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# Performance Evaluation of Copper Slag Based Geopolymer Concrete: Mechanical Strength and Durability Perspectives

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## Abstract

**Objectives**: To replace copper slag (CS) as a fine aggregate in geopolymer concrete (GPC) and to study its influence on both mechanical and durability properties. **Methods:** Copper slag was used to replace fine aggregate in the preparation of M40 grade GPC. CS was replaced at varying proportions of 0%, 10%, 20%, 30%, 40%, and 50%. Alkaline solutions to activate the geopolymerization process were prepared in three concentrations such as 8M, 10M and 12M. To study the Mechanical and durability properties of slag-based GPC compressive strength, modulus of elasticity, flexural strength, water absorption, acid resistance and sulphate resistance tests were done. **Findings:** GPC containing 70% fly ash and 30% GGBS as a binder and 40% copper slag replacement as a fine aggregate shows superior performance and selected as an optimum replacement to attain superior mechanical and durability properties. The slag-based GPC showed maximum of 10.32% increase in compressive strength, 23.54% increase in flexural strength, 25.24% increase in modulus of elasticity at 12M concentration. Durability test such as water absorption and resistance to acid and sulphates showed better improvement at 40% replacement and beyond that there is a deterioration leads to 40% copper slag replacement become an optimal mix. **Novelty:** Although the idea of using CS as a fine aggregate is not new, this study focuses on determining the optimum replacement level of CS in a binary blend of fly ash and GGBS-based geopolymer concrete. In addition, the durability properties of the developed GPC are also investigated. Since no standard currently exists for the required strength, this work attempts to establish insights in this area, which contributes to the novelty of the study.

**Keywords:** Geopolymer Concrete; Copper Slag; Compressive Strength; Flexural Strength; Durability

## 1 Introduction

For several years, the construction industry has recognized the potential of geopolymer technology, particularly with the advent of zero-cement systems. Geopolymer concrete is now being adopted in many countries as a sustainable solution to minimize pollution and promote the effective utilization of industrial by-products, aligning with the concept of turning "waste into wealth"[(1)]. The construction industry playas an important role in the utilization of the natural resources leading to the environmental degradation. Incorporating industrial by products into the construction materials provides a sustainable solution to attain the goal. Using recycled concrete aggregate as coarse aggregate and CS as a fine aggregate helps to reduce land fill accumulation, limit natural resource use without compromising the structural integrity[(2)]. Many research works focussed on manufacturing geopolymer bricks using fly ash and copper slag and found significant results and can directly impact local construction industry[(3)]. Geopolymer concrete plays a major role in the prefabricated industry by manufacturing bricks, blocks and paver blocks etc., paver blocks using fly ash and copper slag showed increased compressive strength for the different molarity concentrations[(4)]. Several mineral admixtures have been used to produce geopolymer concrete are fly ash, GGBS, cenosphere, bottom ash to increase its binding properties. Because of using all these admixtures increases the packing density and increases the strength up to an optimum level[(5)]. Study has been taken place on GGBS based GPC containing CS and steel fibres enhance its mechanical properties such compressive, bond and impact strength significantly. The enhancement in the mechanical properties is attributed to particle packing and reduced porosity leads to the matrix densification of GPC mixtures[(6)]. The combination of Ultra fine GGBS and fly ash enhances the ambient curing performance promotes eco-friendly construction and can be used as an alternative binder for sustainable GPC. Ultrafine GGBS GPC replacement up to 15% reaching 48.29 MPa, 55.46 MPa and 57.01 MPA after 56 days[(7)]. The GPC mix with 15% Ultra fine GGBS content at 14M NaOH concentration provides highest compressive strength and reduced shrinkage cracks[(8)]. Addition of copper slag in the GPC provides a viable solution to the industrial waste management. Past research works also reported that adding copper slag as a fine aggregate enhance the engineering properties of the GPC significantly. Nevertheless, excessive replacement levels may lead to bleeding, segregation, and reduced durability due to increased free water in the matrix. Therefore, optimizing the replacement percentage is critical to achieving balanced performance. Comparative study has taken place between slag-based GPC and vermiculite-based GPC, shown slag-based GPC with an optimal replacement level of 30% to 50% outperformed than vermiculite-based GPC. This is because of enhanced alkali activation in the slag-based GPC compared to the vermiculite-based GPC, which leads to the enhanced polymerisation and densified mix[(9)]. However, regarding this very limited research works have been taken place. Complete replacement of FA with CS in fly ash-based GPC improved compressive, tensile and flexural strength by 53.8%, 66.9% and 39.3% respectively compared to the control GPC but durability properties have not been studied properly[(10)]. Addition of CS as a fine aggregate in GPC significantly enhances the performance by densifying the microstructure reducing crack width and improving compressive strength up to 60% replacement level. However excessive CS content led to reduced strength gain owing to the presence of $Fe_2O_3$ [(11)]. Overall, the utilization of copper slag in GPC enhanced the compressive strength while reduces the demand for the river sand and also solution to the disposal of industrial by product leads to the waste management. However, their durability properties of the GPC mixtures are not studied properly.

Keeping all the above points, the present study aims to study the mechanical and durability properties of copper slag-based GPC containing fly ash and GGBS as binder. Furthermore, the study encourages the utilization of industrial by products in the field of construction industry to reduce the disposal of industrial byproducts as a land disposal.

## 2 Methodology

### 2.1 Materials

The binding material utilized herein is fly ash and GGBS, and their properties are stated in Table 1 and 2. Fly ash collected from Mettur and GGBS bought from Astra chemicals. The natural river sand and copper slag was utilized as a fine aggregate, with a maximum particle size of 4.75mm and a fineness modulus of 2.8 and 3.3 respectively. Figure 1 shows the particle size distribution of the fine aggregate and copper slag. Crushed granite with a maximum particle size of 20mm and a minimum particle size of 12mm was used for coarse aggregate. The specific gravity of coarse aggregate is 2.72. The above ingredients were mixed using alkali activator solution. Sodium hydroxide and sodium silicate is used as an alkaline activator.

The CS based GPC mixture of M40 grade compositions designed are shown in Table 3, wherein CS 0 represents the conventional GPC, CS 10 represents 10% replacement of FA with CS, CS 20 represents 20% replacement of FA with CS, CS 30 represents 30% replacement of FA with CS, CS 40 represents 40% replacement of FA with CS and CS 50 represents 50% replacement of FA with CS.

**Table 1.** Physical Properties of Fly Ash

| Sl No. | Properties | As per Supplier |
|---|---|---|
| 1. | Colour | Grey |
| 2. | Particle Shape | Mostly Spherical |
| 3. | Specific Surface Area | 250 - 600 $m^2$/kg |
| 4. | Bulk Density | 540 – 860 kg/$m^3$ |
| 5. | Specific Gravity | 2.1 – 2.6 |

**Table 2.** Physical Properties of GGBS

| Sl No. | Properties | As per Supplier |
|---|---|---|
| 1. | Colour | Off-White |
| 2. | Particle Shape | Angular |
| 3. | Specific Surface Area | 275 - 450 $m^2$/kg |
| 4. | Bulk Density | 1100 - 1300 kg/$m^3$ |
| 5. | Specific Gravity | 2.85 – 3.00 |

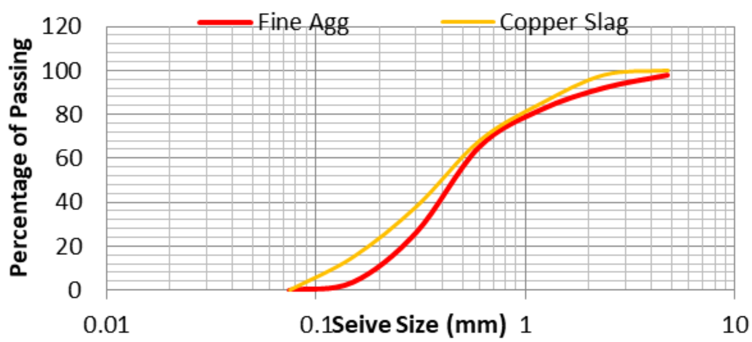


**Fig 1.** Particle size Distribution of Fine Aggregate

### *2.1.1. Mixing Methods*

To prepare geopolymer concrete mixture, activator solution of 8M, 10M and 12M concentrations were prepared 24 hrs before casting. During casting fly ash, GGBS, Copper Slag, Fine aggregate and coarse aggregate were mixed thoroughly to get a uniform mixture. Prepared alkali activator solution is used to mix the GPC. Immediately after mixing, slump test conducted using slump cone and the values were tabulated in Table 4.

Geopolymer concrete mixture was poured into the 150 x 150 x 150 mm cubic moulds, 150 x 300 mm cylinder moulds and 100 x 100 x 500 mm prism moulds. All the moulds were compacted on a vibrating table. After 24 hrs, all molds were demolded and the specimens were kept under ambient curing for 28 days. Table 5 is showing the details of the specimens.

## 2.2 Testing Methods

### *2.2.1. Compressive Strength Test*

The compressive strength of the GPC cube specimens of 150 × 150 × 150 mm was measured using a Compressive testing machine. Eighteen specimens of each GPC mix fraction were tested—three after 7 days of curing and three after 28 days—and the average of the results was used to determine the representative strength for three different molarity. A total of 108 specimens were examined to assess the compressive strength of GPC mixes. Figure 2 depicts the experimental setup.

### *2.2.2. Flexural Strength Test*

Flexural strength was assessed using prism specimens in a loading frame with a 5 tonnes capacity. The specimens had a test span of 400 mm and sized 150 × 150 × 500 mm. Three specimens were tested for each mix, at 28 days and the average results were taken into account. In compliance with IS 516:2021, a total of 54 specimens were analysed to assess the flexural strength of GPC. Figure 3 depicts the experimental setup.

**Table 3.** CS based Geopolymer Concrete Mixture Compositions

| Sl No. | Mix ID | Fly Ash kg/m³ | GGBS kg/m³ | Copper Slag kg/m³ | Fine Agg kg/m³ | Coarse Agg kg/m³ | Soium Hydroxide NaOH kg/m³ | Sodium Silicate $Na_2SiO_3$ kg/m³ | Water in NaOH kg/m³ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 19.2 | | 40.8 |
| 1 | CS 0 | 294 | 126 | 0 | 665 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |
| | | | | | | | 19.2 | | 40.8 |
| 2 | CS 10 | 294 | 126 | 66.5 | 598.5 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |
| | | | | | | | 19.2 | | 40.8 |
| 3 | CS 20 | 294 | 126 | 132.5 | 532.5 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |
| | | | | | | | 19.2 | | 40.8 |
| 4 | CS 30 | 294 | 126 | 199.5 | 465.5 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |
| | | | | | | | 19.2 | | 40.8 |
| 5 | CS 40 | 294 | 126 | 266 | 399 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |
| | | | | | | | 19.2 | | 40.8 |
| 6 | CS 50 | 294 | 126 | 332.5 | 332.5 | 1235 | 24 | 150 | 36 |
| | | | | | | | 28.8 | | 31.2 |

**Table 4.** Slump Value for CS based GPC mixtures

| Sl No | Mixture ID | Slump (mm) | | |
|---|---|---|---|---|
| | | | 8M | 10M |
| 12M | | | | |
| 1 | CS 0 | 100 | 98 | 93 |
| 2 | CS 10 | 104 | 101 | 95 |
| 3 | CS 20 | 107 | 103 | 97 |
| 4 | CS 30 | 109 | 107 | 99 |
| 5 | CS 40 | 118 | 112 | 101 |
| 6 | CS 50 | 112 | 106 | 97 |

### 2.2.3. *Modulus of Elasticity Test*

In compliance with IS: 516-1959, cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in height were used to measure the modulus of elasticity. After being ambient curing for 28 days, the specimens were undergone for the test. A digital CTM with a 2000 kN capacity was used for testing, and an axial compressive load was applied. Until the maximum load was achieved, deformations were measured using a dial gauge with a 0.01 mm least count at each 10 kN load increment until the peak load. Figure 4 depicts experimental setup.

### 2.2.4. *Water Absorption*

Eighteen cubes of size 150 mm were tested for water absorption as per ASTM C 642. Each value represents the average results of three specimens in the same group. Before immersing in the water all cubes were weighed and measured as $W_1$. The specimens were immersed in water for 24 hrs; the specimens were removed from water and kept for surface dry, and weight was measured as $W_2$. Water absorption of the specimens calculated by the below mentioned formula.

$$\text{Absorption after Immersion} = \frac{W_2 - W_1}{W_1} \times 100$$

Where, $W_1$ = Initial Weight of the Cube, $W_2$ = Weight of the Cube After Immersion

**Table 5.** Details of the Specimens for Experimental Investigation

| Specimen Details | Tests Conducted | Standard Documents | Total No. of Specimens |
|---|---|---|---|
| **Mechanical properties** | | | |
| Cube (150 x 150 x 150 mm) | Compressive Strength | IS: 516:1959 | 3 x (6 x 6) = 108 |
| Prism (500 x 100 x 100) | Flexural Strength | IS 516:1959 (Affirmed to 2004) | 3 x (6 x 3) = 54 |
| Cylinder (150mm diameter, 300mm height) | Modulus of Elasticity | IS 516:2020 | 3 x (6 x 3) = 54 |
| **Durability properties** | | | |
| **Specimen Details** | **Tests Conducted** | **Standard Documents** | **Total No. of Specimens** |
| Cube (100 x 100 x 100 mm) | Water Absorption | ASTM C 642 | 3 x (6 x 3) = 54 |
| Cube (100 x 100 x 100 mm) | Hydrochloric Acid Resistance | ASTM C 267 | 3 x (6 x 3) = 54 |
| Cube (100 x 100 x 100 mm) | Sulphuric Acid Resistance | ASTM C 267 | 3 x (6 x 3) = 54 |
| Cube (100 x 100 x 100 mm) | Sulphate Resistance | ASTM C 267 | 3 x (6 x 3) = 54 |

**Fig 2.** Compressive Strength Test Setup


**Fig 3.** Flexural Strength Test Setup

**Fig 4.** Modulus of Elasticity Test Setup

### *2.2.5. Acid and Sulphate Resistance*

54 cubes of size 150mm were tested for acid and sulphate resistance. Eighteen cubes were immersed in hydrochloric acid, eighteen cubes were immersed in sulphuric acid, eighteen cubes were immersed in sodium sulphate solution to analyse the resistance towards the abovementioned solution. The initial mass of all the specimens was measured. For acid resistance, samples were immersed in 5% HCL and 5% $H_2SO_4$ solution for about 28 days. For Sulphate resistance, specimens were immersed in 5% of $Na_2SO_4$ solution. The samples were taken out after 28 days, surface dried, and their masses determined. All models were tested in compression to assess the strength loss.

$$\text{Weight Loss} = \frac{W_2 - W_1}{W_1} \times 100\%$$

$$\text{Strength Loss} = \frac{CS_2 - CS_1}{CS_1} \times 100\%$$

Where, $W_1$ = Initial Weight of the Cube, $W_2$ = Weight of the Cube After Immersion
$CS_1$ = Initial Compressive Strength, $CS_2$ = Compressive Strength after Immersion

# 3 Results and Discussions

## 3.1 Compressive Strength

Figure 5 shows compressive strength of the slag-based GPC mixtures. Compressive strength of GPC mixtures with all molarity showed increment with the increase of CS addition up to 40% replacement.

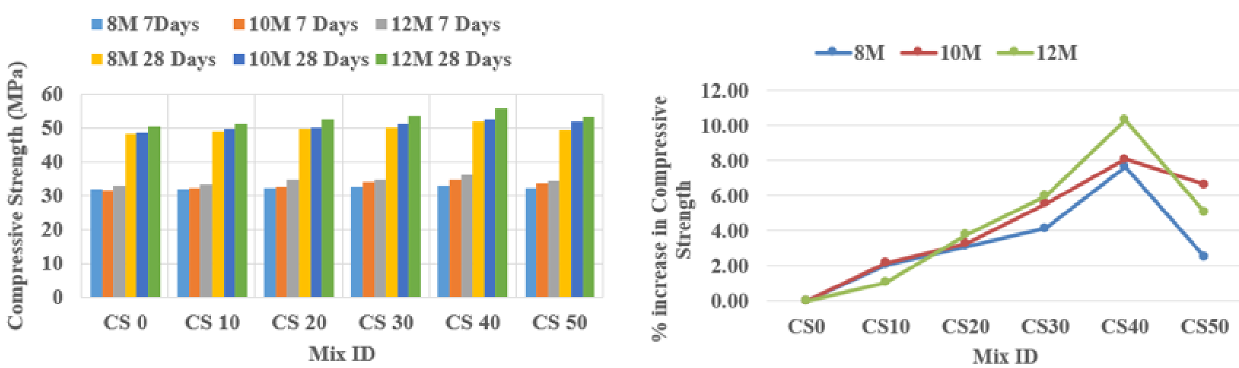


**Fig 5.** Compressive Strength and Percentage variation in strength with respect to molarity

Compressive strength of 70% fly ash and 30% GGBS with 40% slag replaced as a fine aggregate shows higher compressive strength of about 51.98 MPa, 52.6 MPa and 55.93 MPa at 8M, 10M and 12M respectively. Beyond the 40% replacement of FA with slag there is a reduction in the compressive strength is observed. The enhancement in the compressive strength is attributed to the improvement in the particle packing density due to the filler effect of slag addition. Copper slag particles are dense, abrasive and compressible helps to absorb and distribute the stress concentrated in the matrix. Smooth surface and sharp edges increase the bond strength of the binding matrix. However, the strength reduced beyond 40% addition is mainly due to the excessive presence of CS leads to the negative impact causes reduction in the strength development of compressive strength.

An increasing trend in the compressive strength is observed in all molarity levels from the mix CS 0 to CS 40, beyond that reduction in strength is observed in all the molarity levels. Among the mixes, CS40 demonstrates the highest improvement in compressive strength across all molarity levels, indicating that 40% copper slag replacement is the optimum proportion. Compressive strength of GPC mix CS 40 is increased about 7.66%, 8.07% and 10.32% at 8M, 10M and 12M respectively compared to the control mix CS 0. Beyond 50%, addition of CS negatively impacts the compressive strength of the GPC mixture.

CS particles are finer and act as a filler which enhance the particle packing thereby improving the strength of the concrete. similar to our study, the replacement ratio is below the optimum level of 40%, compressive strength shows improvement. Earlier studies have also reported that increasing the proportion of CS as a fine aggregate replacement generally leads to higher compressive strength [12]. Nagarajan et al. investigated CS-based GPC with complete replacement of fine aggregate, reporting an improvement in compressive strength of about 53.8%. Their results differ from the present study, mainly because GGBS was not included in their mix [10]. Increasing the copper slag content to replace river sand, the strength of concrete improves, which ids attributed to higher silica content in copper slag compared to sand. Geopolymer concrete exhibits maximum strength at 40% replacement, while further increase beyond this level leads to a reduction in strength which is similar to the present study [13].

## 3.2 Flexural Strength

Figure 6 shows flexural strength of the slag-based GPC mixtures. Flexural strength of GPC mixtures with all molarity showed increment with the increase of CS addition up to 40% replacement.

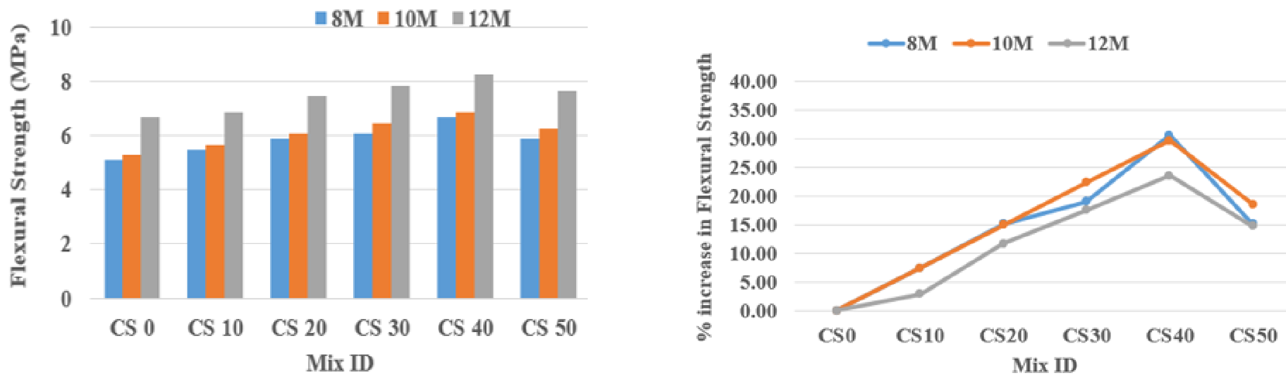


**Fig 6.** Flexural Strength and Percentage variation in strength with respect to molarity

Flexural strength of 70% fly ash and 30% GGBS with 40% slag replaced as a fine aggregate shows higher flexural strength of about 6.67 MPa, 6.86 MPa and 8.24 MPa at 8M, 10M and 12M respectively. Beyond the 40% replacement of FA with slag there is a reduction in the flexural strength is observed. The enhancement in the flexural strength is attributed to the filler effect and matrix densification. The angular shape and rough surface of CS enhance the interfacial bond between the aggregate and the geopolymer matrix, transfer the stress in the better way with higher flexural capacity.

An increasing trend in the flexural strength is observed in all molarity levels from the mix CS 0 to CS 40, beyond 40% reduction in strength is observed in all the molarity levels. Among the mixes, CS40 demonstrates the highest improvement in flexural strength across all molarity levels, indicating that 40% copper slag replacement is the optimum proportion. Flexural strength of GPC mix CS 40 is increased about 30.53%, 29.68% and 23.54% at 8M, 10M and 12M respectively compared to the control mix CS 0. Beyond 40%, addition of CS negatively impacts the flexural strength of the GPC mixture. At CS 40, 8M mix achieves highest flexural strength gain because it gives the suitable balance between dissolution of aluminosilicate materials and workability ensuring uniform binder formation and effective stress transfers across the matrix. 10M mix also shows a comparable improvement in the geopolymerization however it is slightly lesser than the 8M concentration. Even though 12M concentration showed maximum flexural strength at 40% replacement, the strength gain is relatively lower than 8M and 10M.

Earlier studies shows that flexural strength enhanced with the addition of copper slag up to a certain limit, beyond that there if reduction in the flexural strength. The similar trend follows in the present study, and it is attributed to the low water absorption capacity of CS, which increases the amount of free water in the mix. Comparative investigations on ground and unground CS in ultra-high-strength concrete (UHSC) under different curing conditions revealed that using ground CS as a fine aggregate results in a continuous increase in flexural strength. Furthermore, the beneficial effect of CS is more pronounced after grinding compared to its unground form which is similar to the present work[(12)]. The flexural strength was found to be exhibit an increasing trend with an increase in the substitution of river sand for copper slag[(10)]. Studies on the use of copper slag (CPS) as a replacement for sand in concrete and mortar indicate that flexural strength generally improves up to an optimum substitution level, after which it declines. Moderate replacement levels enhance strength due to better particle interlocking, compaction, and uniform distribution within the mix. However, higher replacement ratios reduce flexural strength, largely because of excess free water and reduced bonding efficiency. Ground CPS performs better than unground material, and in some cases, the addition of nano-silica has been shown to partially offset the strength loss at very high replacement levels. Based on the earlier studies reviewed CS improved flexural strength up to an optimum level beyond that reduction occurs in the strength[(14)].

### 3.3 Modulus of Elasticity (MOE)

Figure 7 shows MOE of the slag-based GPC mixtures. MOE of GPC mixtures with all molarity showed increment with the increase of CS addition up to 40% replacement.

MOE of 70% fly ash and 30% GGBS with 40% slag replaced as a fine aggregate shows higher MOE of about $3.67 \times 10^4$ MPa, $3.71 \times 10^4$ MPa and $3.92 \times 10^4$ MPa at 8M, 10M and 12M respectively. Beyond the 40% replacement of FA with slag there is a reduction in the MOE is observed. The enhancement in the MOE is attributed to the filler effect of slag particles and matrix densification. The angular shape and rough surface of CS enhance the interfacial bond between the aggregate and the geopolymer matrix, reduces porosity and improves stiffness. Beyond 40%, MOE value reduction attributed to the excess slag

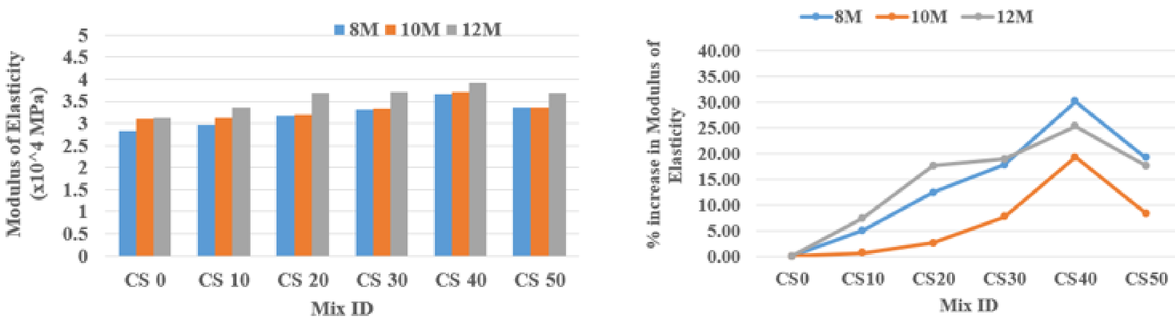


**Fig 7.** MOE and Percentage variation in strength with respect to molarity

particles overwhelming the available binder, leading to inadequate coating of aggregates and poor bonding at the interfacial transition zone (ITZ). Further increasing CS content, reduces the homogeneity of the mix and increases the risk of microcracks due to brittleness, thereby lowering the elastic stiffness of the composite.

An increasing trend in the MOE is observed in all molarity levels from the mix CS 0 to CS 40, beyond 40% reduction in MOE is observed in all the molarity levels. Among the mixes, CS40 demonstrates the highest improvement in MOE across all molarity levels, indicating that 40% copper slag replacement is the optimum proportion. MOE of GPC mix CS 40 is increased about 30.14%, 19.29% and 25.24% at 8M, 10M and 12M respectively compared to the control mix CS 0. Beyond 40% replacement, the excess CS content reduces workability and leads to insufficient binder coating on aggregate particles. This weakens the interfacial transition zone (ITZ), creates heterogeneity, and increases microcrack formation, ultimately causing a decline in MOE at higher replacement levels.

Research findings on the elastic modulus of concrete incorporating copper slag (CS) show mixed trends. Several studies report that CS concrete exhibits an elastic modulus similar to that of control mixes, with some indicating a slight improvement depending on the replacement level. The increase in modulus has also been linked to its correlation with compressive strength. Conversely, other studies have observed a marginal decrease in elastic modulus when CS is used, which has been attributed to the presence of impurities in the slag. Overall, the influence of CS on elastic modulus is not consistent, showing both minor gains and slight reductions depending on mix proportions and material characteristics [(12)]. The elastic modulus of GPC specimens was evaluated using control mixes and mixes with full replacement of fine aggregate by copper slag, with varying NaOH molarity. Test results obtained from compressometer measurements of axial and lateral strain were compared with theoretical predictions. It was found that the commonly used design equations tended to overestimate the modulus of elasticity. In contrast, equation provided a closer estimation of the experimental values, indicating its suitability for predicting the elastic modulus of GPC with copper slag [(10)].

### 3.4 Water Absorption

Figure 8 shows water absorption of the slag-based GPC mixtures. Water absorption of GPC mixtures with all molarity showed decrease in the absorption with the increase of CS addition up to 40% replacement.

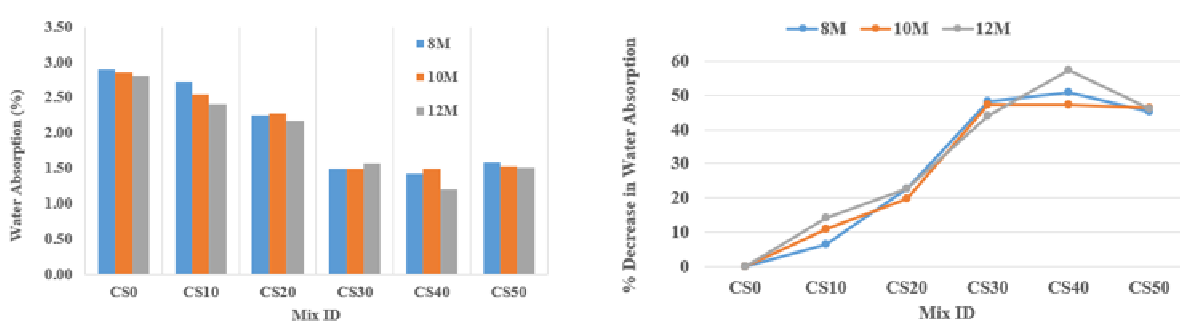


**Fig 8.** Water Absorption and Percentage decrease in absorption with respect to molarity

Water Absorption of 70% fly ash and 30% GGBS with 40% slag replaced as a fine aggregate shows lesser absorption of about 1.42%, 1.50% and 1.20% at 8M, 10M and 12M respectively. An increasing trend in the decrease in water absorption is uniform till 40% replacement beyond that there is a decline. At the replacement level CS40, water absorption has reduced up to 47.33%, 50.97% and 57.41% at 8M, 10M and 12M concentration respectively. This enhancement is due to presence of denser geopolymer matrix with fewer capillary pores available for water ingress. Amorphous silica present in CS involves in the additional geopolymerization reaction, which ultimately leads to pore refinement. However, beyond the 40%replacement level water absorption slightly increases which is because of insufficient geopolymer binder availability to coat excess CS particles effectively. The lack of adequate binder leads to poor workability, weaker ITZ formation, and the development of microcracks or voids within the matrix. These defects increase pore connectivity, allowing more water to penetrate the concrete, which accounts for the observed decline in performance at higher CS contents.

In alkali-activated slag cement systems, CS consistently lowers water absorption across all replacement levels. This is because the refined, blocked pore structure effectively resists water infiltration [12]. Overall, the results indicate that replacing sand with CS up to about 40% is optimal. At this level, water absorption is minimized due to micro-filling effects that make the matrix denser and less permeable. Beyond 40%, absorption increases as workability decreases, and the heavier slag particles cause settlement, leaving behind more voids and a porous microstructure. This trend is closely reflected in void content measurements, which also show the lowest values at 40% replacement before rising sharply. In summary, a 40% CS replacement strikes the best balance: it reduces porosity, limits water absorption, and helps maintain long-term durability as similar to the present study [14].

### 3.5 Acid and Sulphate Resistance

Figure 9 shows weight and strength loss of the slag based GPC cubes immersed in HCL, $H_2SO_4$ and $Na_2SO_3$ solutions.

From the Figure 9(a) it is evident that the loss in the weight of the GPC cubes after the immersion in HCL acid for 28 days is 0.878%, 0.813% and 0.771% at 8M, 10M and 12m respectively. The loss in the strength of the GPC cubes after the immersion in HCL acid for 28 days is 6.41%, 6.29% and 5.81% at 8M, 10M and 12M respectively. Both weight and strength loss are relatively small, indicating that the geopolymer matrix effectively resisting the chloride ion penetration. At higher molarity levels, matrix becomes denser and reduces pore connectivity leads to limiting acid ingress and dissolution of binder phases.

From the Figure 9(b) it is evident that the loss in the weight of the GPC cubes after the immersion in $H_2SO_4$ acid for 28 days is 2.038%, 1.905% and 1.713% at 8M, 10M and 12m respectively. The loss in the strength of the GPC cubes after the immersion in $H_2SO_4$ acid for 28 days is 8.33%, 6.29% and 7.78% at 8M, 10M and 12M respectively. Compared to HCL immersion higher weight and strength losses were observed is due to the aggressive nature of sulphuric acid. Sulphates induce the formation of expansive gypsum and ettringite like compounds. These compounds weaken the matrix and leading to greater weight and strength loss to the GPC mixtures.

From the Figure 9(c) it is evident that the loss in the weight of the GPC cubes after the immersion in $Na_2SO_3$ acid for 28 days is 0.477%, 0.445% and 0.394% at 8M, 10M and 12m respectively. The loss in the strength of the GPC cubes after the immersion in $Na_2SO_3$ acid for 28 days is 4.89%, 4.41% and 3.97% at 8M, 10M and 12M respectively. The slight reduction in weight is observed due to the superfacial leaching and minor surface degradation. At higher molarity levels dense matrix leads to reduced pore connectivity thereby restricting the ingress of sulphite ions and minimizing material loss. Moderate strength reduction is attributed to the surface softening and microcracking induced by the weak acid attack. These microstructural damages reduce the ability of the cubes to transfer load effectively. However, as the molarity increases, the enhanced geopolymerization produces a denser matrix, leading to better acid resistance and lower strength loss.

Based on past studies it is observed that addition of CS in conventional concrete improve its both mechanical and durability properties up to an optimum replacement the similar trend observed in the GPC mixtures also. This is mainly because the dense C–S–H gel structure formed limits the penetration of sulphates, while CS itself contributes as an auxiliary cementitious material. That said, the picture changes in environments rich in magnesium sulphate. The ferrous compounds in CS react to form ferrous salts, which accelerate disintegration, mass loss, and strength decline. Research findings indicate that CS concrete deteriorates more severely than conventional mixes when exposed to sulphuric acid, whereas AASC made with sand shows comparatively better durability [12].

## 4 Conclusions

The current study is evaluated the performance of copper slag-based GPC with respect to its mechanical strength and durability properties. The work focused on M40 grade GPC, where fine aggregate was partially replaced with copper slag at levels between 0% and 50%. Alkaline activator solutions of 8M, 10M, and 12M were used to study the effect of molarity. Results showed that

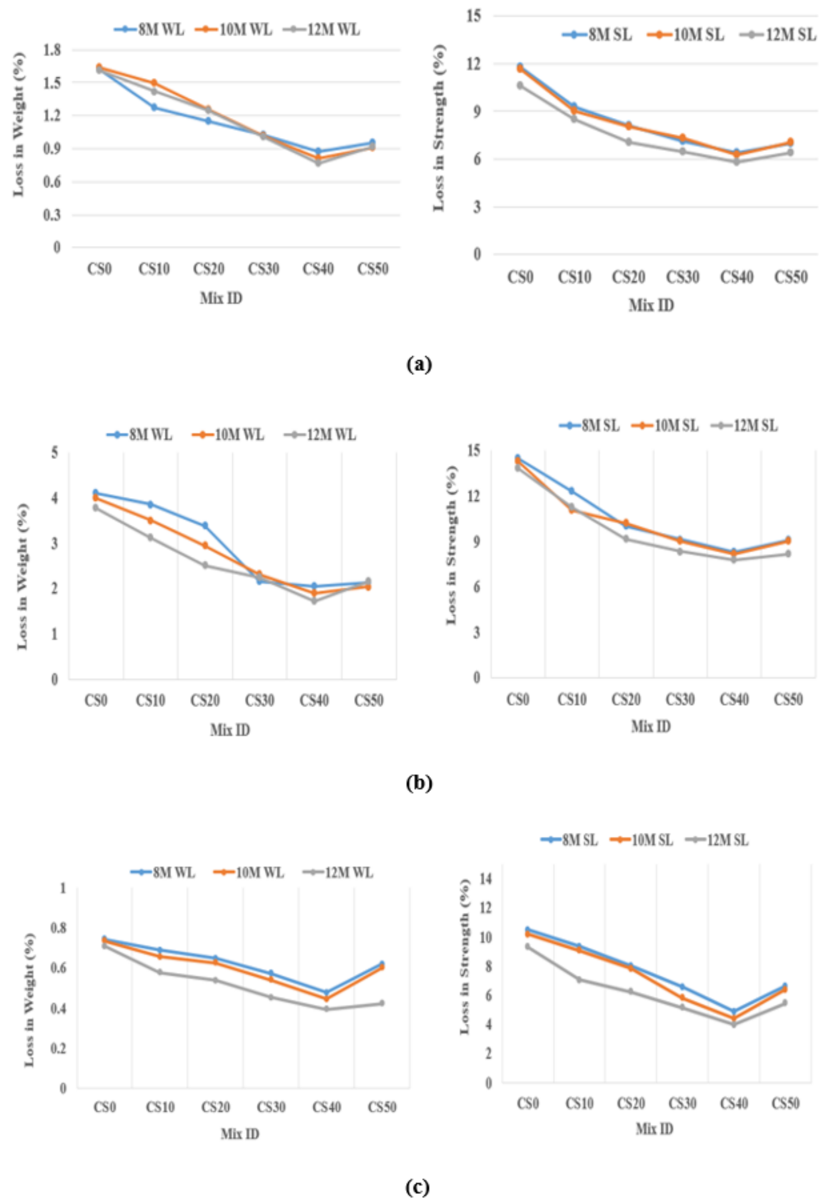


**Fig 9.** (a) HCL Immersion (b) $H_2SO_4$ Immersion (c) $Na_2SO_3$ Immersion Loss in Weight and Strength of Slag based GPC Mixes

the best performance was achieved with 40% copper slag replacement, combined with a binder mix of 70% fly ash and 30% GGBS.

1. Regarding mechanical properties, Mix CS40 containing 40% CS replacement showed increased compressive strength of about 10.32%, flexural strength of about 30.53% and modulus of elasticity of about 30.14% at 12M concentrations compared to the control mix CS0.
2. Beyond 40% there is a reduction in the strength, representing 40% replacement as an optimum replacement level.
3. Regarding durability properties, GPC mix CS40 showed reduced water absorption and enhanced resistance to acid and sulphate environments.
4. Water absorption of CS40 reduced up to 50.97%, 55.33% and 57.41% compared to CS0 at 8M, 10M and 12M respectively.

5. Weight and strength loss of CS40 due to acid and sulphate environment is approximately about 50% compared to CS0 at all molarity concentrations.
6. This improvement in the durability is because of the pore refinement and enhanced geopolymerization process.

The present study is limited to M40 grade GPC with 8M, 10M and 12M concentration levels, lower or higher concentrations may provide additional insights into the effect of alkalinity on geopolymerization. Durability evaluation is restricted to water absorption, acid and sulphate resistance, it can be extended to chloride penetration, carbonation, long-term drying shrinkage.

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