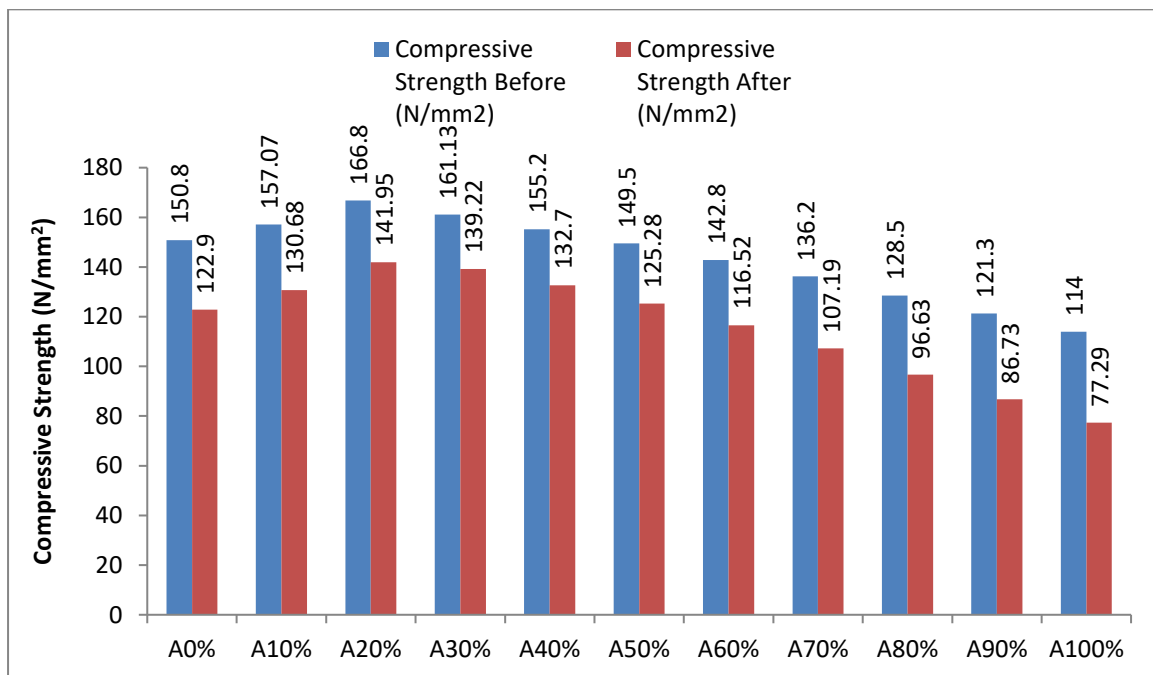


Figure: 3 Comparison of Compressive strength in Acid attack

Discussion: Results from the durability test show that M150 UHPC remains structurally strong despite being exposed to an acidic environment; nevertheless, the extent of degradation depends largely on the amount of slag used. As observed in the analysis above, A20% exhibited the maximum strength value; however, further observations from

the experiment reveal that the percentage weight loss steadily increases once copper slag replacement is higher than 40%. What this clearly means is that although copper slag is stable chemically, its effect on the impermeability of the UHPC mixture cannot be ignored.

5. Conclusions

- The conclusions derived from the experimental analysis performed in this research are as follows:
- Incorporation of copper slag in UHPC has a significant impact on mechanical and durability properties of the latter.
- An optimum percentage of 20% copper slag replacement in the UHPC composition results in obtaining the highest compressive strength of about 166.8 MPa.
- Better particle packing and reduced porosity contribute to enhanced compressive strength of UHPC.
- The split tensile strength also revealed similar trends of increase with increasing amounts of copper slag, thus proving better inter-particle bonding at smaller replacement amounts.
- Strength was decreased for higher amounts of copper slag (above 50%) due to poor cohesion in the matrix.
- Copper slag content moderately contributed to improved durability against acidic environment; however, at high amounts, increased porosity resulted in deteriorated properties.
- The research proves that copper slag is an effective additive allowing for the production of high-strength UHPC while using less cement and cutting down costs.

6. Acknowledgement

It is with pleasure that we extend our sincere appreciation to Dr. Vinay Patel, the Principal of Birla Vishwakarma Mahavidyalaya Engineering College (BVM), Gujarat, India; Dr. Reshma L. Patel, Head and Professor of Civil Engineering, BVM, Gujarat, India; and Mr. Chiragbhai Patel, Design Cell Infra Support Pvt. Ltd., Gujarat, India for their inspiration and infrastructure support for the study.

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