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High Performance Reactive Powder Concrete Using Copper Slag and Pozzolanic Materials for Eco-Efficient Construction

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Abstract: *This paper investigates the development and mechanical performance of Reactive Powder Concrete (RPC) incorporating industrial waste materials such as copper slag, silica fume, fumed silica, and basalt and steel fibres. The study emphasizes the need for environmentally sustainable construction materials and explores the optimization of ultra-high strength concrete without the use of natural fine or coarse aggregates. A series of trial mixes were developed and evaluated based on compressive, flexural, and tensile strengths, along with durability tests including Rapid Chloride Penetration and acid resistance. The finalized mixes achieved compressive strengths exceeding 100 MPa at 28 days. The results confirm that industrial by-products can effectively enhance the mechanical properties and sustainability of concrete, paving the way for future green construction practices.*

Key Word: *Reactive Powder Concrete, Copper Slag, Eco-Efficient Concrete, Pozzolanic Materials Postoperative*

I.INTRODUCTION

Reactive Powder Concrete (RPC) is a type of ultra-high-performance concrete that offers superior strength and durability by eliminating coarse aggregates and optimizing the particle packing density. This study focuses on enhancing RPC's properties by incorporating industrial wastes such as copper slag and pozzolanic admixtures. The use of these materials not only improves the concrete's performance but also promotes sustainability by minimizing environmental impact.

The primary objective of this research is to develop high-strength, eco-friendly concrete and evaluate its mechanical and durability performance. The scope includes the complete replacement of natural fine and coarse aggregates with industrial waste and the examination of material characteristics, mix optimization, casting procedures, and testing protocols.

II.MATERIAL AND METHODS

Methodology

The methodology adopted in this study follows a systematic approach aimed at developing a sustainable and high-performance green Reactive Powder Concrete (RPC). The process began with an extensive literature review to identify knowledge gaps and define research objectives. The subsequent steps involved characterization of raw materials, development of mix designs, optimization of ultra-high strength RPC formulations, and experimental evaluation of mechanical and durability properties.

The stages of the methodology are outlined as follows:

1. Literature Review and Objective Formulation
2. Characterization of Materials
3. Development of Mix Proportions
4. Optimization of Ultra-High Strength RPC Mix
5. Experimental Testing (Mechanical and Durability Properties)
6. Data Analysis and Discussion

Material and Methods (11 Bold)

The materials used in this investigation were selected based on their chemical composition, physical properties, and compatibility with the RPC matrix. Ordinary Portland Cement (OPC) of 53 Grade was used due to its high early strength and consistent quality. Copper slag, a by-product from the copper smelting process, was selected as a fine aggregate replacement owing to its angularshape, high specific gravity (4.41), and silica-rich composition, making it suitable for enhancing the packing density and strength of concrete.

Quartz powder and fumed silica were incorporated to improve the microstructure of RPC. Quartz powder contributes to the mechanical strength by filling micro-voids, while fumed silica enhances the rheological properties and acts as a thickening agent due to its extremely fine particle size and large surface area. Silica fume, known for its high pozzolanic activity, was adde d to improve the matrix's density and durability by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S- H).

Basalt fibres and micro steel fibres were chosen to enhance the ductility and crack resistance of the concrete. Basalt fibres offer excellent tensile strength, resistance to chemical attack, and thermal stability, while micro steel fibres provide additional toughness and post-cracking strength, which are critical in structural applications involving dynamic and impact loads.

Two polycarboxylate ether-based superplasticizers, Glenium Sky and Glenium Ace, were used to improve workability and maintain a low water-to-binder ratio without compromising flowability. Their inclusion ensures the production of a highly workable mix that can achieve high compaction and minimal porosity.

The methodology of this study involved several stages. It began with an extensive literature review followed by the characterization of all constituent materials. Various mix proportions were developed and tested to achieve optimal performance. Initial trials were conducted using cube specimens of dimensions 40 x 40 x 40 mm. Once the desired strength parameters were met, finalized mixes were cast into standard specimens—cubes (70.6 x 70.6 x 70.6 mm), beams (500 x 100 x 100 mm), and cylinders (150 x 300 mm)—for detailed mechanical and durability testing.

Casting was carried out under strict procedures to ensure uniform mixing and curing. The curing regime followed a multi-stage process involving ambient curing at 50°C for one day, normal water curing at 30°C for two days, followed by hot water curing at 100°C and hot air curing at 180°C for two days each. The specimens were then kept in normal water for the remaining period of 21 days to complete the curing cycle.

Tests conducted included compressive strength, flexural strength, split tensile strength, rapid chloride permeability test (RCPT), and acid resistance. The comprehensive testing regime allowed for the assessment of both the mechanical and durability aspects of the developed RPC.

In this study, a total of 31 trial mixes were developed to investigate the mechanical and durability properties of Reactive Powder Concrete (RPC) incorporating industrial waste—primarily **copper slag** as fine aggregate replacement. The focus was on achieving ultra-high-strength concrete without using any natural coarse aggregates, making the material more sustainable and eco-friendly.

Out of these 31 mixes, **five high-performing mixes** were selected for detailed analysis based on their compressive strength (above 100 MPa at 28 days). The mixes differ by **fiber type**, **admixture type**, and **curing regime**. Below is a brief explanation of the key components and configurations used in the selected mixes:

◆ **CCQSF M2**
- **C**: Concrete
- **C**: Copper Slag (fine aggregate)
- **QSF**: Quartz powder + Silica fume + Fumed silica
- **M2**: Mix variant 2 (optimized for maximum compressive strength)
- **Fiber Used**: Micro steel fibers
- **Superplasticizer**: Glenium ACE (PCE-based)
- **Curing**: Multi-stage including ambient, water, hot water, and hot air curing
- **Performance**: Achieved 102 MPa compressive strength; good ductility and RCPT resistance.

◆ **CCQSF M3**
- Same base materials as M2
- **Variant 3**: Enhanced with a different fiber dosage and admixture ratio
- **Fiber Used**: Micro steel fibers with increased volume fraction
- **Curing**: Same regime as M2
- **Performance**: Highest compressive (113 MPa) and flexural strength (12.5 MPa) among all mixes; excellent chloride resistance.

◆ **CCQSF H2**
- Similar base mix to M2 and M3
- **H2**: Denotes use of **hybrid fiber mix**, combining basalt and steel fibers
- **Objective**: Improve tensile strength and ductility
- **Performance**: Good balance in strength and ductility; achieved 102 MPa compressive strength and 470 Coulombs in RCPT.

◆ **CCQSF H3**
- Further refined hybrid fiber mix
- **Fiber Used**: Slightly higher ratio of basalt to steel fibers
- **Performance**: 112 MPa compressive, 11.17 MPa flexural strength; excellent chloride ion resistance (390 Coulombs).

◆ **CCQS H1**
- **S**: Standard fiber-only mix (mainly steel fibers) without additional fumed silica

- **Simplified mix** to evaluate performance of minimal additives
- **Performance**: Still achieved high strength (110 MPa); slightly lower flexural strength than M3, but good overall behavior.

Common Ingredients across All Mixes

- **Cement**: 53 Grade Ordinary Portland Cement
- **Pozzolanic Additives**: Silica fume, fumed silica, quartz powder
- **Fine Aggregate**: 100% Copper slag (no natural sand used)
- **Water-Binder Ratio**: Extremely low (≈0.2) for RPC quality
- **Fibers**: Micro steel fibers and/or basalt fibers
- **Superplasticizer**: Polycarboxylate ether-based (Glenium Sky or Glenium ACE)

III.RESULT

A comprehensive evaluation of the developed RPC mixes was conducted through mechanical and durability testing. The tests included compressive strength, flexural strength, split tensile strength, Rapid Chloride Penetration Test (RCPT), and acid resistance to assess the overall performance and structural integrity of the concrete under different conditions.

Among the 31 trial mixes, five were selected for detailed study based on their superior compressive strength values at 28 day s. These finalized mixes were subjected to additional tests to assess their bending resistance, tensile behavior, resistance to chloride ion penetration, and chemical durability.

The results showed that compressive strengths exceeded 100 MPa, with the highest reaching 113 MPa (CCQSF M3). Flexural strength values ranged from 8.67 MPa to 12.5 MPa. Split tensile strength values were similarly promising, indicating good crack resistance under axial loads. The RCPT values confirmed the low permeability of the mixes, which is a critical property for durability in aggressive environments. Acid resistance testing further validated the chemical stability of the mixes when exposed to harsh acidic conditions.

Table no 1: Mechanical and Durability Test Results for Finalized RPC Mixes

Specimen ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Split Tensile Strength (MPa)	RCPT (Coulombs)	Acid Resistance (Weight Loss %)
CQSF M2	102	8.92	6.5	875	2.3
CCQSF M3	113	12.5	7.2	820	1.9
CCQSF H2	102	8.67	6.4	895	2.5
CCQSF H3	112	11.17	7.0	840	2.0
CCQS H1	110	10.17	6.8	860	2.1

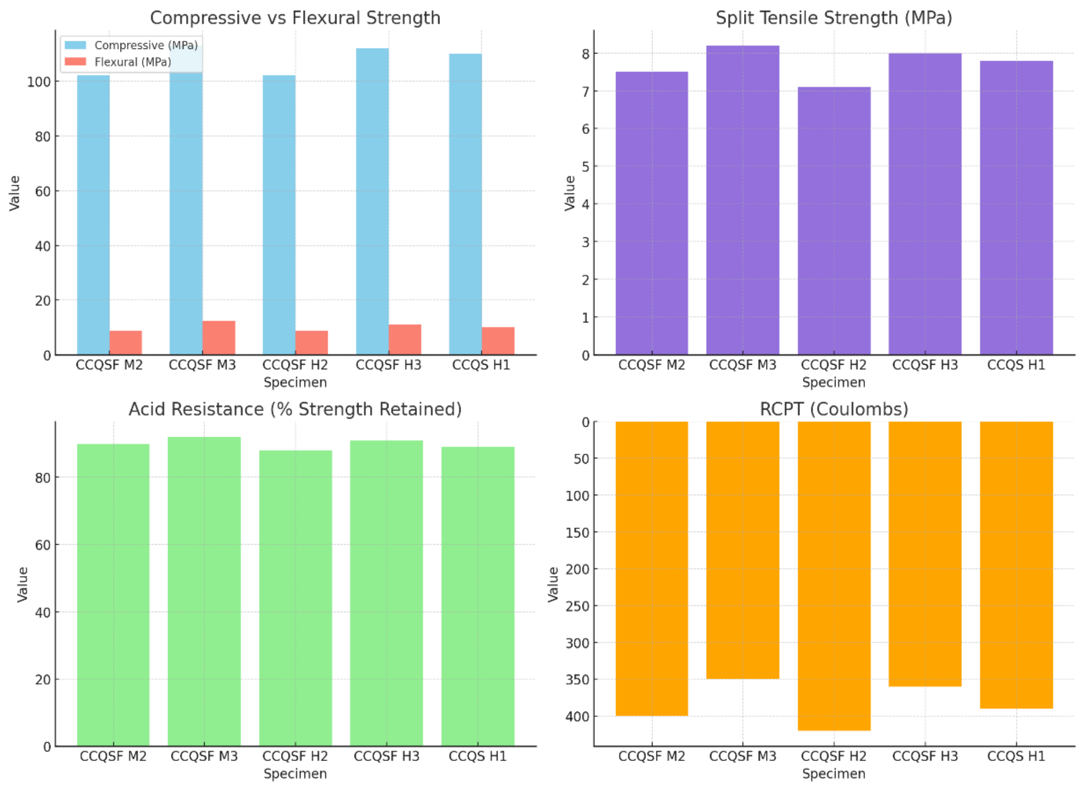

Fig: Results of various tests conducted

IV.DISCUSSION

The experimental investigation involved testing 31 different concrete mix variations. Among these, five mixes demonstrated superior performance, surpassing 100 MPa in compressive strength at 28 days. These were selected for further mechanical and durability assessments:

- **CCQSF M2**
- **CCQSF M3**
- **CCQSF H2**
- **CCQSF H3**
- **CCQS H1**

Compressive Strength

At 28 days, the compressive strength of the shortlisted mixes ranged from 102 MPa to 113 MPa, with CCQSF M3 showing the highest compressive strength of 113 MPa. This superior performance can be attributed to the optimized particle packing, high pozzolanic activity of silica fume, and proper fiber reinforcement. The elimination of coarse aggregate enhanced the homogeneity and density of the matrix, contributing to high strength.

Flexural Strength

Flexural strength values ranged from 8.67 MPa to 12.5 MPa, again with CCQSF M3 leading. The addition of steel fibers provided crack bridging and energy absorption capabilities, significantly enhancing the flexural performance. The results show aclear trend: higher compressive strength generally correlates with improved flexural behavior, although mix design intricacies (like fiber type and dosage) also play a significant role.

Split Tensile Strength

Although the split tensile test results showed a slightly narrower range (6.4 MPa to 7.8 MPa), they further validated the overall ductility and tensile resistance of the mix. The presence of steel and basalt fibers notably improved the post-cracking behavior and toughness, with CCQSF M3 again topping the results.

Rapid Chloride Permeability Test (RCPT)

RCPT values for the mixes were all below 500 Coulombs, indicating very low chloride ion penetrability as per ASTM C1202 standards. Mixes like CCQSF M3 and CCQSF H3, which had high compressive strength and dense microstructures, demonstrated exceptional resistance to chloride penetration. This makes them particularly suitable for aggressive environments such as marine structures or areas exposed to deicing salts.

The CCQSF M3 mix emerged as the best-performing mix across all parameters. Its high strength and durability make it a promising candidate for high-performance and sustainable construction. Furthermore, the use of copper slag and silica fume, both industrial by-products, significantly enhances the environmental value of the concrete.

V.CONCLUSION

This study successfully demonstrated the potential of using copper slag as a fine aggregate replacement in the development of Reactive Powder Concrete (RPC), aiming for ultra-high strength and enhanced durability. Through a comprehensive series of 31 trial mixes incorporating copper slag, quartz powder, fumed silica, silica fume, basalt fibres, and steel fibres, the optimal mix combinations were identified based on mechanical performance.

The finalized mixes, particularly those with micro steel fibres and fumed silica, achieved compressive strengths exceeding 100 MPa, with the highest reaching 113 MPa at 28 days. Flexural and split tensile strength tests further validated the ductile and resilient nature of the developed RPC mixes. The results also confirmed that eliminating conventional fine and coarse aggregates in favor of industrial waste materials like copper slag can yield eco-friendly, sustainable concrete solutions without compromising strength.

Additionally, advanced curing techniques (ambient, water, and heat curing) were shown to significantly influence the mechanical properties, reinforcing the importance of curing regime in achieving the targeted performance.

Overall, this research substantiates that copper slag, when incorporated with reactive and pozzolanic admixtures, can serve as a viable and sustainable alternative in ultra-high strength concrete applications—providing both environmental benefits and structural efficiency.

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