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Mechanical Properties and Flexural Behaviour of Copper Slag Based Geopolymer Concrete Beams

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Abstract

Objectives: The aim of this study is to evaluate the mechanical properties and flexural behaviour of Copper Slag (CS) Based Geopolymer Concrete (GPC) beams, emphasizing strength enhancement, structural performance, and sustainable material utilization. **Methods:** Copper slag is used to replace fine aggregate in the incremental way from 0% to 50% in the GPC with the binder as fly ash and GGBS. Sodium based alkaline solution with 8M, 10M and 12M concentrations have been used to assess the mechanical and flexural behaviour of the GPC beams through standard testing procedure. **Findings:** GPC mixture 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 flexural properties. The slag-based GPC showed maximum of 10.32% increase in compressive strength, 23.54% increase in flexural strength at 40% replacement. GPC beam of mix CS 40 with 12M shows ultimate load carrying capacity of about 65kN and ultimate deflection of 39.89mm which is 8.33% and 10.69% higher than mix CS 0 of 12M. **Novelty:** Utilizing fly ash, GGBS, and copper slag in geopolymer concrete reduces usage of cement and natural sand, lowers greenhouse gas emissions, and conserves resources. By eliminating the use of cement and fine aggregates, these structural members help to save natural resources and cut down on energy use, making construction more sustainable.

Keywords: Geopolymer Concrete; Copper Slag; Fly ash; GGBS; Deflection; Load Carrying Capacity

1 Introduction

The most common material in the building sector is concrete, but the combustion and calcination processes involved in cement manufacturing result in significant worldwide CO_2 emissions. Growing environmental concerns prompt more study into sustainable substitutes like "Green Concrete" [1]. Aside from cement, aggregates make up a significant component of concrete, particularly fine aggregates like river sand, which are becoming scarcer as a result of overuse. As a result, scientists are now investigating substitutes including M-Sand, copper slag, foundry sand, and quarry dust. One possible substitution in this study is copper slag, which is still underutilised and frequently regarded as a waste among the aforementioned options [2]. Globally, the copper sector produces over 24.6 million tonnes of slag a year. Most of the created slag debris is left unused and disposed of as waste, while some is utilised in the production of abrasive tools and sand blasting. It becomes a sustainable alternative to use such leftovers in concrete as a substitute for the fine aggregate. Because of its superior stability, abrasion resistance, and soundness, it is a good material for aggregate applications [3]. Because copper slag contains iron, it improves density and decreases permeability through pozzolanic processes when added to concrete. Its incorporation enhanced the long-term performance in terms of durability and mechanical qualities. Furthermore, copper slag enhances the flexural behaviour of reinforced concrete beams by enhancing stiffness, ductility, energy absorption, and load deflection response [4]. One such material for a sustainable development study on no-cement, no-water concrete is GPC. It is created by the dissolution of alumino silicate minerals in an alkaline solution followed by polymerisation that results in the formation of Si-O-Al-O links in an amorphous state. Its need for heat curing during polymerisation restricts GPC's applicability in the building sector [5].

Although it decreased workability, the addition of high-volume copper slag boosted compressive strength by up to 90% replacement. By improving its mechanical qualities by almost 50% after 28 days, stem curing outperforms ambient curing. When silica fume was applied in excess of 2%, microstructural examination also revealed improved ITZ, N-A-S-H gel, white deposits, and improved durability [6]. In geopolymer concrete, substituting GGBFS and SCBA for fly ash as the binder lengthened the setting time and increased water consumption, but at 10% replacement of SCBA, compressive strength rose by 22%. It has been demonstrated that GPC with industrial byproducts can produce sustainable GPC [7]. After 56 days of ambient curing, the compressive strength of GPC increased to 57 MPa in 10M, 12M, and 14M mixes when GGBS was employed as a partial substitute for low calcium fly ash. Because of the better bonding and decreased chloride penetration shown by the RCPT results, the combined usage of CS and GGBS increased strength and durability [8]. Prior research shown that fly ash-based GPC does not perform well in ambient curing; however, the addition of GGBS to the blend enhances its strength and stability during ambient curing [9].

Keeping all these points, the present study focuses on the flexural behavior of the fly ash GGBS based GPC with CS as a partial replacement for the fine aggregate under ambient curing. Replacing fly ash with GGBS improves its mechanical and flexural properties under ambient curing. Using copper slag as a fine aggregate not only a sustainable utilization of industrial wastes but also be a solution to the over exploitation of river sand. This investigation aims to understand how the inclusion of GGBS and CS influences the flexural strength, crack behavior and overall structural performance of GPC beams.

2 Methodology

2.1 Materials

The characteristics of fly ash and GGBS, the binding materials used here, are listed in T**ables 1 and 2**. With a maximum particle size of 4.75 mm and fineness moduli of 2.8 and 3.3, respectively, natural river sand and copper slag were used as a fine aggregate. The fine aggregate and copper slag's particle size distribution is displayed in Figure 1. For coarse aggregate, crushed granite with a minimum particle size of 12 mm and a maximum particle size of 20 mm was utilised. The coarse aggregate has a specific gravity of 2.72. Alkali activator solution was used to combine the aforementioned elements. Alkaline activators such as sodium hydroxide and sodium silicate are employed.

Table 1. Physical Properties of Fly Ash

Sl No.	Properties	As per Supplier
1.	Colour	Grey
2.	Type of fly ash	Low-calcium (Class F)
3.	Particle Shape	Mostly Spherical
4.	Specific Surface Area	250 - 600 m^2/kg
5.	Bulk Density	540 – 860 kg/m^3
6.	Specific Gravity	2.1 – 2.6
7.	Average Particle size	10 to 45 μm

Table 3 displays the CS-based GPC mixture of M40 grade compositions designed, where CS 0 stands for the conventional GPC, CS 10 for 10% FA replacement with CS, CS 20 for 20% FA replacement with CS, CS 30 for 30% FA replacement with CS, CS 40 for 40% FA replacement with CS, and CS 50 for 50% FA replacement with CS.

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
6.	Average Particle size	15 to 30 μm

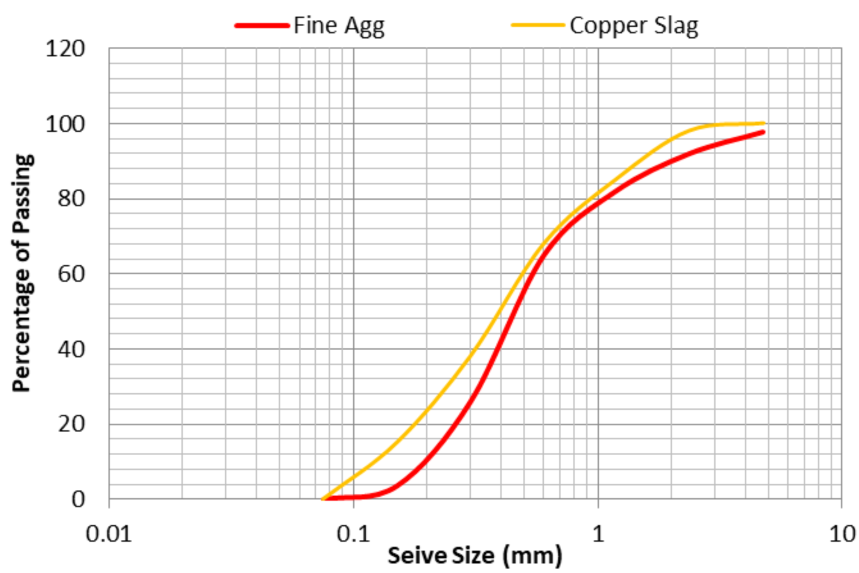


Fig 1. Particle size Distribution of Fine Aggregate

2.1.1. Mixing Methods

An activator solution with concentrations of 8M, 10M, and 12M was made 24 hours before to casting in order to prepare the geopolymer concrete mixture. To create a consistent mixture, fly ash, GGBS, copper slag, fine aggregate, and coarse aggregate were completely mixed before adding alkaline activator solution. The GPC is mixed with a prepared alkali activator solution. A slump test was performed using a slump cone as soon as the mixture was mixed, and the results were recorded in Table 4.

GPC mixture was poured into the 150 x 150 x 150 mm cubic moulds, 150 x 300 mm cylinder moulds and 3200 x 150 x 250 mm beam moulds. Cube and cylinder specimens were compacted on a vibrating table and beam moulds were compacted using vibrator needle. After 24 hrs, all molds were demolded, and the specimens were kept under ambient curing for 28 days.

2.2 Testing Methods

2.2.1. Compressive Strength Test

The compressive strength of CS based GPC specimens was assessed using a compressive testing machine. A loading rate of 0.5 MPa/s was used to test the 150 mm x 150 mm × 150 mm specimen. Six specimens were tested for each proportion of the CS based GPC, three for seven days and three for twenty-eight days. The test findings were averaged to determine the compressive strength.

2.2.2. Modulus of Elasticity Test

An axial compressive load was applied to the specimens using a digital Compression testing machine with a 2000 kN capacity. A dial gauge with a minimum count of 0.01mm was used to observe deformations at intervals of 10kN until the maximum load was reached. To determine the modulus of elasticity, the initial tangent modulus—that is, the slope of the stress-strain curve generated from the origin—was determined. Three specimens were tested for each mix and findings were averaged.

Table 3. CS based Geopolymer Concrete Mixture Compositions

Sl No.	Mix ID	Fly Ash kg/m^3	GGBS kg/m^3	Copper Slag kg/m^3	Fine Agg kg/m^3	Coarse Agg kg/m^3	Molar-ity M	Sodium Hydroxide NaOH kg/m^3	Sodium Silicate Na_2SiO_3 kg/m^3	Water in NaOH kg/m^3
							8	19.2		40.8
1	CS 0	294	126	0	665	1235	10	24	150	36
							12	28.8		31.2
							8	19.2		40.8
2	CS 10	294	126	66.5	598.5	1235	10	24	150	36
							12	28.8		31.2
							8	19.2		40.8
3	CS 20	294	126	132.5	532.5	1235	10	24	150	36
							12	28.8		31.2
							8	19.2		40.8
4	CS 30	294	126	199.5	465.5	1235	10	24	150	36
							12	28.8		31.2
							8	19.2		40.8
5	CS 40	294	126	266	399	1235	10	24	150	36
							12	28.8		31.2
							8	19.2		40.8
6	CS 50	294	126	332.5	332.5	1235	10	24	150	36
							12	28.8		31.2

Table 4. Slump Value for CS based GPC mixtures

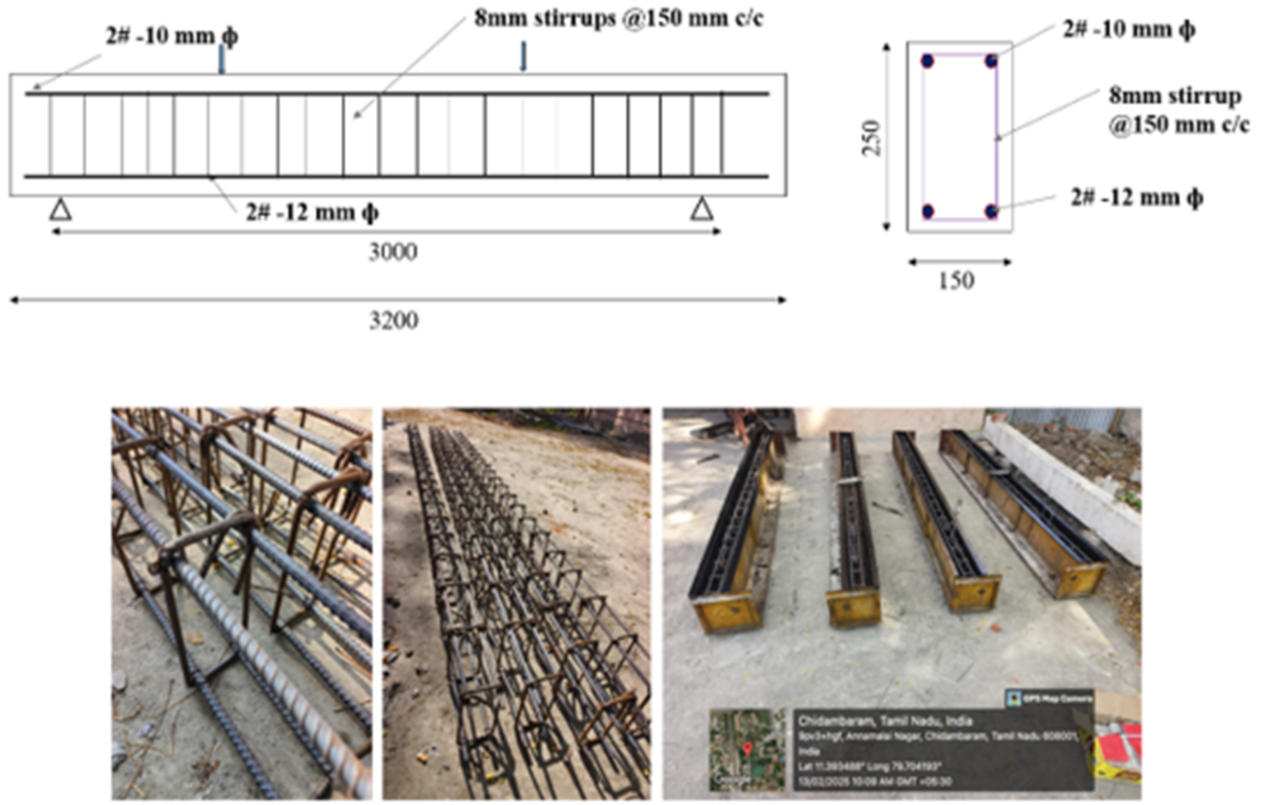
Sl No	Mixture ID	Slump (mm)		
		8M	10M	12M
1	CS 0	100	98	93
2	CS 10	104	101	95
3	CS 20	107	103	97
4	CS 30	109	107	99
5	CS 40	118	112	101
6	CS 50	112	106	97

2.2.3. Flexural Behaviour of Beams

To evaluate the flexural properties of CS based GPC, two beams were cast for each of the mix CS0 and CS40 at 8M, 10M and 12M concentration used in this investigation. There were twelve beams in total, two in each molarity concentration were cast and tested. The proposed beam's reinforcing details are displayed in Figure 2(a). A four-point bending test under static load conditions was carried out. The length of the beams is measured and split into three equal sections, each of which has a length of L/3, before the beam specimen is placed into the loading frame. In order to determine the crack pattern, grid patterns are then drawn inside the beam's flexural area.

The hinged and roller supports of the loading frame are positioned differently depending on the length of the beam specimen. The beam is then positioned above the loading frame. A two-point loading condition was used to determine the simply supported beams' load-bearing capacity. The laboratory loading configuration for the beam is depicted in Figure 2(b). Using a steel spreader (I-section) and a hydraulic jack with a 500kN capacity and a 0.83kN minimum count, the load is gradually imparted to the beam specimen.

Dial gauges positioned beneath the load and mid-span with a least count of 0.01 were used to detect deflection for a 2.5kN load increment. The beam showed deflection and flexural cracks appeared along its span as the applied load was gradually increased. Along with determining the failure mode for every test specimen, measurements of crack width and crack propagation were also documented. With a precision of 0.02 mm, the crack width was measured.



(a)

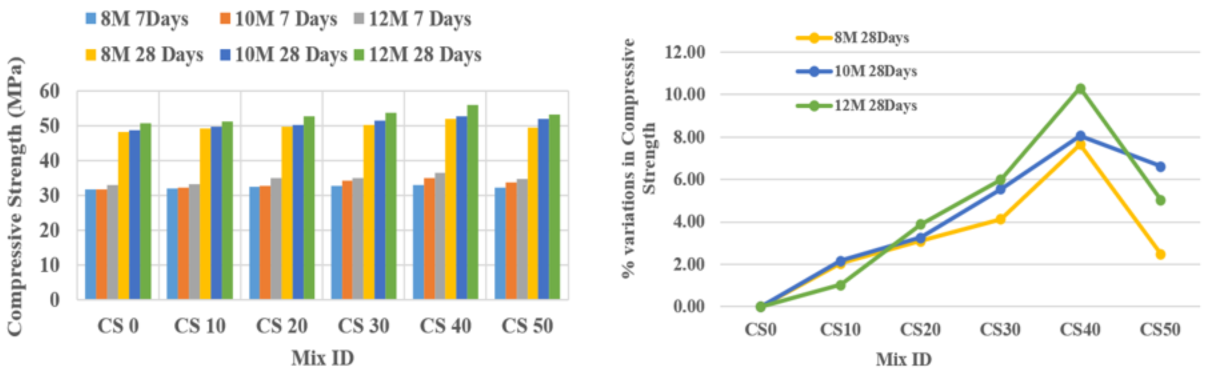
(b)

Fig 2. (a) Reinforcement Details of the Beams, (b) Loading Setup for the Beams

3 Results and Discussion

3.1 Compressive Strength

Compressive strength of GPC and CS based GPC mixes were shown in the Figure 3(a) and percentage increase in compressive strength with respect to the molarity concentration showed in Figure 3(b).



(a) Compressive Strength (b) Percentage increase in Compressive Strength

Fig 3. (a) Compressive Strength (b)Variations in the Compressive Strength of GPC and CS based GPC

From the above figure, CS based GPC mix CS40 at all molarity levels showed better performance compared to all other mixes. At the end of 28 days ambient curing, mix CS40 showed compressive strength of about 51.98 MPa, 52.6 MPa and 55.93 MPa at 8M, 10M and 12M respectively. Percentage increase in the compressive strength of the mix CS40 compared to the mix CS0 is about 7.66%, 8.07% and 10.32% at 8M, 10M and 12M concentration respectively.

The increment in the compressive strength is because of the copper slag addition. Enhancement in the compressive strength is attributed to the angular and glassy particles replacing the sand as a filler material fills the voids and improves the packing density and lowering porosity [1]. In addition, CS has a low internal water absorption compared with the fine aggregates leads to enhanced geopolymerization and produces a denser inter facial transition zone between binder and aggregate becomes one of the reasons for the increased compressive strength [6]. The glassy phases in the CS supply additional reactive silicates and oxides that help form more binding gel which improves the overall binder matrix [7]. At 8M concentration 7.7% improvement is because of the micro filling and densification. In 10M and 12M concentrations, the activator is strong enough to dissolve more of the glassy particles of CS and fly ash leads to the additional chemical binding along with the filler effects resulting in the 8.1% and 10.3% enhancement in the compressive strength [8]. Beyond 40% addition of CS there is decline in the compressive strength at all the molarity concentrations. At higher replacement level of CS, it acts as an inert filler rather than a reactive material leads to the reduction in the strength [1]. Higher percentage of CS dilute the binder matrix leading to less reactive binder per unit volume to form N-A-S-H gels. This results in the weaker skeleton formation and reduced compressive strength. Excessive angular particles and poor ITZ leads to stress concentration points which ultimately leads to the crack initiation and propagation reduced the strength beyond 40% [2].

3.2 Modulus of Elasticity

Stress Strain curve for the GPC and CS based GPC mixes at 8M, 10M and 12M concentrations are shown in Figure 4.

From the above stress strain graph, it is evident that mix CS0 exhibited gradual increase in stress and strain, reaching peak stress slightly lesser than the mixes with copper slag. Addition of CS from 10 to 40% exhibited improvement in the stress strain behaviour with CS40 showing the highest peak stress of about 32 MPa indicating enhanced load carrying capacity. This improvement can be attributed to the densified structure because of the addition of copper slag leads to the reduced porosity and a stronger ITZ which is observed in the earlier studies [9]. Beyond 40% replacement of CS a slight reduction observed in the stress strain curve. This indicates addition of CS beyond 40% showed a negative impact on the stress strain curve. Similar trend

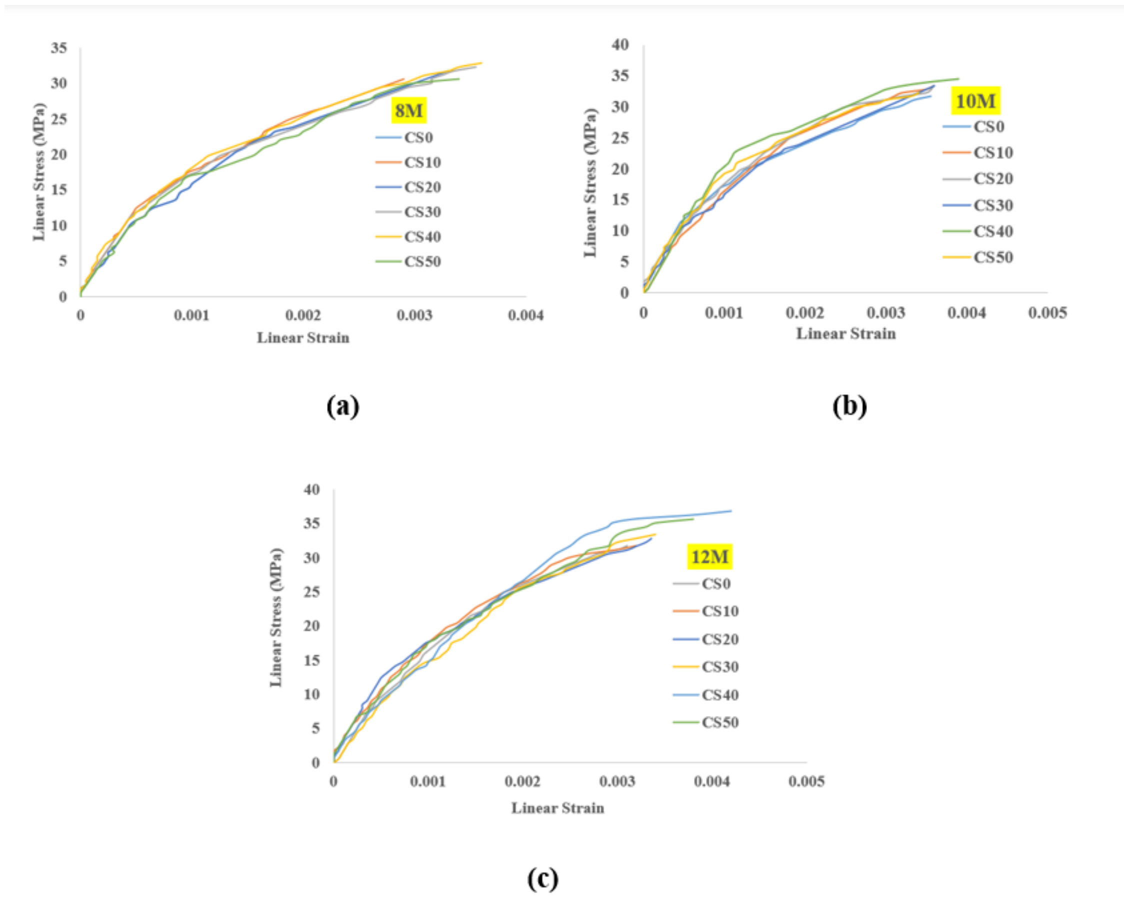


Fig 4. Stress Strain Curve for CS based GPC (a) 8M, (b) 10M and (c) 12M

is observed in the past research works and it is attributed mainly due to the dilution of reactive binder content at the higher replacement levels. All this together weakens the matrix and limits the geopolymer gel formation.

Modulus of elasticity of GPC and CS based GPC mixtures were tabulated in Table 5. From the results it is observed that mixture CS40 showed higher E value of about 3.67x10^4, 3.71 x10^4 and 3.92 x10^4 MPa which is 30.14%, 19.29% and 25.24% higher than GPC mix without copper slag (CS0) at 8M, 10M and 12M respectively.

Table 5. MOE for CS based GPC mixtures

Days	Modulus of Elasticity (x 10^4 N/mm^2)		
Mix ID	**8M**	**10M**	**12M**
CS 0	2.82	3.11	3.13
CS 10	2.96	3.13	3.36
CS 20	3.17	3.19	3.68
CS 30	3.32	3.35	3.72
CS 40	3.67	3.71	3.92
CS 50	3.36	3.37	3.68

At higher molarities, amorphous phases in copper slag contributes to the additional reactive silica and iron oxides which enhances the formation of additional binding gel. This gel formation enhances matrix rigidity, thereby improving the modulus of elasticity[7]. The modulus of elasticity is compared with the compressive strength as it reflects the simultaneous increase in compressive strength at this replacement level[6].

3.3 Flexural Load – Deflection Behaviour

The flexural load deflection behaviour of GPC and CS based GPC beams shown in Figure 5. The effect of using copper slag as a fine aggregate in the GPC is captured by comparing the flexural behavior of the GPC and CS based GPC beams at 8M, 10M and 12M concentrations. The comparisons show that the addition of the copper slag showed a slight improvement in the load carrying capacity but improved both the cracking and post-cracking behavior of the GPC beams with the same reinforcement ratio.

From the graph it is observed that all the mixes showed a nonlinear increase in the load with deflection as similar to the concrete beams under flexural loading. Up to 10mm deflection, it is linear and represents elastic behavior, after that the curve flattens and represents cracking and yielding. After 25mm deflection, load levels off indicating the post cracking and ductile failure stage. At 8M concentration, both GPC and CS based GPC showed moderate performance. However, CS40 carried slightly higher load compared to CS0. At 10M concentration similar trend observed but the load carrying capacity of the beams improved slightly compared to the 8M concentration. At 12M concentration CS based GPC mix CS40 showed the best performance by sustaining higher loads and larger deflections before the failure. It is observed that the load carrying capacity increased by the 40% replacement of copper slag and increased molarity enhances the geopolymerization resulting in the higher strength and better load deflection behaviour. Using 40% copper slag as a replacement for fine aggregate around 33 to 37.8% increase in 7 days and 28 days compressive strength is observed compared to the mixes without copper slag. This enhancement is attained due to the improved microstructure[10].

Addition of copper slag up to 40% and 12M concentration consistently increased the load carrying capacity of the beams by carrying maximum of 65kN and deflection about 39.89mm is observed. Around 8.5% increment in the load carrying capacity is observed in the CS based GPC mix CS40 when compared to the GPC mix CS0. Around 10.5% increment in the deflection is observed in the CS based GPC mix CS40 when compared to the GPC mix CS0. It is observed that replacing fine aggregate with copper slag increased not only compressive strength but also its flexural strength specifically when increasing NaOH molarity concentration.[11].

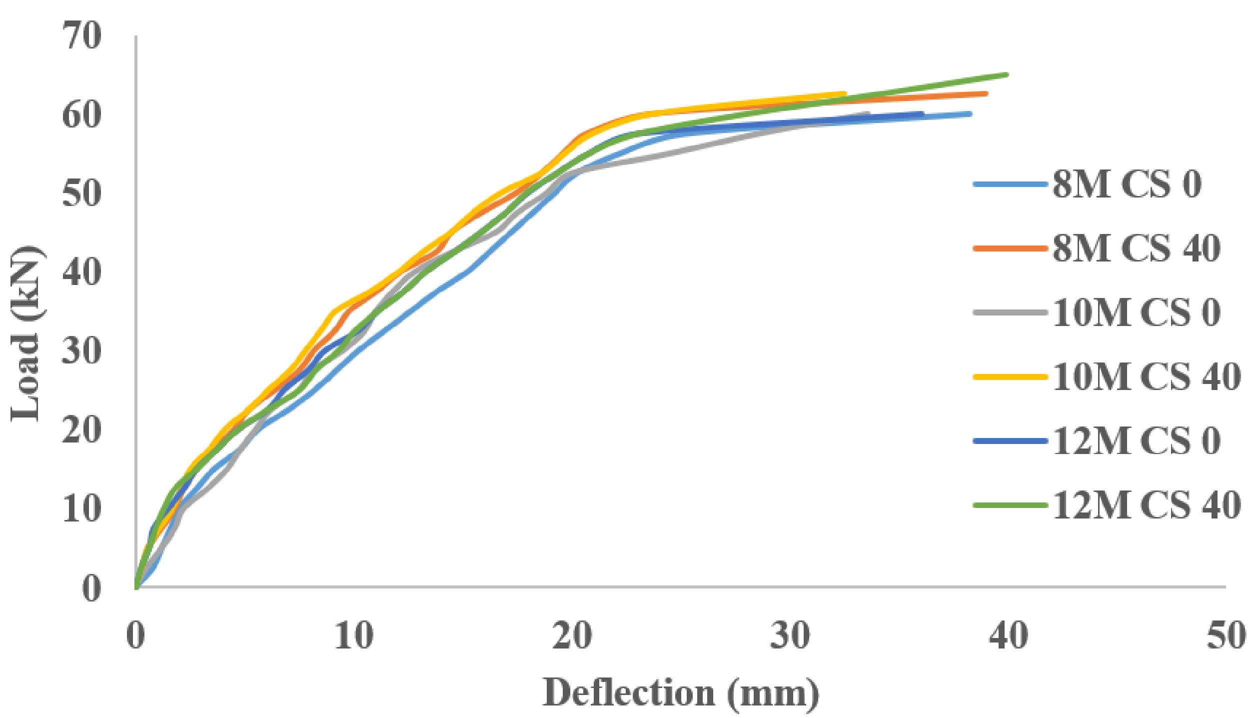


Fig 5. Load Vs Deflection curves of CS based GPC Beams

3.4 Crack Width

As load increases, cracks initiated and grows as per the load increase. However, at the beginning stage of loading, crack width increases slowly. As the load reaches nearer to the ultimate stage, increment in the crack width grows rapidly until the beam fails. Figure 6 is showing the relationship between the load and crack width which is similar to the trend of logarithmic function during the development of the crack.

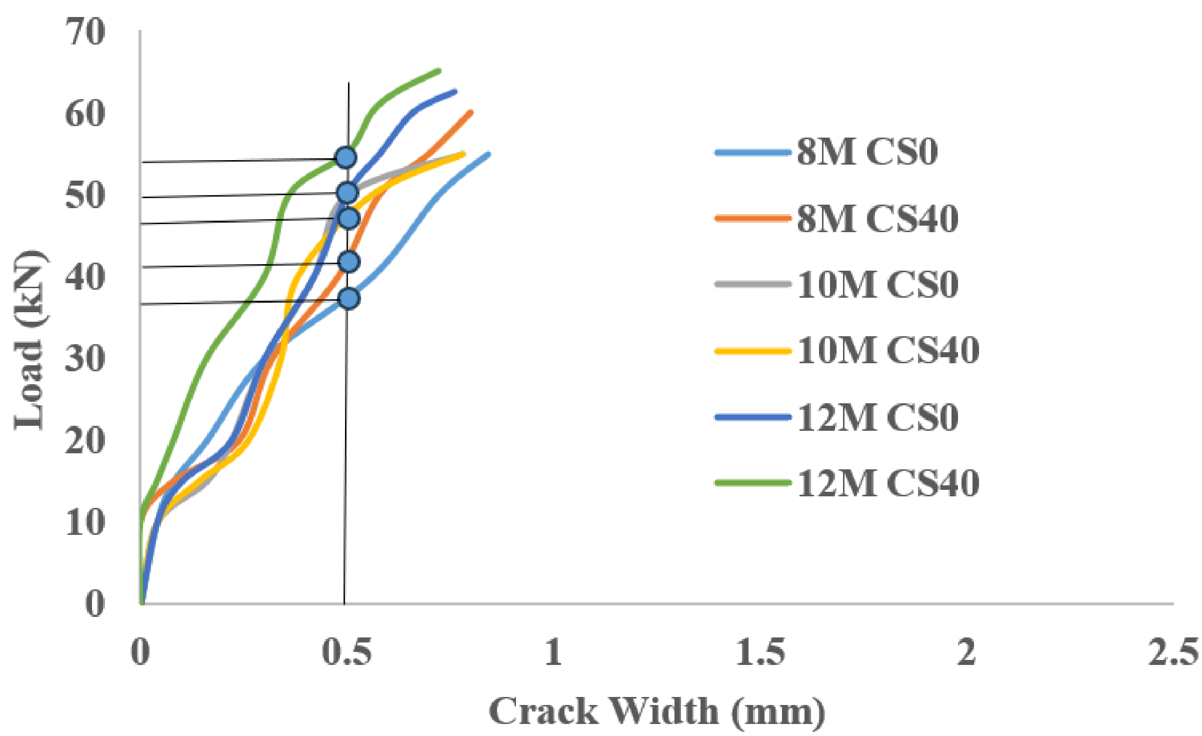


Fig 6. Load Vs Crack Width of GPC and CS based GPC Beams

From the above graph it is observed that when crack width reaches 0.5mm, load in CS0 was 37.69 kN, 50 kN and 50 kN at 8M, 10M and 12M respectively in the GPC mixtures. Similarly in the CS based GPC mixture CS40, the load for making 0.5mm crack width was observed as 42 kN, 46.67 kN and 55 kN at 8M, 10M and 12M respectively. Crack widening under applied loads is slowed down by a stronger geopolymer matrix with better binder-aggregate bonding. By adding more reactive silica and iron oxides, copper slag creates a denser microstructure and lessens interface imperfections, which better prevents cracks from growing. Once microcracks start, mechanisms like aggregate interlock, crack bridging, and a reinforced interfacial transition zone slow down their propagation. Under the same pressure, crack spreading is limited by a stronger interfacial transition zone. By improving crack bridging and producing more tortuous crack courses, copper slag particles or improved particle packing enable the material to withstand more loads once the crack width appears. Higher loads at 0.5 mm fracture width are the result of the CS40 mixes increased post-cracking toughness, which prevents a quick drop in load but instead allows them to carry load even after crack formation. Because of the denser microstructure and stronger bonding, a stiffer composite structure requires greater loads to reach 0.5 mm because cracks open more slowly under stress. Additionally, at higher load levels, CS40 mixtures may promote scattered cracking rather than a dominant fracture, which keeps individual crack widths smaller and raises the load associated with a 0.5 mm crack. Similar trend observed in earlier studies[(12)] The addition of steel fibres to alkali slag concrete beams considerably decreased the maximum crack widths under equivalent loads and postponed the onset of cracks. Beams with 1.0% steel fibres demonstrated a 20% decrease in crack width at 40 kN, and a 40% reduction at 80 kN when compared to plain beams. The reason for this improvement is because steel fibres' crack-bridging activity prevented cracks from spreading both before and after the longitudinal reinforcement gave way[(13)].

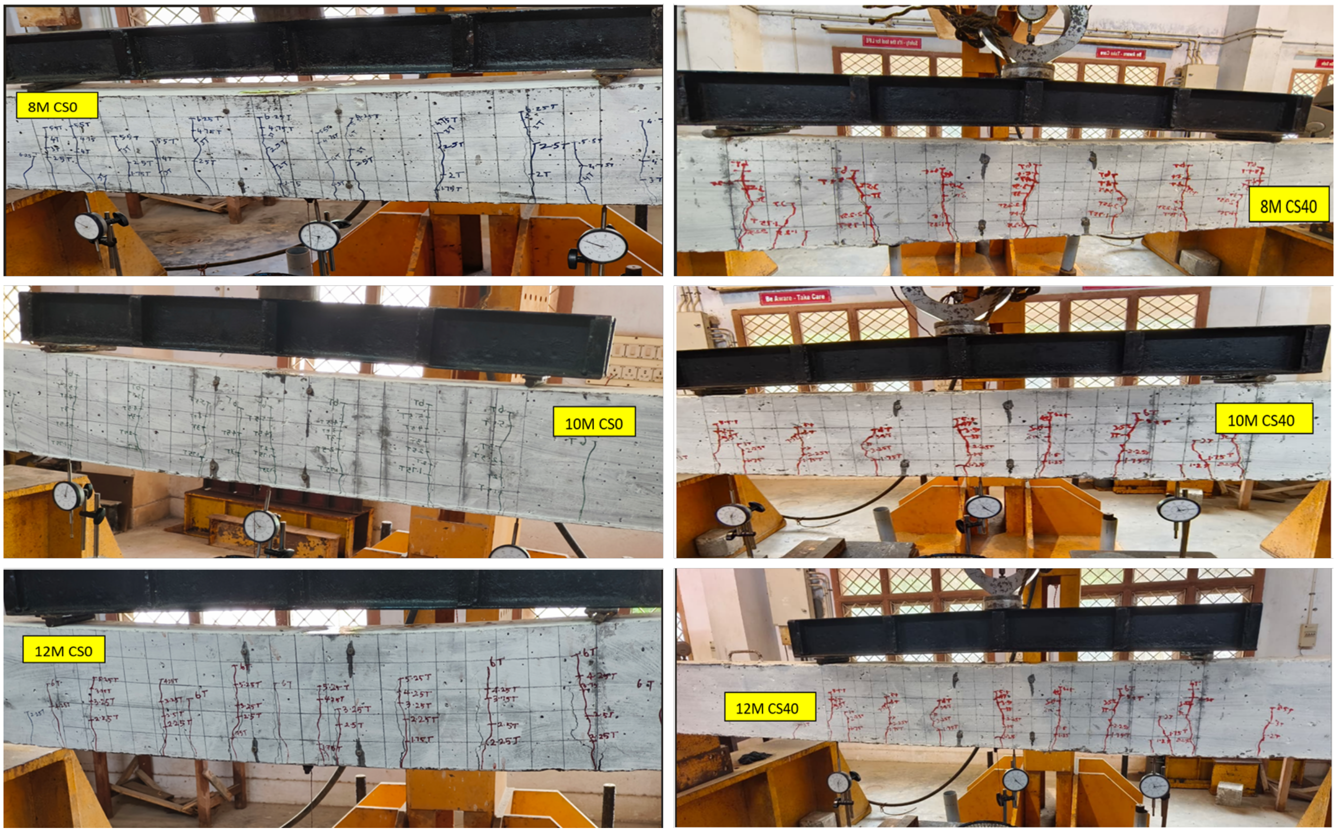


Fig 7. Crack Patterns of CS based GPC beams

From Figure 7, it is observed that flexural failure in all six beams. Initially the vertical cracks were observed in the midspan and gradually appeared near the support also. Maximum number of cracks observed in the GPC beam specimen and crack width are also high when compared to the other CS based GPC beams.

4 Conclusion

The present study investigated the flexural behaviour and mechanical performance of fly ash, GGBS based GPC incorporating copper slag as a partial replacement for the fine aggregates under ambient curing conditions. Based on the experimental results obtained, the following conclusions can be drawn:

- CS based GPC mixture CS40 achieved compressive strength of 51.98 MPa, 52.6 MPa and 55.93MPa at 8M, 10M and 12M respectively which is 7.66%, 8.07% and 10.32% higher than the control GPC mixture CS0 at 8M, 10M and 12M respectively.
- CS based GPC mixture CS40 showed higher peak stresses and strain capacity than the control GPC mixture CS0. Highest peak stress of 32MPa was observed in the mix CS40 confirming its enhanced load carrying capacity.
- Inclusion of copper slag improved the stiffness of the GPC. Mix CS40 showed improved MOE by 30.14%, 19.29% and 25.24% compared to the control GPC mixture at 8M, 10M and 12M respectively.
- Every beam possessed typical nonlinear flexural behaviour, which includes an elastic stage up to about 10 mm deflection, yielding and cracking, and a ductile post-cracking reaction beyond about 25 mm. Compared to CS0 mixes, the CS40 mixes continuously demonstrated greater load and deflection capacity.
- CS40 maintained the best performance at 12M, supporting a 65 kN load with a maximum deflection of about 39.89 mm. Superior ductility and toughness were demonstrated by CS40, which attained a 10.5% higher deflection and an approximate 8.5% higher load capacity than CS0.
- The graphs of fracture width against load demonstrated that CS40 mixes were more effective than CS0 mixes at preventing crack widening.

- Crack propagation was postponed, and cracking was more evenly distributed throughout the span in CS40 due to improved microstructure, a stronger ITZ, and improved crack-bridging processes.

Unlike most earlier studies that restricted evaluation to cube and cylinder tests, this research demonstrates the structural-level performance of copper slag–based GPC beams, including nonlinear flexural behavior, enhanced load–deflection capacity, and superior crack control.

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