

# Assessment of Mechanical and Durability Characteristics of Geopolymer Concrete Using Coal Mine Bottom Ash and Copper Slag

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**Abstract** This study aims to evaluate the combined influence of Coal Mine Bottom Ash (CMBA), Copper Slag (CS), Demolition Waste (DW) and Manufactured Sand (M-Sand) on Geopolymer Concrete (GPC) with the objective to enhance the sustainability, mechanical performance and durability characteristics. Six mixes (M1-M6) were designed by varying the proportions of CMBA, CS and DW. Fresh, mechanical, microstructural and durability properties of the mixes were assessed. A 10% increase in workability was observed with 40% CMBA compared to the mix with the absence of CMBA, contributing to better flowability. Mixes with CS exhibited a 5% reduction attributed to CS's angularity and increased specific gravity. The mix with 40% CMBA recorded 22.9%, 27.1%, and 28.4% higher compressive, split tensile, and flexural strength than the initial mix. The mix with 20% CMBA and 20% CS showed closer performance gains of 20-24% confirming the benefit of combined reinforcement. Microstructural Analysis revealed that the mix with 40% CMBA exhibited denser matrices and fewer microcracks whereas the one with 0% CMBA exhibited porous zones and weak interfaces. Water absorption was observed to decrease by 33.8% in a similar manner indicating improved impermeability. Compressive strength retention after acid exposure varied from 81% to 98.11% with the lowest

weight loss of 1.4% confirming better chemical resistance. Future work will focus on long-term durability assessments and structural behaviour of reinforced elements under loading conditions. Overall, the results demonstrate that integration of these mineral wastes produces a GPC with superior mechanical strength, reduced permeability and enhanced acid resistance, confirming its suitability for sustainable structural applications.

**Keywords** Geopolymer Concrete, Coal Mine Bottom Ash, Copper Slag, Durability, Demolition Waste, Strength Retention, Sustainable Construction

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## 1. Introduction

To address the growing need for sustainable construction practices, extensive research is being undertaken, out of which the search for alternatives to conventional cement concrete is one such area of interest. Among the various promising alternatives, geopolymer concrete has presented significant results, attributing to its ability to reduce carbon footprint as it utilizes industrial by-products as precursors of aluminosilicate [1]. GPCs are synthesized using

materials which are rich in silica and alumina using alkaline solutions such as sodium hydroxide (NaOH) and Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) [2]. Coal mine bottom ash (CMBA), a byproduct from thermal power plants and mining operations, presents a major concern to the environment during disposal and its utilisation overcomes the waste management issues as well as enhances circular economy practices in mining sectors [3]. Copper Slag is a metallurgical residue that possesses high specific gravity and excellent mechanical properties, hence making it a potential substitute for natural coarse aggregates [4].

Various studies have been performed to explore the feasibility of utilising industrial by-products in geopolymer concrete. Devanath et al. [5] reported that coal bottom ash enhanced the strength development when used in binary or ternary blends with both fly ash and GGBS, suggesting it is a valuable supplementary material in geopolymer formulations. Studies by Selvi et al. [6] reported that copper slag, when used as a replacement for coarse aggregates, improved the density and strength of concrete mainly due to its angular shape and low water absorption. Studies by Sergio et al. [7] discussed the use of demolition waste as coarse aggregates, which indicated medium trends in compressive strength, showing that, though feasible, the standalone usage of DW may require enhancement through supportive materials in order to meet higher strength demands. GGBS is widely recognized as a material that can be incorporated to enhance the early age strength in geopolymer concrete due to the presence of high calcium content. Part et al. [8] reviewed the fly ash-based GPC to highlight the potential to reduce carbon emissions and industrial waste generation. The study further highlighted the importance of alkaline activator concentration on the strength of GPC. Camarini et al. [9] investigated the high strength GPC by incorporating varying proportions of fly ash and GGBS. It was reported that a blend of 60% GGBS and 40% fly ash achieved a compressive strength of 71 MPa under hot curing at 70 °C for 24 hours. Krishna et al. [10] studied the performance of GPC incorporated with copper slag as a partial replacement for fine aggregates. The results indicated that incorporating up to 50% copper slag contributed to the enhancement of both the compressive strength and density of concrete. The study examined the feasibility of utilising waste copper slag as a partial substitute for fine aggregates in concrete. The findings supported the effective utilization without compromising the mechanical performance of material. Sreekeasha et al. [11] studied the mechanical and durability aspects of GPC utilising the ceramic tile waste as a partial replacement for natural aggregates. The study indicated that the incorporation of ceramic waste improved the impact energy and durability of the concrete. Gabriel et al. [12] studied the durability of geopolymer mortar made with waste cement concrete and glass powder and reported an enhanced resistance to acid and sulphate attack, thus highlighting the potential of utilising the demolition waste in GPC applications. Tahwia et al. [13] presented an

experimental study on high performance GPC using fly ash, GGBS and copper slag. The study highlighted that, the synergistic use of the materials results in improved mechanical as well as durability aspects of GPC. Biney et al. [14] evaluated the strength and durability of geopolymer mortar with concrete waste powder and GGBS. The study highlighted that with 20% replacement of concrete waste powder with GGBS, the results indicated enhanced compressive strength and reduced porosity. Innovative approaches are also being developed to make concrete more environmentally friendly. This includes utilisation of  $\text{CO}_2$  in the curing process, facilitating storage of Carbon within the concrete [15].

While previous studies have demonstrated the benefits of incorporating materials like CMBA, CS, DW and M-sand in GPC individually, studies on the integration of all these components are limited. The objective of this study was to comprehensively evaluate the synergistic effects of the industrial by-products on fresh, mechanical, microstructural and durability performance of GPC incorporating all the materials. By addressing these objectives, this study aims to optimize material performance while promoting sustainability under varying environmental conditions.

With reference to the previous studies that investigated individual incorporation of coal mine bottom ash, copper slag or demolition wastes in geopolymer concretes, this study presents a holistic integration of all these mineral wastes within a single geopolymer matrix. The novelty lies in evaluating the synergistic effects of these materials on both mechanical and durability performance, thereby establishing a comparative framework for sustainable mix optimization.

## 2. Materials and Methods

### 2.1. Materials

This experimental work utilised a combination of industrial by-products and recycled materials to develop a sustainable GPC. Fly ash and GGBS slag served as primary aluminosilicate sources for the matrix, while coal mine bottom ash was introduced as a partial replacement for fine aggregates alongside manufacturing sand. Copper slag and demolition wastes were used as coarse aggregates with partial replacements for each other. Alkaline activators, namely NaOH and  $\text{Na}_2\text{SiO}_3$  were used to initiate and sustain the geopolymerisation process.

The fly ash sourced for the study had a specific gravity of 2.21 with about 90% of its particles passing through a 45  $\mu\text{m}$  sieve and a density of 1136.15  $\text{kg}/\text{m}^3$ . GGBS of specific gravity of 2.85 with 95% passing through a 45  $\mu\text{m}$  sieve and a bulk density of 1233.02  $\text{kg}/\text{m}^3$  was sourced alongside flyash from Raichur Thermal Power Plant, Raichur Karnataka. CMBA, utilised as a partial replacement for fine aggregate, presented a specific gravity

of 2.2, a particle size around  $600\mu\text{m}$ , and a density of  $1150\text{kg/m}^3$ , which is obtained from Raichur Thermal power plant as well. The primary fine aggregate utilised in this study was M-Sand which was sourced locally from Bangalore, Karnataka. M-sand had a specific gravity of 2.65, fineness modulus of 2.8 and a bulk density of  $1522.77\text{kg/m}^3$ . CS, sourced from Enore Chemicals, Tuticorin, Tamil Nadu, was employed as a partial and full replacement for coarse aggregates with a specific gravity of 3.54, a particle size ranging from 16-20mm and a bulk density of  $1842.3\text{kg/m}^3$ . Demolition Waste (DW), sourced from construction debris locally, exhibited a specific gravity of 2.4 and particle sizes up to 20mm with a bulk density of  $1342.6\text{kg/m}^3$ . The alkaline activator used in the study included an 8M NaOH solution with a specific gravity of 1.34 and a  $\text{Na}_2\text{SiO}_3$  solution with a specific gravity of 1.5. Figure 1 presents the raw materials used in the current study.



Figure 1. Raw materials used in the study

### 2.1.1. Characterisation of Binders and Aggregates

The chemical composition of the binders was determined using X-ray fluorescence (XRF) and is presented in Table 1. Fly ash exhibited high contents of silica ( $\text{SiO}_2$ ) and alumina ( $\text{Al}_2\text{O}_3$ ) with relatively low calcium oxide (CaO), thus classifying it as low-calcium, that is, Class F ash [16]. Such composition favors the formation of sodium aluminosilicate hydrate (N-A-S-H) gels, which are responsible for long-term strength gain. The GGBS indicated a relatively higher CaO content along with  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , showing its latent hydraulic behavior, which contributes to early-age strength development through calcium aluminosilicate hydrate (C-A-S-H) gel formation [17]. CMBA contained intermediate proportions

of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and CaO, confirming the dual pozzolanic and cementitious potential. Furthermore, Ferric oxide ( $\text{Fe}_2\text{O}_3$ ) content in all the materials can assist in improved matrix densification through secondary phase development [18].

Loss on Ignition (LOI), which is the percentage mass lost when the sample is heated to  $950\text{-}1000\text{ }^\circ\text{C}$ , mainly due to the removal of moisture, carbonates and unburnt carbon, was observed to be low ( $<2\%$ ). This indicated the presence of well-burnt and stable precursors, thus ensuring higher reactivity and consistent geopolymerisation [19].

Table 1. Chemical Composition of Raw Materials (wt.%)

Oxide Composition	Fly Ash (FA)	GGBS	CMBA
$\text{SiO}_2$	54.3	33.1	46.7
$\text{Al}_2\text{O}_3$	26.4	14.2	18.5
CaO	6.2	37.8	17.9
$\text{Fe}_2\text{O}_3$	8.5	1.9	8.1
MgO	1.2	6.1	2.3
$\text{Na}_2\text{O} + \text{K}_2\text{O}$	2.4	1.8	2.0
LOI	0.9	1.2	1.6

FA and GGBS exhibited specific gravities of 2.21 and 2.85, respectively, with over 90% of the particles passing through a  $45\mu\text{m}$  sieve. This ensures high reactivity due to a larger surface area [20]. The CMBA exhibited a specific gravity of 2.20 with a coarser particle size. This enabled it to function as both a micro-filler and a partial binder [21].

## 2.2. Mix Proportions

The mix design for the GPC was evaluated on the basis of previous studies and iterative laboratory trials. The design parameters were selected to study the individual and combined effects of CMBA, CS and DW on properties of GPC. In the study, the proportions of all GPC specimens were designed with a constant binder content of  $400\text{kg/m}^3$  with equal parts of FA and GGBS in a 1:1 ratio. Fine aggregates' quantity was maintained at  $650\text{kg/m}^3$  while coarse aggregates content was considered to be  $1200\text{kg/m}^3$ . NaOH solution was used at 4% of binder weight and  $\text{Na}_2\text{SiO}_3$  was incorporated at 10% of binder weight. CMBA, CS and DW were varied and utilised as partial replacements for fine and coarse aggregates by weight. Table 2 presents the mix proportions of the GPC used in this study.

**Table 2.** Mix Proportions of Geopolymer Concrete (per m<sup>3</sup>)

Mix ID	FA: GGBS	M-Sand	CMBA	CS (%)	DW (%)	NaOH: Na <sub>2</sub> SiO <sub>3</sub>
	Alumino-Silicate Source	(% by weight of Fine Aggregates)		(% by weight of Coarse Aggregates)		Alkaline Activators
M1	1:1	100	-	-	100	1:2.5
M2		80	20	-	100	
M3		60	40	-	100	
M4		100	-	20	80	
M5		80	20	20	80	
M6		80	20	40	60	

The alkaline activator solution was prepared 24 hours prior to the mixing by dissolving NaOH pellets in distilled water to obtain an 8M solution. The solution was further allowed to cool to room temperature. Na<sub>2</sub>SiO<sub>3</sub> solution was blended with NaOH solution in a 2.5:1 ratio by weight. It must be highlighted that the total water content of 56kg in the mix was utilised solely for these activator solutions with 34kg and 22kg for NaOH and Na<sub>2</sub>SiO<sub>3</sub>, respectively. Initially, dry mixing was carried out where all the solid constituents including FA, GGBS, M-Sand, CMBA, CS and DW were thoroughly mixed in a pan blender for about 2 to 3 minutes to ensure uniform distribution. The alkaline solution is then added to the dry mix and stirred continuously. The wet mixing is continued for 3 to 4 minutes until a homogeneous and workable mixture is obtained. Figure 2 presents the preparation of geopolymer concrete in the laboratory setup.



**Figure 2.** GPC Preparation in Laboratory Setup

### 2.3. Testing Methods

The fresh concrete was placed in steel moulds in layers and compacted to eliminate any entrapped air. The workability of the fresh GPC is assessed using the standard slump cone test in accordance with IS 1199:1959 [22]. The slump value was recorded as soon as the mixing was done to evaluate both consistency and flow characteristics of the mix. Figure 3 presents the slump cone apparatus used for

the study.

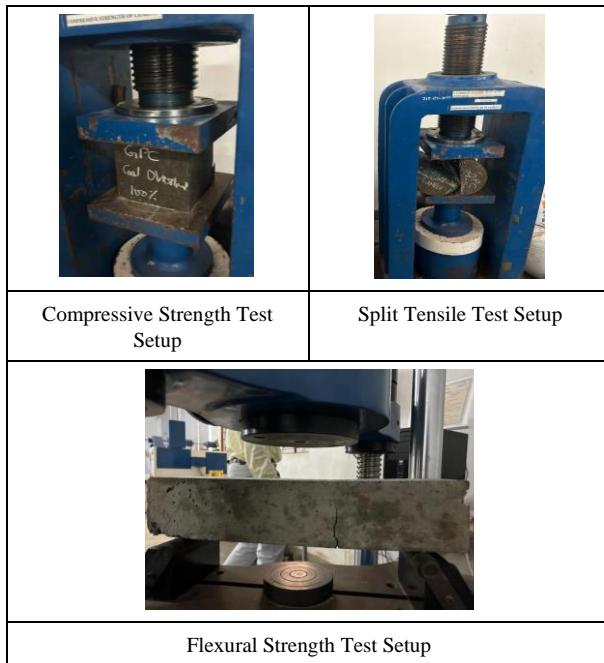


**Figure 3.** Slump cone apparatus used to study the workability of the mixes

The concrete was further cast into moulds for assessing the mechanical properties. Specimens were cast in the form of 100mm x 100mm x 100mm cubes to check for compressive strength as per IS 516:1959 [23], 150mm diameter x 300mm height cylinders to assess split tensile strength as per IS 5816:1999 [24] and prisms of 100mm x 100mm x 500mm for flexural strength test in accordance with IS 516(Part 2/Sec 1):2021 [25]. All moulds were immediately covered with plastic sheets to prevent early moisture loss due to evaporation as per IS 9013:1978 [26]. The specimen was then demoulded after 24 hours and cured in ambient conditions until the day of testing. A total of 9 samples each were tested at 7, 14 and 28 days.

A compression Testing Machine (CTM), model AIM 206-20, Aimil Ltd, with a maximum load capacity of 2000kN, was used to determine the compressive strength, and the loading rate was fixed to 5.2kN/s as suggested in IS 516:1959. Split Tensile Strength Test was conducted using Universal Testing Machine (UTM), Instron model 5980, with a load capacity of 1000kN and a loading rate of 1.5kN/min as per IS 5816:1999. Flexural strength test was performed using three-point loading method as per IS 516(Part 2/Sec 1):2021 with a loading rate of 0.05MPa/s. Figure 4 presents the test setups for compression, split

tensile and flexural strength tests, respectively.



**Figure 4.** Test setups for compression, split tensile and flexural strength tests

Microstructural characterization of the specimen post fracture was performed using Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX). Surface morphology, phase distribution and elemental composition of the matrix were examined during the process. SEM analysis was conducted using Hitachi Model S-3500N scanning electron microscope. The model operated under high-vacuum conditions at an accelerating voltage of 20kV. The instrument was equipped with an electron source made of tungsten facilitating high-resolution imaging. Small fragments were carefully extracted from the fractured surface of the specimen and gently cleaned. This was followed by oven-drying at 60 °C for 24 hours to remove residual moisture. All samples were sputter coated with a thin conductive layer of gold-palladium (Au-Pd) using an ion sputter coater JEOL JFC-1600 for approximately 90 seconds with a current of 10mA.

Durability aspects of the mixes were studied to arrive at optimal mixes for further studies. Water absorption tests as per ASTM C642 were conducted, where 100mm cubes were oven dried at 105 °C for 24 hours until a constant mass was obtained [27]. The dry weight was recorded, and the specimens were immersed in water for 48 hours. The saturated weight was then recorded and water absorption was evaluated. The acid resistance test was conducted as per IS 526(Part 5/Sec 1):2018 where 100mm cubes were immersed in 5% H<sub>2</sub>SO<sub>4</sub> solution for 28 days [28]. Post immersion, weight loss and reduction in compressive strength were recorded. The compressive strength after exposure was compared with that of an unexposed specimen.

### 3. Results and Discussions

#### 3.1. Effect of Composition on Workability of GPC

The slump values observed across the six geopolymer mixes exhibited noticeable variations mainly influenced by the type and proportion of coarse aggregate replacements. Table 3 presents the variations in the slump values across the mixes.

**Table 3.** Average Slump Values for Geopolymer Concrete Mixes

Mix ID	Average Slump Value (mm)
M1	100
M2	105
M3	110
M4	95
M5	100
M6	97

M1 utilised M-sand as 100% of fine aggregates and DW as 100% of coarse aggregates. It demonstrated good workability with a slump value of 100mm. Incorporation of CMBA as a partial replacement for M-sand improved the workability of the mixes M2 and M3, attributed to the fact that the bottom ash has a finer particle size and spherical morphology, facilitating improved paste formation and providing a lubricating effect [29]. Further, CMBA contributed marginally to binder like behaviour due to its alumina and silica presence, aiding in paste cohesion [30]. The mixes with CS, which are M4, M5 and M6 exhibited a decline in slump values as compared to CMBA rich mixes. This trend coheres with previous studies, in which the angularity and heaviness of copper slag led to reduced workability due to poor particle packing and higher friction between the aggregates [31]. Mix M5 included both CS and CMBA, which exhibited the mitigation of negative effects of CS on flowability, advertising the advantages of dual usage of industrial by-products in offering the synergistic improvements in concrete's fresh properties [32]. Presence of DW either partially or fully led to acceptable workability confirming that appropriate grading can facilitate maintaining workable mixes [33].

#### 3.2. Effect of Composition on Mechanical Properties of GPC

Mechanical performance of the GPC mixes indicated a clear increase in trends in strength development across compressive, split tensile and flexural strength tests at 7, 14 and 28 days as indicated in Figure 5. Among the mixes, M3 which incorporated 40% CMBA as a replacement for M-sand exhibited the best results. It was observed that M3 indicated a 22.9%, 27.1% and 28.4% increase in compressive, split tensile and flexural strength tests, respectively, when compared to M1. These improvements

are attributed to the finer particle size and pozzolanic activity of CMBA which led to improvement in paste-aggregate interface and densified the matrix mainly due to microstructural packing and enhanced geopolymer gel formation [34]. M2 which utilised 20% CMBA presented notable improvements with 13.9%, 16.9% and 17.1% increases in compression, split tensile and flexural strength, respectively. The results reaffirmed that a minimal inclusion of CMBA enhanced matrix cohesion and crack resistance. The results aligned with those of Zhou et al. [35] who observed improved early and long-term performance with moderate ash additions in GPC matrices. Mix M4, which included 20% CS as a replacement for DW, indicated slightly lower performance at early stages, mainly due to the angular and inert nature of CS. Considering the 28-day strength, it was observed that M4 surpasses M1 by 5-6% in overall strength parameters. Initial studies discussed this aspect of delayed strength development, where they mentioned that while CS contributed to limited reactivity, it improved the long-term mechanical integrity of concrete through its density and ability to act as a micro-filler [36]. M5, which combined 20% CMBA and 20% CS presented almost equal performance to M3. It demonstrated a 20.3%, 24.4% and 24.2% increase in compressive, split tensile and flexural

strengths compared to M1. The combination of CMBA's pozzolanic and CS's filler effects contributed to the balanced improvements in workability and strength. Mix M6 with 20% CMBA and 40% CS showed constant increases in compressive strength and tensile strength over M1, although the flexural strength was lower than M3 and M5. Higher content of CS contributed to affecting the homogeneity of the mix, thus compromising the matrix continuity [37].

### 3.3. Observations on Microstructural Analysis

The micrographs in Figure 6 revealed a porous matrix for M1 mix indicating larger unreacted fly ash and GGBS particles and microcracks at the aggregate matrix interface exhibiting poor interfacial bonding. This can be attributed to high porosity and weak ITZ, thus contributing to lower strength and higher water absorption as observed by Kumar et al. [38]. M2 mix presented improved particle packing with fewer voids and observed CMBA partially embedded in the matrix with minimal bonding and microcracks. It was inferred that CMBA contributed to the mix as a microfiller leading to improved compactness and enhanced bond zones as confirmed through studies by Reddy et al. [39].

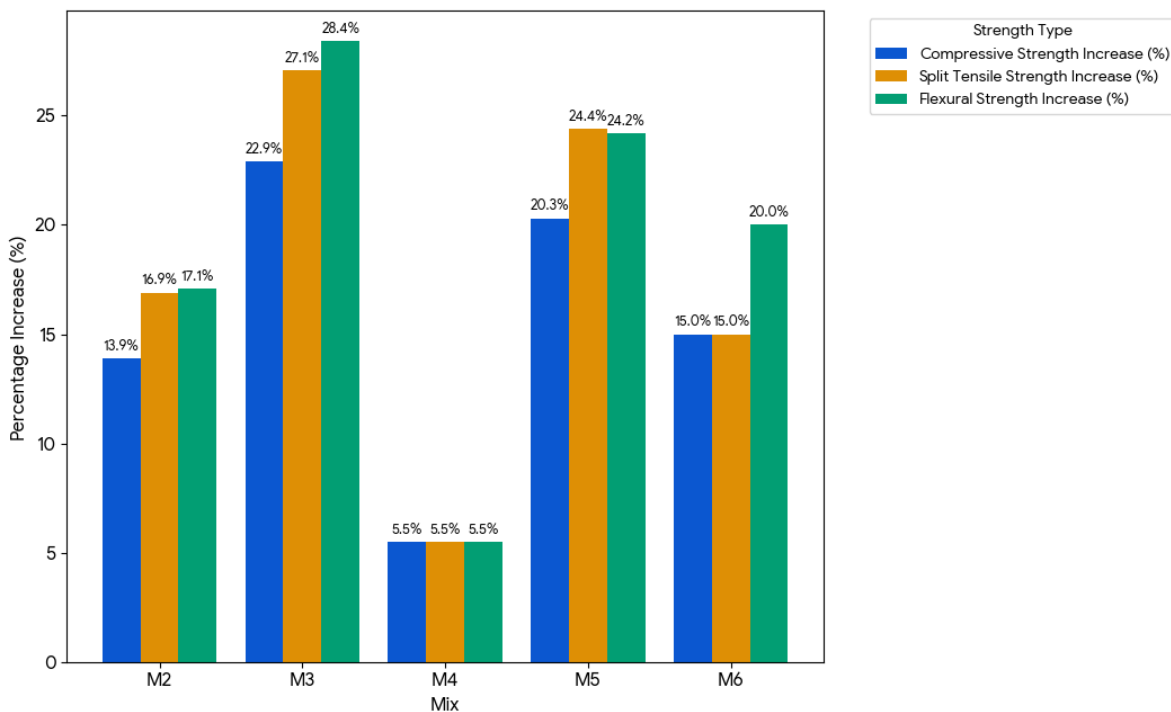
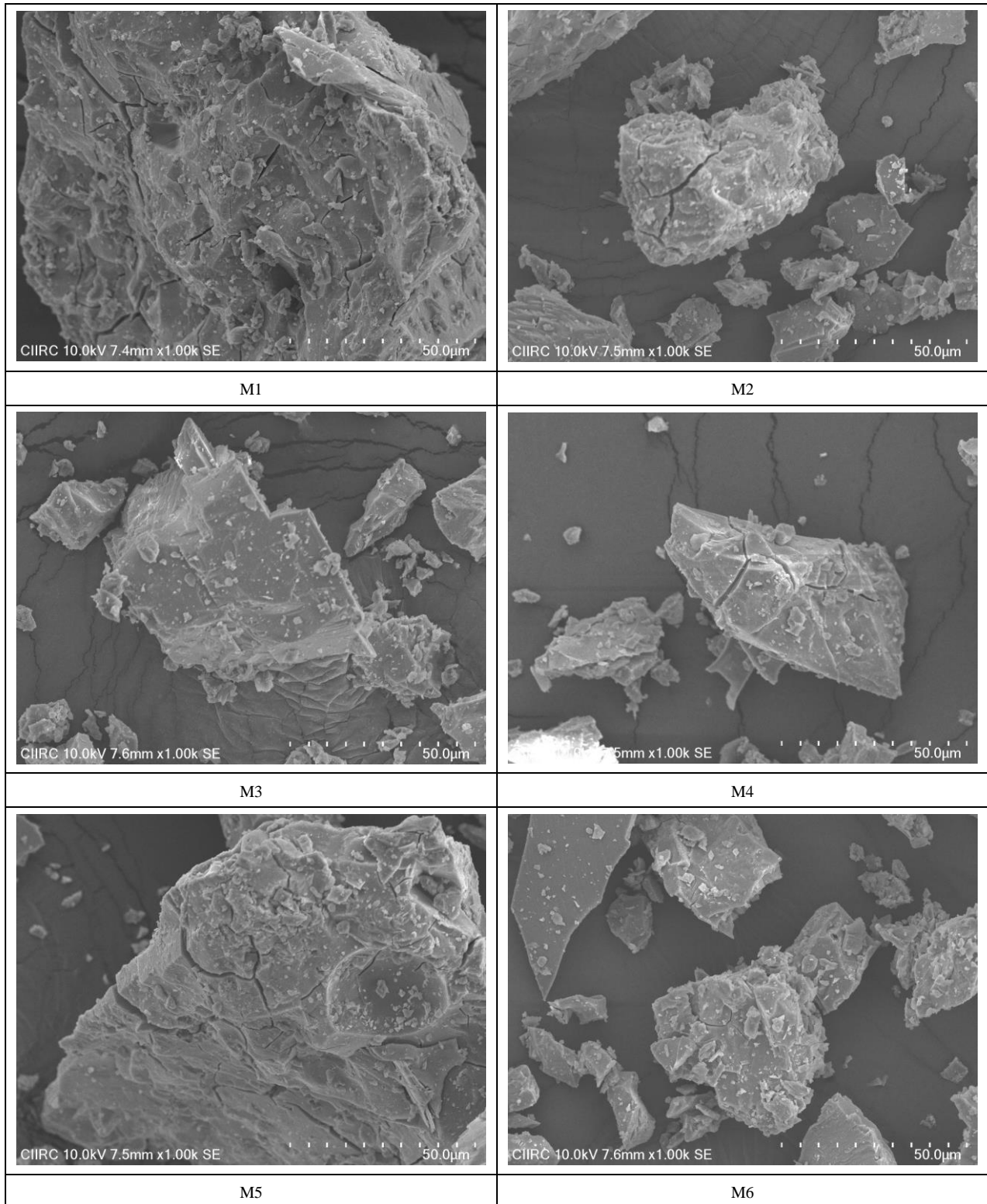


Figure 5. Percentage increase in strengths in GPC mixes with respect to M1



**Figure 6.** SEM Analysis of Mixes

M3 mix with 40% CMBA exhibited a denser matrix with minimal unreacted particles due to increased Geopolymeric gel distribution and a denser interface between CMBA and the binder with minimal cracks. The presence of CMBA in this optimal quantity led to well packed and highly crosslinked structure with higher strength and durability

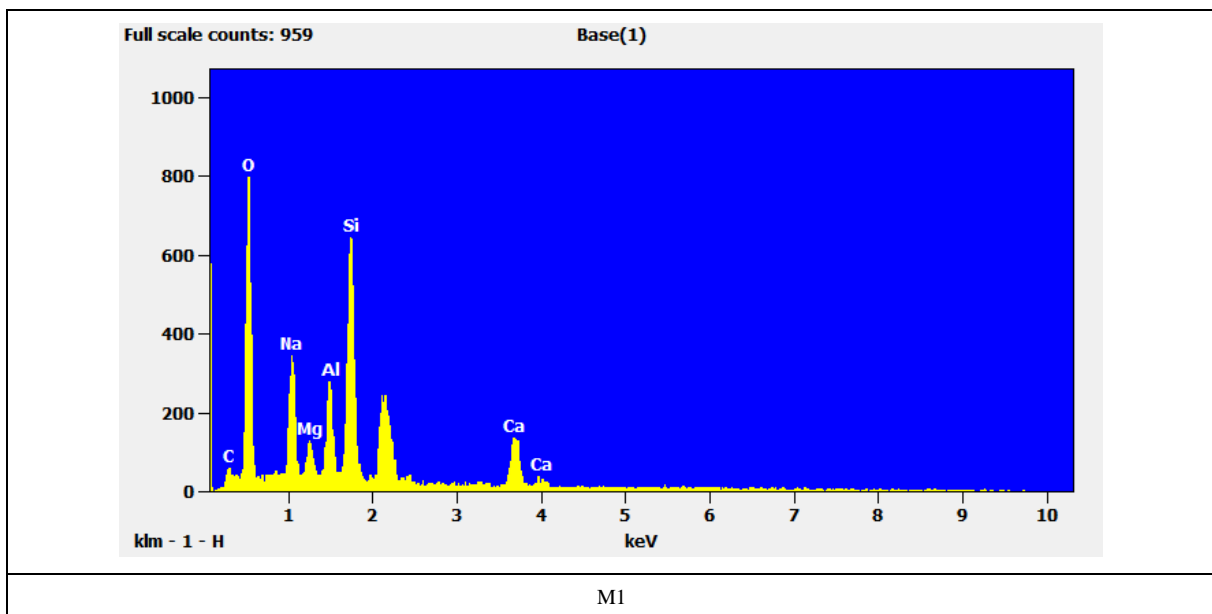
aligning with the studies by Shilar et al. [40]. M4 presented sharp angular CS particles tightly embedded in matrix with some microcracks near CS matrix interface due to a reduction in rigidity. Similar work by Zheng et al. [29] presented that CS improved the density but compromised on the flexibility. Mix M5 presented a balanced

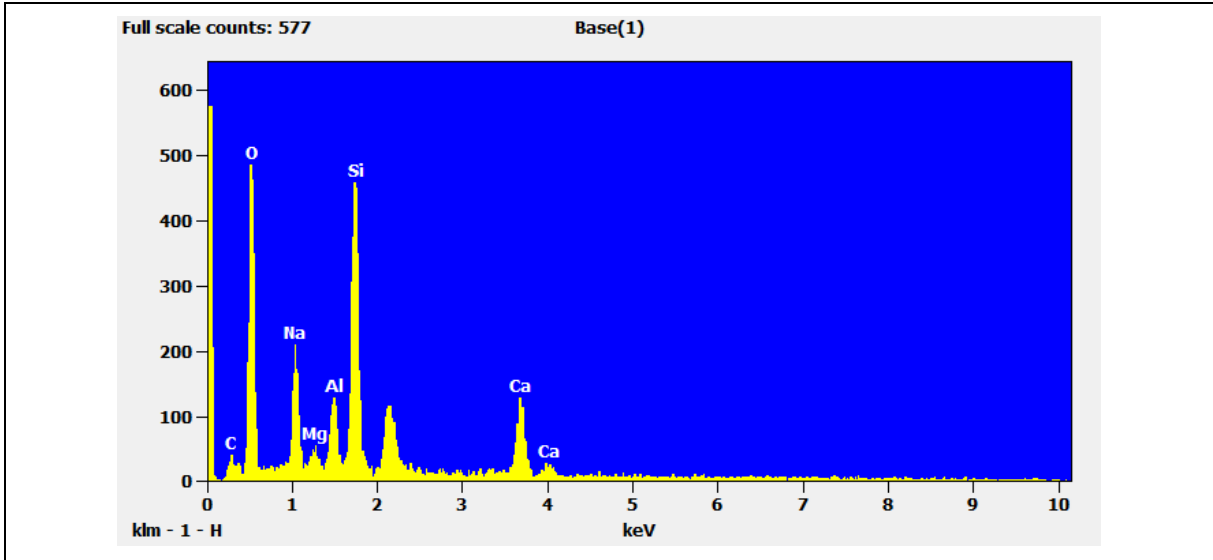
microstructure in which CMBA refined the voids and CS provided mechanical anchoring. M6 presented the densest matrix amongst all the mixes with smooth fracture paths indicating maximum refinement and bonding with minimal microcracks [41].

The Energy Dispersive X-ray (EDX) spectra in Figure 7 reveal a distinct compositional variation among the six geopolymer mixes. While M1 exhibited strong Si and moderate Al peaks, they were accompanied by noticeable Ca and Fe signals. The relatively higher content and unreacted silicate peaks indicate incomplete geopolymerisation and weaker binding at the interface. This further corresponds to the porous morphology and lower strength observation [42]. The spectra for M2 displayed increased Al and Si intensities with slight reductions in Ca peaks compared to M1. This improvement suggests better N-A-S-H and C-A-S-H gel formation and denser packing due to the contribution of CMBA's microfiller properties [43]. M3 indicated the most pronounced Si and Al peaks among the mixes with minimal Ca presence, thus confirming an advanced degree of geopolymerisation. The lower Ca/Si ratio indicated dominance of N-A-S-H gel formation. This resulted in a

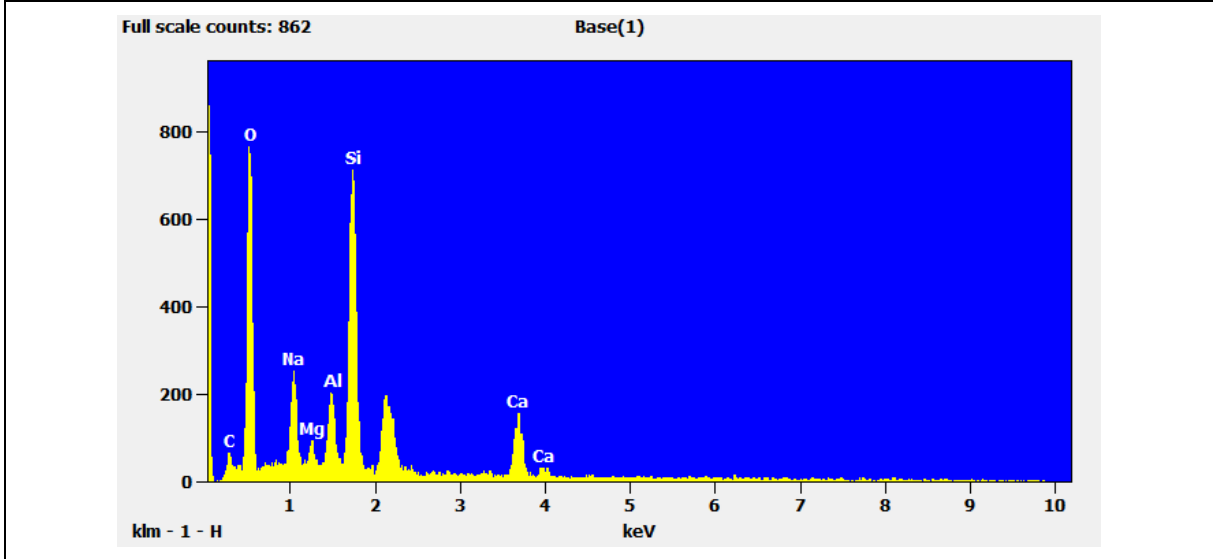
highly compact microstructure and enhanced compressive and flexural strength [44]. M4 demonstrated a slightly higher Fe and Ca peaks, along with sharp Si peaks. Elevated Fe intensity originates from the metallic components of copper slag [45]. Although the matrix appears dense, minor interfacial has occurred around angular CS particles, aligning with observed microcracks at aggregate boundaries. M5 reflected balanced Si and Al peaks with moderate Ca intensity. This implies synergistic gel development where CMBA enhances the reactivity and CS contributes to structural densification [46]. M6 exhibited strong Si and Al peaks with very low Ca content. This signifies extensive geopolymerisation and highly cross-linked gel structure. The reduced Ca/Si and Fe peaks indicate chemical stability and minimized unreacted residues [47].

Thus, the EDX analysis confirmed that increasing the Si/Al ratio and lowering the Ca/Si ratio particularly in M3 and M6 promote the formation of a well-polymerized aluminosilicate network. The compositional transition from Ca-dominant mix to Si-Al rich mix correlates directly with improved microstructural compactness, mechanical strength and durability performance.

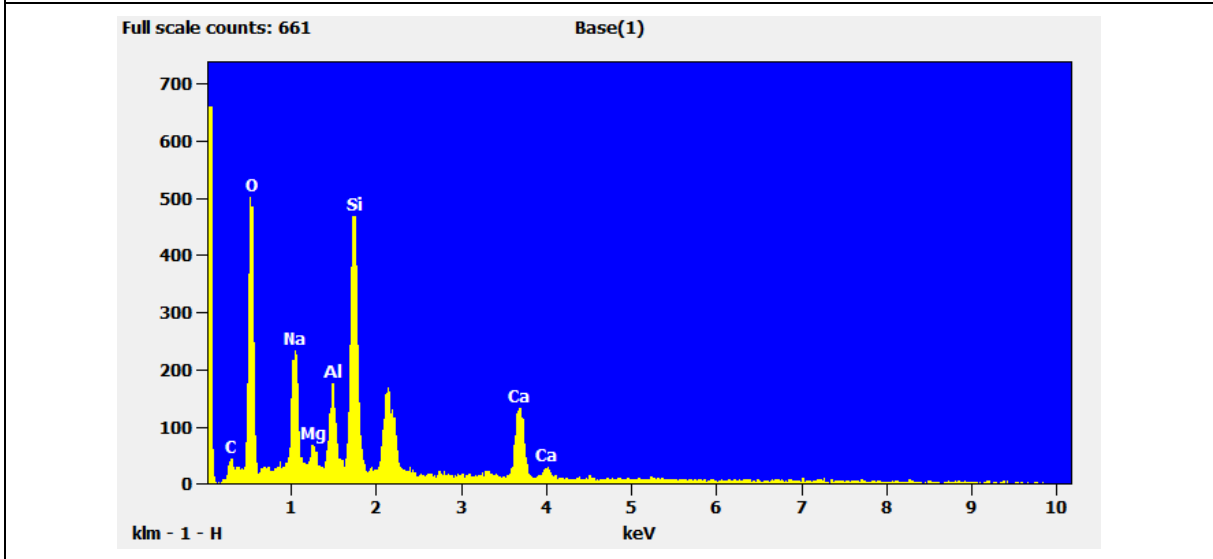




M2



M3



M4

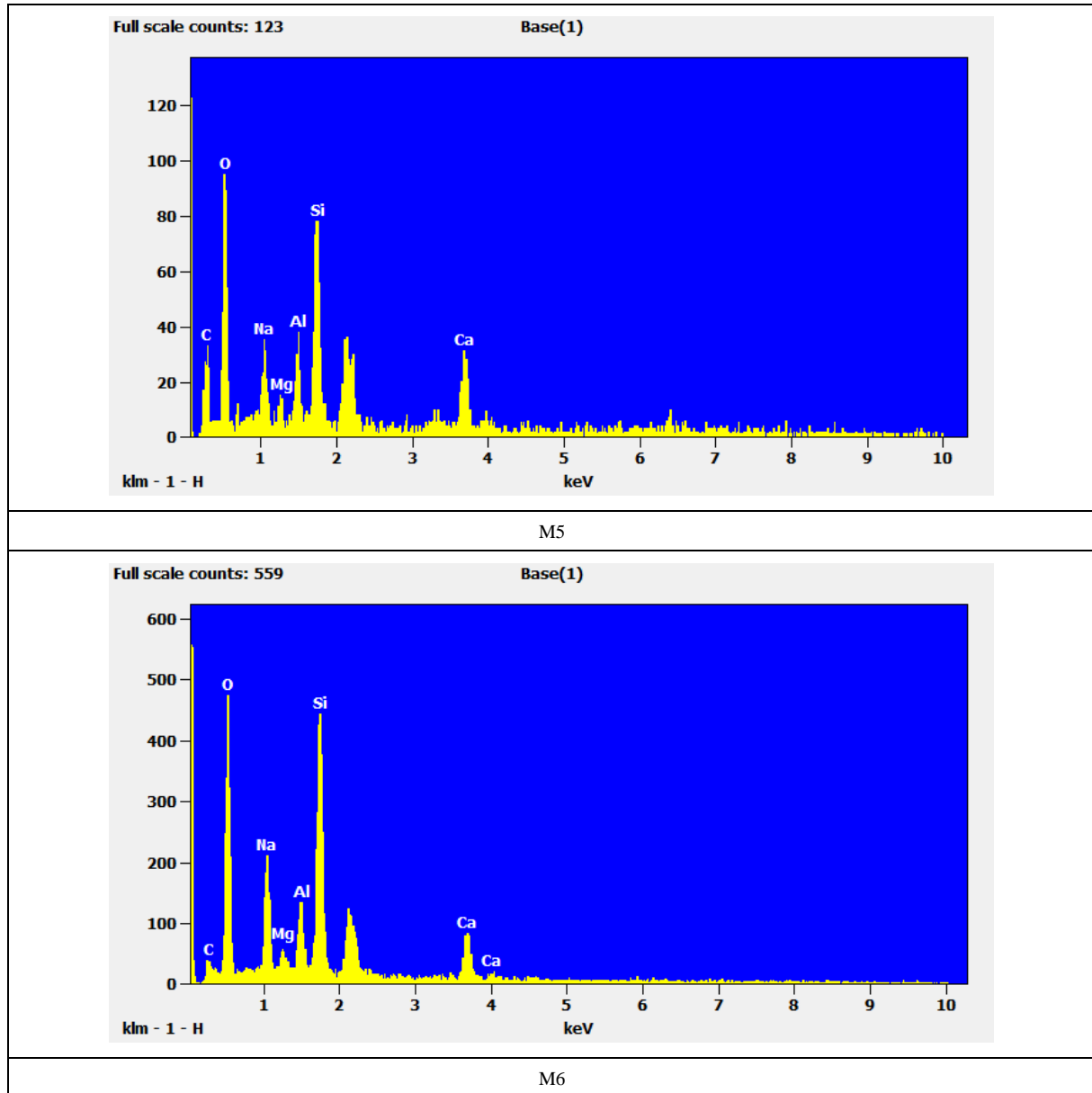


Figure 7. EDX Analysis of Mixes

### 3.4. Durability Studies

It was observed from Figure 8 that M1 exhibited a higher water absorption of 6.8% suggesting a porous structure, indicating higher fly ash and demolition waste content. M6 mix presented the lowest water absorption of 4.5% indicating lower porosity as the reason for the reduced absorption value. GGBS contributed to dense matrix formation whereas PS refined the pore structure. It was further inferred that the incorporation of GGBS and silica-rich materials improved the packing density and reduced the capillary porosity which led to a lowering of water absorption. This was due to the limitation of water ingress by a denser matrix which shall facilitate the long-term durability, specifically in aggressive environments [12].

Further durability tests were performed with respect to

acid exposure for a period of 28 days after curing of the specimen. An average of 9 specimens for each curing age was considered for the strength retention studies post acid exposure. It was observed that M1 with 100% M-sand and DW exhibited the lowest strength retention in the range of 80.88% to 83.01% indicating medium durability when exposed to sulphuric acid. Absence of CMBA and CS resulted in presenting higher porosity and weaker resistance to acid. The findings align with the studies that reported that conventional aggregate systems in GPC are less effective in acid resistance due to lower dense microstructures [36]. M2 and M3 mixes exhibited improved strength retention up to 90.03% at 28 days. As the finer CMBA particles enhanced the geopolymerisation process, it led to a denser matrix and refined pore structure, and, in turn, reduced acid ingress [37]. M4, M5 and M6

mixes incorporating CS indicated the highest strength retention with M6 results of 98.11% at 28 days, exhibiting excellent strength against acid exposure. CS's angular, dense and chemically inert nature restricted the penetration of the acidic media and minimized the degradation [38]. Moreover, M5 and M6 which included both CMBA and CS

demonstrated a synergistic effect causing in almost complete retention of compressive strength after 28 days in acidic conditions. Figure 9 presents the compressive strength retention of multiple geopolymer and alkali activated mixes when exposed to 5% sulphuric acid for 28 days.

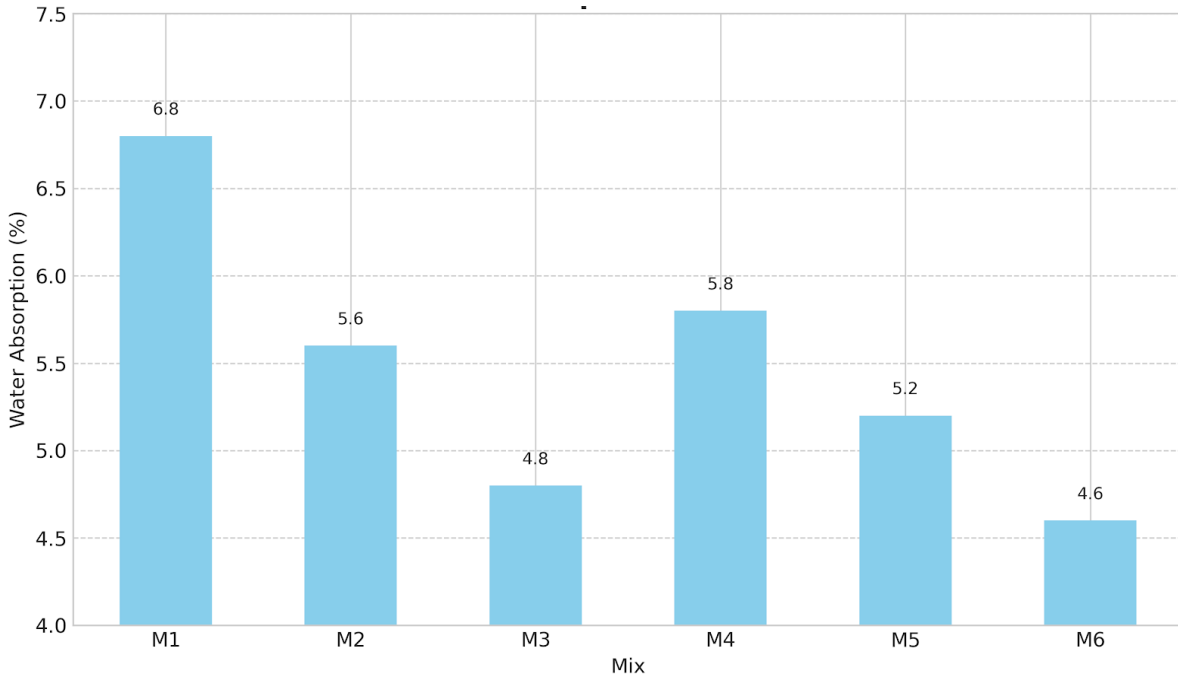


Figure 8. Comparison of Water absorption amongst the mixes

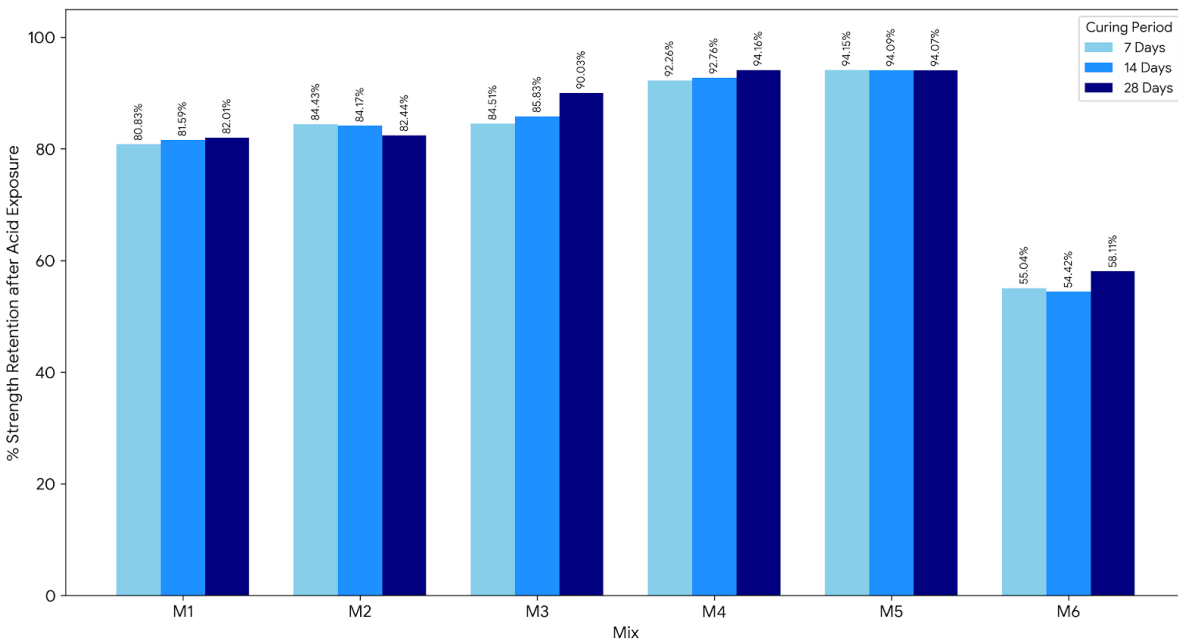


Figure 9. Compressive Strength Retention (%) after Acid Exposure

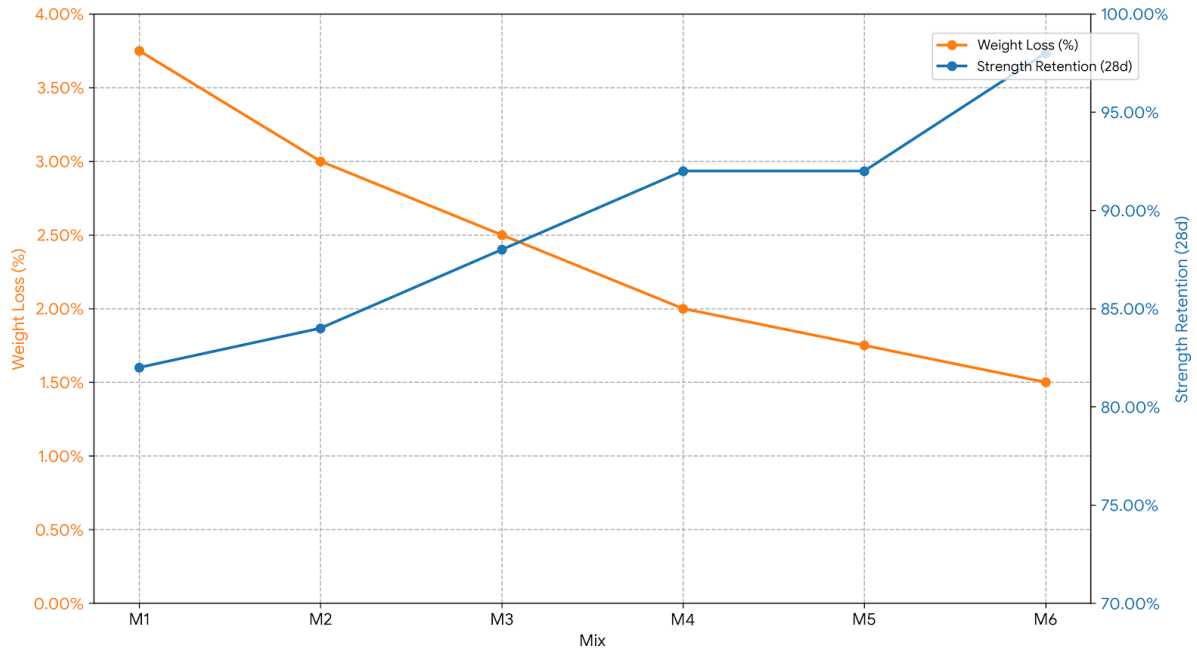


Figure 10. Comparing weight loss (%) and strength retention (%) for mixes

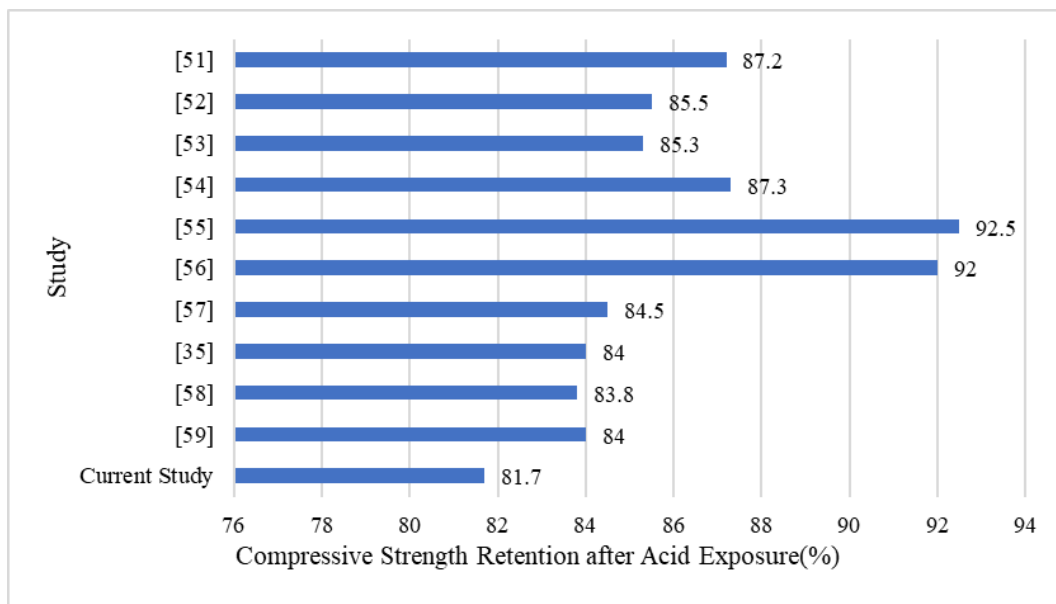


Figure 11. Comparison of the current study with previous acid exposure studies

Current study aligns with these, hence, confirming that FA-GGBS interaction significantly adds to improved acid resistance. The multi component mix enhances the pore refinement, matrix densification and acid neutralization capacity [48]. The dual axis plot presented in Figure 10 illustrates the results of the modification of compositions with industrial by-products leading to a significant improvement in acid resistance. M6 emerges as the most durable against acid attack due to dense microstructure and low permeability. A clear inverse relationship can be observed between weight loss and compressive strength retention. The findings were found to

be consistent with literature, which emphasized the durability benefits of using CS and GGBS [49]. A minimal weight loss of 1.4% and a maximum strength retention of 98% were observed due to the combined effect of 20% CMBA and 40% CS. The weight loss under acidic conditions is predominantly due to the degradation and leaching of soluble compounds in the matrix, with higher weight loss indicating poorer chemical stability. The response indicates the durability benefits of CS and GGBS in aggressive environments and the potential to study the optimization further [50].

As represented in Figure 11, current studies show a

considerable average compressive strength retention of 91.3% aligning it among the top performers in acid resistance. Lowest retention was exhibited in studies by Bakharev et al. [51] and Van Jaarsveld et al. [52] at 77.5% indicating poorer durability in terms of acid exposure. Luhar et al. [53] and Nath et al. [54] studied the effects of combining FA and GGBS. These blends demonstrated better chemical resistance than FA alone, attributed to enhanced C-A-S-H formation, thus reducing porosity. It can be observed that only Mavroulidou et al. [55] and Tejas et al. [56] reported higher values of 92.5% and 92% respectively. Liew et al. [57] included durable aggregates like CS and other slag-based systems, thus improving the compactness and reducing the permeability of acidic ions. These studies utilised FA with alkaline activators which in turn led to porous matrices and minimal acid resistance. Lack of robust aggregates and denser structure explains the significant drop in the strength. Earlier studies like Davidovits [58] and Amar [59] discussed the moderate retention of around 84-85% attributing to lower binder reactivity, non-optimized curing and absence of Supplementary Cementitious Materials (SCM).

For a holistic performance evaluation, the mechanical and durability behavior of the GPC mixes was compared with that of the conventional Ordinary Portland Cement (OPC) reported in literature. Studies on OPC based systems of comparable strength grades (M30-M40) have generally reported compressive strengths ranging from 32-38MPa at 28 days and water absorption values between 6.5-8% under ambient curing conditions [60,61]. In contrast, the optimized geopolymer mix M3 in this study achieved a 22.9% higher compressive strength and a 33.8% lower water absorption, demonstrating better matrix refinement and reduced permeability.

Similarly, under acid exposure, conventional OPC concretes typically exhibit a strength retention below 80-85% due to calcium leaching and decalcification of the C-S-H gel [62,63]. In comparison, current GPC mixes retained 90-98% of their initial strength, confirming their enhanced resistance to chemical degradation. This improvement can be attributed to the formation of chemically stable N-A-S-H and C-A-S-H gel that lack free calcium hydroxide phases, thereby limiting acid ingress and dissolution.

## 4. Conclusions

The study investigated the combined effects of CMBA, CS, DW and M-sand on mechanical as well as durability performance of GPC. Following findings were observed and conclusions drawn from the study.

With reference to workability, mixes incorporating CMBA (M2 and M3) exhibited increased slump values of 105mm and 110mm, respectively while M3 showed a 10% increase in workability as compared to M1 with 100mm slump. Mixes with CS (M4, M5 and M6) indicated a slight

reduction in slump reaching up to 95mm, thereby indicating a 5% decrease in workability, attributed to the angular nature and higher specific gravity of CS. M5, which combined CMBA and CS exhibited balanced workability, thus, highlighting the synergistic effect of industrial-by-products.

Considering the Mechanical Strength aspects, M3, with 40% CMBA, presented the best mechanical performance with 22.9%, 27.1%, and 28.4% higher compressive, split tensile, and flexural strength, respectively, compared to M1. Further, M5 with 20% CMBA and 20% CS combination achieved strength enhancements close to M3 with a 20-24% increase in mechanical parameters, thus highlighting the benefits of combined reinforcements. M6 with increased CS content up to 40% exhibited improved compressive and split tensile strength, but exhibited slightly lower flexural strength, mainly due to reduced homogeneity in the matrix.

The microstructural observations indicated that M3 and M6 showed the densest matrices with fewer microcracks and increased homogeneity, coinciding with the mechanical properties' inferences. M1 exhibited the porous structure with weakened interfaces, indicating lower strength and higher water absorption. It was also observed that CMBA contributed to improved packing and gel formation in geopolymer while CS enhanced the anchoring and density.

Durability performance was observed on the basis of water absorption capacity, weight loss and compression strength retention after exposure to acidic conditions for 28 days. It was seen that water absorption reduced from 6.8% to 4.5% from M1 to M6, presenting a 33.8% reduction in porosity predominantly due to improved refinement in the matrix in the presence of GGBS, CS, and CMBA. M1 was seen to retain only 81% compressive strength whereas M3 and M5 retained 90% and 94% of the initial compressive strength, respectively. M6 indicated the highest retention with 98.11% and a minimum weight loss of 1.4%, marking it as the most chemically durable mix. The study also demonstrated that integration of CS and CMBA enhanced the chemical stability significantly, aligning with and at places outperforming the results from various previous studies.

With the study presenting a holistic utilization of industrial by-products in a single matrix, an enhanced mechanical and durable mix shall be obtained without compromising on the workability. The results also offer a sustainable waste management solution by redirecting the dependency on conventional cement, sand and coarse aggregates. It also encourages circular economy practices in mining, metallurgical and construction sectors. The study also validates the previous outcomes that presented that CMBA acts as both a partial binder and a microfiller, whereas, CS enhances the long-term mechanical strength and acid resistance.

When compared with the conventional OPC concrete of similar grade, the geopolymer mixes demonstrated 10-15% higher strength, lower water absorption and superior

chemical stability, mainly due to the absence of calcium hydroxide and formation of durable aluminosilicate gels. Hence, the outcomes of this study affirm the potential of multi-component geopolymer systems as viable, low-carbon alternatives to conventional cement-based concrete for structural and environmental applications.

Future scope of the study includes long-term durability studies including freeze-thaw conditions and chloride ingress, and investigation of structural behaviour of reinforced elements using the proposed mix design under loading conditions.

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