Research Article

Journal of Environmental Nanotechnology

Mechanical Properties and Stress-strain Relationship of Slag and Fly Ash-based One-part Geopolymer Concrete Cured at Ambient Conditions

Malathy Ramalingam[1*], Deepalakshmi Damotharan[1], Nekhil kaarthik Srinivasan[1] and Harshini Kankesh[1]

Department of Civil Engineering, Sona College of Technology, Salem, TN, India

Received: 14.04.2025 Accepted: 03.06.2025 Published: 30.06.2025

*malathycivil@sonatech.ac.in

ABSTRACT

This study explores the mechanical properties and stress-strain behavior of slag and fly ash-based one-part geopolymer concrete (OPGC) cured under ambient conditions. Twelve mix designs (M1–M12) were designed by varying the key parameters of binder quantity (350–500 kg/m³), water-to-binder (W/B) ratio (0.35–0.45), and aggregate proportions to study their effects on workability, strength, and elasticity. The compressive strength tests revealed that it ranged between 27 to 43 MPa. Strength was found to improve with increased binder quantity and reduced W/B ratio at the end of 28 days. Split tensile strength increased from 1.22 MPa to 3 MPa over the same period, following a similar trend. Young's modulus, an important indicator of material stiffness, increased from 8.7 GPa to 10.6 GPa with increased binder content and reduced W/B ratio. Slump values varied between 82 mm and 148 mm, which is more than sufficient for structural applications. These results underpin the sustainability and high performance of ambient-cured OPGC as a substitute material in place of traditional Portland cement concrete, thus offering a feasible solution toward reducing carbon emissions in the construction industry. Such a study renders a vast understanding of the mechanical behavior and the workability of OPGC, opening avenues for further acceptability in structural uses.

Keywords: One-part geopolymer concrete; Fly ash; Ground granulated blast furnace slag (GGBFS); Compressive strength; Split tensile strength; Young's modulus; Water-to-binder ratio.

1. INTRODUCTON

Concrete is the most extensively used building substance. However, the conventional production process releases enormous amounts of carbon dioxide into the world's atmosphere. It is the common binder in conventional concrete-Ordinary Portland cement (OPC), That contributes about 8% of the total CO_2 emissions into the global atmosphere, mainly because of the calcination process. In an attempt to identify an environmentally friendly substitute, a great deal of attention has been given to geopolymer concrete (GPC). Geopolymer concrete is a cement-free binder system. The geopolymerization process is applied in a stable polymeric network based on the incorporation of aluminosilicate-rich by-products from industrial processes like Fly ash and GGBS, (that is, ground granulated blast furnace slag (Zhao *et al*. 2023; Srinivasa *et al*. 2023).

Geopolymer concrete has several advantages, such as low greenhouse gas emission, durability, and chemical resistance. It can be considered a sustainable alternative to minimize the environmental footprint of the construction industry. However, a conventional GPC system, or two-component geopolymer concrete, may exist in the form of alkali activator solutions, including sodium hydroxide and sodium silicate. Although these activators are effective for initiating geopolymerization, there are a couple of drawbacks to practical applications. The major disadvantages of two-part geopolymer concrete are handling complexity, associated risks on the safety aspects related to the mix when handled, and more cost in terms of production. Liquid alkali activators are quite caustic in nature and should be cautiously stored and dealt with to avoid accidents and the resultant costs. High viscosity presents problems in mixing, and workability on a larger scale does not even guarantee consistency. Such limitations have made the spread of two-part GPC very limited even though it proves to be useful for environmental sustainability (Yang *et al*. 2022; Yong-Jie *et al*. 2023).

These drawbacks, to some extent, were overcome by developing a single part geopolymer concrete commonly known as "just add water" geopolymer concrete. In this system, pre-mixed dry mix combinations consist of solid alkali activators like powdered sodium hydroxide and sodium metasilicate source materials, which are pre-mixed with aluminosilicate source materials like fly ash and GGBS.

Later on, only water needs to be added to the dry mix, which will trigger geopolymerization without the need for handling hazardous liquids. This process reduces the difficulty of mixing; it is safe, and geopolymer concrete can be made even more scalable to be used on construction sites (Chen *et al*. 2023; Ma *et al*. 2023).

The two most significant additives in this process for one-part geopolymer concrete are GGBS and Flyash, which introduce the quantity of silica and alumina required by the polymeric network. The industrial byproduct addition not only develops the mechanical strength of the concrete but also provides a solution for waste management as it reduces materials going into the landfills. Studies represent that compressive strength and workability, along with durability in the long term, are ideal properties that arise due to the fly ash-GGBS-based blend over OPC-based systems (Chen *et al*. 2023; Santos *et al*. 2023).

The performance of geopolymer concrete is mainly attributed to the method of curing. Traditionally, heating has been in practice for ages since it increases the rate of the geopolymerization reaction, but such heating is quite energy-intensive, thereby reducing the environmental advantage of GPC. Ambient curing, however, relies on the natural conditions in the environment and can be used. Some studies reveal that ambient curing almost provides the same mechanical and durability characteristics as the other one-part geopolymer concretes provided under the same optimized mix design, which would better fit into real applications (Wan-En *et al*. 2023; Mahfoud *et al*. 2023).

Compressive strength, tensile strength, and modulus of elasticity are one of the significant mechanical properties that define the role of one-part geopolymer concrete to assess the performance of the structure. One-part GPC has consistently demonstrated compressive strengths similar to and, on occasion, greater than those for OPC-based concrete (Luo *et al*. 2024a; Luo *et al*. 2024b).

Its strength and stiffness are formed by a denser microstructure and greater interparticle bonding associated with geopolymerization. In addition, tensile strength and modulus of elasticity have been demonstrated as being sufficient for structural applications, especially under load-bearing conditions (Lin *et al*. 2024b).

The other important characteristic for geopolymer concrete is stress-strain behavior that can help understand the material behavior under compression loading. For OPC concrete, similar to one-part geopolymer concrete, it shows an initial elastic phase after which it hardens with strain and then fails. By incorporating fly ash and GGBS, there is a change slope of the elastic region and the ultimate strain that has been affected; hence, further investigations are needed into the characteristic stress-strain applicable in this material itself (Zhao *et al*. 2024; Konduru and Karthiyaini, 2024).

Besides the mechanical properties, one-part geopolymer concrete displays excellent durability against sulfate attack, chloride penetration, and even elevated temperatures. It is quite properly applied on severe exposures such as industrial plant constructions and on marine structures (Lin *et al*. 2024a; Lin *et al*. 2024b).

This equally indicates the loss of existence within the matrix of the binder for any calcium hydroxide in this particular binding, which could elucidate improving a factor for enhanced durability through decreasing the chemical attacks on the concretes as mentioned in (Doan *et al*. 2024).

The composition mix design of one-part geopolymer concrete requires optimization to maintain the balance between workability and strength. Fly ash-to-GGBS ratio, alkali-to-binder ratio, and content of water have been stated as responsible for controlling fresh and hardened properties of concrete. Investigations reported that powder form of alkali activators added to geopolymer resulted in uniform workability along with the achievement of target strength levels when the concrete is cured under ambient conditions (Zhang *et al*. 2024; Samadi *et al*. 2024). The schematic representation of One-part and Two-part Geopolymer is given in Fig. 1.

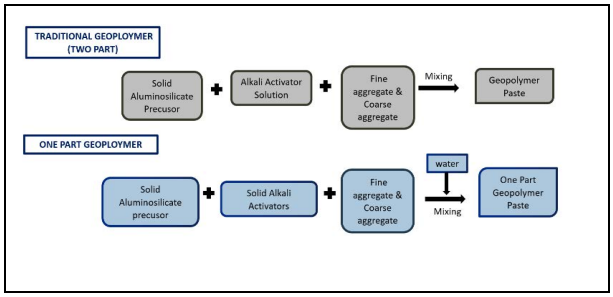


Fig. 1: The schematic representation of One-part and Two-part Geopolymer

In the system presented here, a systematic experimental study of the mechanical properties and stress-strain response of one-part geopolymer concrete synthesized with fly ash and slag cured under ambient conditions was carried out. The present work includes an extensive analysis of critical structural characteristics, including compressive strength, tensile strength, elastic modulus, and the entire stress-strain relationship, to fully characterize the material response to various loading conditions.

The proposed work is based on the technical basis for the advancement of one-part geopolymer concrete as a substitute to a conventional cement-based

material. The study will include a comprehensive analysis of its mechanical performance to contribute toward solving critical environmental challenges presented by traditional construction practice and to facilitate the progress of sustainable and environmentally friendly building resources.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Industrial by-products used in this research work are Ground Granulated Blast Furnace Slag (GGBS) and fly ash. GGBS employed in this study was sourced locally, with a specific gravity of 2.85 g/cm^3 and fineness of 4500 cm^2/g. Table 1 through XRF chemical composition of GGBS was determined as below. D10, D50, and D90 are determined to understand the particle-size distribution using laser particle size analyzer. In that case, for GGBS, it's 1.2 µm, 10.3 µm, and 22.5 µm (Fig. 2). Here another industrial by-product was fly ash employed in this research was sourced locally, with a Specific gravity of 2.55 g/cm³ and fineness of 3800 cm²/g. The flyash chemical composition, with major oxides like SiO_2, Al_2O_3, and Fe_2O_3, is presented in Table 2. D10 was 2.1 µm, D50 was 12.5 µm, and D90 was 30.7 µm as determined by laser diffraction for particle size distribution of fly ash (Fig. 2).

Table 1. Chemical composition of GGBS

Component	Percentage (%)
SiO_2	32.1
Al_2O_3	13.5
Fe_2O_3	1.2
CaO	40.2
MgO	8.1
SO_3	3.2
$Na_2O + K_2O$	1.7

Table 2. Chemical composition of fly ash

Component	Percentage (%)
SiO_2	54.6
Al_2O_3	26.3
Fe_2O_3	9.7
CaO	3.1
MgO	1.5
SO_3	2.2
$Na_2O + K_2O$	1.8

It initiated geopolymerization from GGBS and Flyash with only the sodium hydroxide powder and the sodium metasilicate powder as the activators for solid alkali. They were mixed in certain ratios for an optimal catalytic effect on the geopolymerization reactions. Among these activators, sodium metasilicate it is essential in faciliating the dissolution of silica and the development of polymer network formation. The following Table 3, provides information regarding the chemical composites of sodium hydroxide powder and also that of the sodium metasilicate powder. The modified activator blending drew special attention for the evaluation made regarding the effect on the kinetics of geopolymerization as well as on the physical properties of this geopolymer.

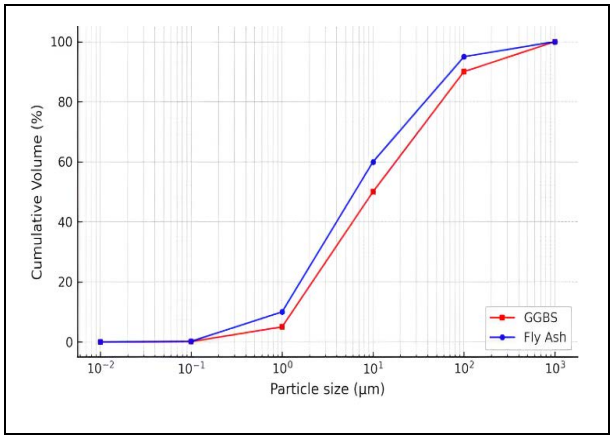


Fig. 2: Particle size distribution of GGBS and FLYASH

It initiated geopolymerization from GGBS and Flyash with only the sodium hydroxide powder and the sodium metasilicate powder as the activators for solid alkali. They were mixed in certain ratios for an optimal catalytic effect on the geopolymerization reactions. Among these activators, sodium metasilicate it is essential in faciliating the dissolution of silica and the development of polymer network formation. The following Table 3 provides information regarding the chemical composites of sodium hydroxide powder and that of the sodium metasilicate powder. The modified activator blending drew special attention for the evaluation made regarding the effect on the kinetics of geopolymerization as well as on the physical properties of this geopolymer.

Table 3. Chemical composition of activators

Component	Sodium metasilicate ($Na_2SiO_3 \cdot 9H_2O$)	Sodium hydroxide (NaOH)
SiO_2 (%)	27	-
Na_2O (%)	29.3	76
H_2O (%)	43.7	24

M-sand, manufactured sand was used for the study as it is a local fine aggregate. Of all the partial replacement options for natural river sand, M-sand is most crucially used in concrete because of its quality consistency and availability. Specific gravity of M-sand used in the study was 2.63 with a fine modulus at 2.92

which of course met the Indian Standard (IS 383: 1970 for the coarse aggregates and for the fine aggregates). For concrete mix preparation, crushed stones of sizes in the form of coarse aggregates were used. Some of the properties of these aggregates are summarized in Table 4. Coarse and fine aggregates used for one-part geopolymer concrete production met the requirements given by IS 383:1970 regarding aggregates to offer concrete of good quality, durable, and strong.

Table 4. Properties of aggregates

Property	M-sand (Fine Aggregate)	Coarse Aggregate
Specific gravity	2.63	2.75
Fineness modulus	2.92	6.85
Maximum grain size	4.25	20 mm

2.2 Mix Design

According to Indian Standard codes, the mix design for concrete is done to optimize its strength and durability with maximum slump 150 mm. Aggregates are selected for this purpose on a nominal size of 20 mm basis from IS: 383:2016, and the aggregates are proportioned volumetrically in proportion with reasonable grading and uniform distribution of particles. The fine aggregates are obtained from Zone 1 gradation, and the proportion of coarse aggregates is carried out in proportion for getting fine to coarse ratio. The W/B ratio has been preferred based on preconceived desirable performance of the concrete. Here, for various mix proportions, 0.45, 0.40, and 0.35 are taken to study the influence on strength and durability. Binder quantity for every mix is determined using W/B ratio taken as suitable ranging between 350 kg/m^3 to 500 kg/m^3.

Table 5. Mix proportions of One-part geopolymer concrete

Mix ID	Binder Content (kg/m^3)	W/B Ratio	Water (kg/m^3)	Activator (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)
M1	350	0.45	157.5	78.75	692	1037
M2	350	0.4	140	70	732	1098
M3	350	0.35	122.5	61.25	772	1160
M4	400	0.45	180	90	746	1122
M5	400	0.4	160	80	787	1182
M6	400	0.35	140	70	828	1243
M7	450	0.45	202.5	101.25	799	1188
M8	450	0.4	180	90	839	1249
M9	450	0.35	157.5	78.75	880	1310
M10	500	0.45	225	112.5	853	1254
M11	500	0.4	200	100	893	1315
M12	500	0.35	175	87.5	934	1376

Water content for every mix is determined by the binder quantity and the water binder W/B ratio, whereas activator content was kept at 50% of water contents in order to achieve enough reactivity. For the remainder volume of the concrete, aggregate mass volume is computed to completely fill it up. Fine aggregate to coarse aggregate ratio is further utilized to adapt final mix ratio as per requirements for workability in this case under controlled aggregate gradation, with proper use of water and no super plasticizers added to the concrete mix. The final mix proportions were different for the 12 mix designs, which adjusted the binder content, W/B ratio, and aggregate volumes appropriately are listed in the Table 5. The concrete mixed well and was homogeneous after mixing. It had a slump controlled at 150 mm so that it had good workability for casting. It has mix designs prepared according to IS 10262:2019.

2.3 Preparation of test specimens

The one-part geopolymer concrete mixes were formulated in a laboratory-scale pan mixer with a mixing capacity of 30 liters as per the standards of IS 1791 for laboratory equipment. It was manufactured by an exact weighing of components, dry binder, Including slag and fly ash on geopolymer, fine aggregate Msand, and coarse aggregate either gravel or crushed stone. Further, solid activator powders, mostly in powdered form, include sodium hydroxide and sodium meta silicate. The first step involved combining the appropriate amount of water with the solid activator powders to come up with the activator solution. This way, the activator will be uniform in consistency before its addition into the dry mix.



Fig. 3: Dry mix of materials

The pan mixer took input of dry ingredients that include the binder, fine aggregate, and coarse aggregate. All constituents were dry mixed for 1 minute for uniform distribution in the Fig 3. The dry mix received the inputs of the activator mixture, water, and solid activator powders. The inputs of the activator mixture were done slowly to avoid uneven mixing. The total mixing time taken was 3 minutes. This includes 1 minute of dry

mixing followed by 2 minutes of wet mixing. In this manner, the fresh concrete obtained would be workable and of uniform consistency. The mixing time used is in conformity with that specified in IS 516: 1959. It would thus ensure proper bonding and homogeneity in the mix as displayed in the Fig. 4.



Fig. 4: Wet mixed concrete

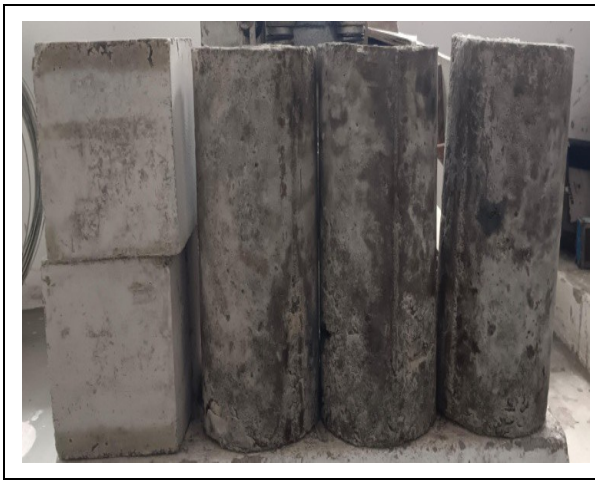


Fig. 5: Ambient curing of specimens

Laboratory specimens were prepared by casting concrete into 150 × 150 × 150 mm cubes and 150 × 300 mm diameter cylinder as per IS 10086: 1982. The concrete mixture was then compacted on a vibrating table in order to remove the air voids and to get an even distribution of the mix in the moulds. Thus, at this stage, there is a provision for uniform strength and density in the final specimens. As in Fig. 5 the Ambient curing was applied to the specimens lastly. Ambient curing is a condition where it aims to recreate the field curing condition in a natural site yet not giving any external source of heat to simulate the cure of concrete under ambient temperature due to environmental natural conditions. This is achieved by keeping it inside an insulated temperature-controlled room or from avoiding it from vigorous evaporation of moisture or from strong heat emanating influences of external heat sources which could have been able to impede hardening and setting geopolymer concrete.

The compressive strength tests are conducted on the test specimens at the specified curing ages of 7, 14 and 28 days, as per IS 516: 1959. These tests check the applied loads that can be tolerated by the concrete, and it checks whether the concrete is apt for structural purposes. This is standard practice adopted during one-part geopolymer concrete preparation and curing, hence ensuring reliable yet consistent access to producing highly durable materials with high strength in construction works.

2.4 Test methods

Several standard tests have been conducted depending on the relevant Indian codes in order to examine the mechanical properties and stress-strain behavior of the fly ash and slag based one- part geopolymer concrete cured under ambient conditions. For fresh concrete slump cone test was done according to IS 1199:2018 with target slump value not exceeding 150 mm. It largely determines the simplicity of mixing, placing and compacting the geopolymer concrete while ensuring adequate workability and uniformity of the mixture for effective placement and sufficient compaction at the site. For the geopolymer concrete, the compressive strength was established on 150 mm × 150 mm cubical test specimens as provided in IS 516:2021. These cubes were loaded uniaxially in an environment-controlled setting to the point of failure. A precise value of compressive strength was achieved by gradually applying the load. This test has been expected to examine the axial load resistance and overall performance of the concrete in relation to its compressive load bearing capacity. It was carried out in accordance with IS 5816: 1999. In the split tensile strength test, the cylindrical specimen dimension was 150 mm diameter and 300 mm in height.

3. RESULTS AND DISCUSSION

The primary aim of the research is to examine the mechanical properties of one-part geopolymer concrete, which was predominantly prepared from fly ash and slag, with a one-part mix ratio, and cured under ambient conditions. The research focused on how the main mix parameters—binder quantity, water-binder (W/B) ratio, and aggregate volume—could influence the workability, strength, and deformation properties of the concrete in Table 6. The results have concluded that, with the one-part geopolymer concrete cured under ambient conditions, not only does it promise great strength and durability but also turns out to be relatively economical, thus presenting a viable option compared to conventional Portland cement concrete.

Table 6: Test Results

Mix ID	Compressive Strength at 7-Day (MPa)	Compressive Strength at 14-Day (MPa)	Compressive Strength at 28-Day (MPa)	Split Tensile (MPa)	Young Modulus (GPa)	Slump (mm)
M1	18.9	22.95	27	1.88	8.7	148
M2	21	25.5	30	2.09	8.7	138
M3	22.4	27.2	32	2.23	8.8	128
M4	21	25.5	30	2.09	8.7	135
M5	23.1	28.05	33	2.3	9.1	125
M6	25.2	30.6	36	2.51	9.7	115
M7	23.1	28.05	33	2.3	9.3	120
M8	25.2	30.6	36	2.51	9.8	110
M9	26.6	32.3	38	2.65	10.02	102
M10	25.2	30.6	36	2.51	10.01	90
M11	28	34	40	2.79	10.4	85
M12	30.1	36.55	43	3	10.6	82

3.1 Workability

Workability refers to the simplicity of handling, mixing, placing, and finishing the concrete. It is affected by the mix composition, particularly the W/B ratio and binder quantity. Workability was determined with the slump test, and hence, a good definite relationship was maintained between the mix W/B ratio, binder quantity, and mix fluidity. which measures the amount of water required to achieve the proper consistency of the concrete mixture to achieve better workability without bleeding and segregation (Ramalingam *et al* 2022). (Fig. 6 Relationship between Slump and the Binder) shows, an increase in the binder quantity lowered the workability of the geopolymer concrete at W/B ratios low. For example, Mix M1 with the binder quantity as 350 kg/m^3 having a water-binder W/B ratio of 0.45 had a slump value of 157.5 mm. In comparison, Mix M12 had a binder quantity of 500 kg/m^3 and water-binder W/B ratio of 0.35 and exhibited an increased slump of 175 mm. This is why the amount of water will inversely influence the workability of geopolymer concrete. The more binder content, the denser mix is, thus water content will be reduced and workability too.

Fig. 7 gives Lower W/B ratios lead to better geopolymerization and will increase the final strength of the material. However, a lower W/B ratio will result in stiffer mix and hence more difficult to handle. Therefore, though strength and durability improve by lowering the W/B ratio, workability will be challenged during the mix design process. Mix M1 with a relatively higher W/B ratio had improved workability and, therefore was easier to place and finish. This, however, came at the expense of some compressive strength as evident from the compressive strengths obtained for M1 and M12.

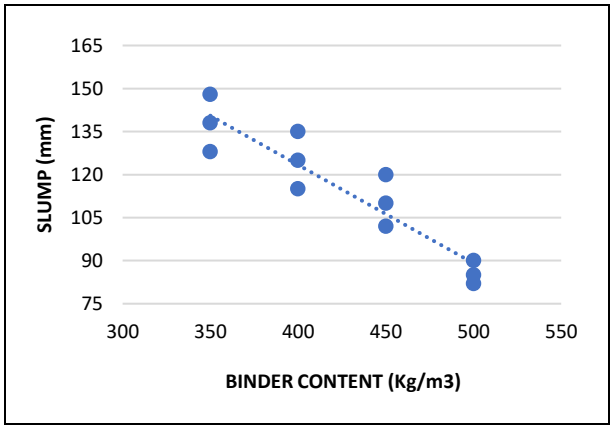


Fig. 6: Relationship between Slump and the Binder

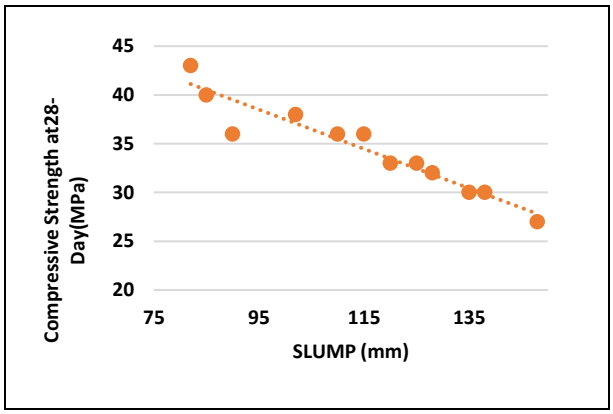


Fig. 7: Relationship between Slump and Compression strength

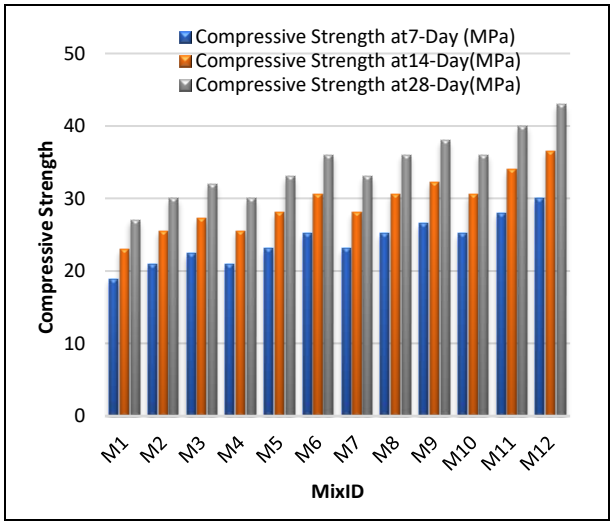


Fig. 8: Compressive strength development on ages

3.2 Compressive Strength

Compressive strength is the key indicator to evaluate the load-bearing ability of concrete. Fig. 8 show that an increase in binder quantity and a reduction in the W/B ratio significantly enhance the compressive strength

of geopolymer concrete. Mix M12, with a quantity of 500 kg/m³ binder and a W/B ratio of 0.35, reached a compressive strength of 43 MPa at 28 days, a remarkable 59% improvement over the 27 MPa recorded by Mix M1 containing 350 kg/m^3 binder, A W/B of 0.45, resulting in reduced microstructure.

Fig. 9 shows continued strength progression from 7 to 28 days across all mixes, but most significantly, Mix M1 supports the hypothesis that ambient curing encourages further continued geopolymerization, hence additional bonding with strength gains due to time. Mix M1 was tested for compressive strength at different ages: after 14 days, the value was 22.95 MPa, whereas after 28 days, the value increased up to 27 MPa. This indicates that the geopolymerization process is not an instantaneous one; the material will continue to harden and get stronger over time, which is one of the fundamental characteristics of geopolymer concrete under ambient curing.

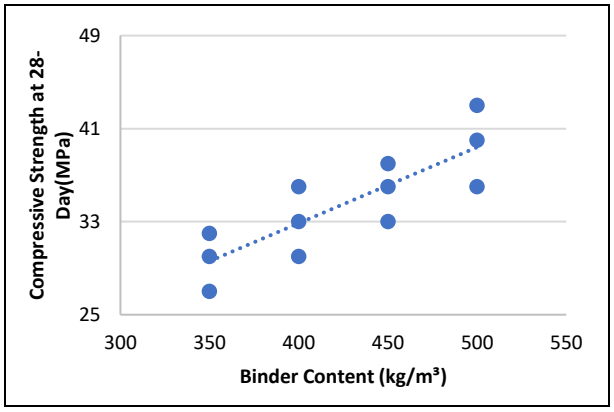


Fig. 9: Relationship between the compressive strength and the Binder content

3.3 Split Tensile Strength

Other very important mechanical properties are tensile strength, especially in materials under tensile stresses or cracking under load. Results from this study confirm that, similar to compressive strength, split tensile strength increases with higher binder quantity and lower W/B ratio. Mix M12 with 500 kg/m^3 binder content and W/B ratio 0.35 had a split tensile strength of 3 MPa at 28 days. In contrast, Mix M1 contained 350 kg/m^3 of binder and W/B ratio at 0.45 had a value of 1.88 MPa.

3.3.1 Compressive and Split Tensile Strength in Concrete

The Compressive and split tensile strength in concrete is related by an empirical formula and included in the Fig. 10.

$$f(t) = 0.41 \times fc \times 0.5 \quad \ldots (1)$$

where, ft is the split tensile strength measured in MPa and fc is the compressive strength measured in MPa.

Such a formula represents a direct but nonlinear relationship between these two properties, which further signify an increase in compressive strength. Further binder contents improve the geopolymerization process, which will create denser, coarser, more coherent matrices that will not easily resist the tensile force. Mix M12 shows an upward trend in split tensile strength from 1.65 MPa at 7 days to 1.97 MPa at 28 days, indicating the same trend of compressive strength improvement over the same period. The trend lines thus focus attention on stress in the continuous process of strengthening by geopolymer concrete under ambient curing in which tensile, as well as compressive, resistance improves simultaneously in all ways.

3.4 Young's Modulus (E)

Young's modulus, a rigidity of the substance, was found to increase as well with greater binder quantity and smaller W/B ratios. The structural application has an important characteristic; the more rigid concrete the higher its capability to resist the elastic deformation resulting from stress applied on it. Mix M12 was seen with a Young's modulus of 10.6 GPa whereas for Mix M1, this value was of 8.7 GPa. This higher Young's modulus is due to the better-developed geopolymer network due to the high binder quantity and lower W/B ratio. The matrix formed is denser under such conditions, resulting in better structural stiffness. Young's modulus can be calculated as follows from an empirical formula and included in the Fig. 11.

$$E_C = 0.7 \times fc \times 0.85 \quad \ldots (2)$$

where, Ec is the Young's Modulus in GPa, fc is the compressive strength in MPa.

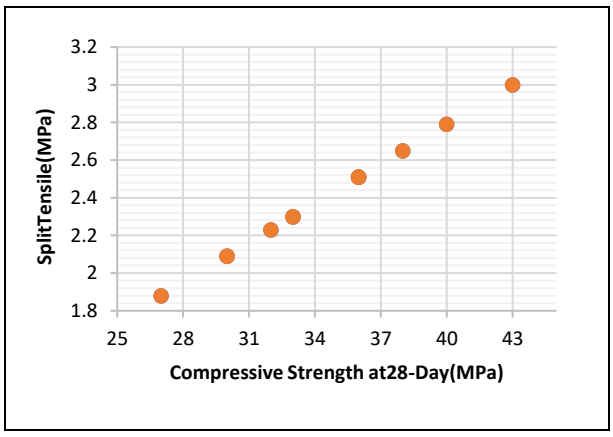


Fig. 10: Relationship between the compressive strength and the tensile strength

The stress-strain relation is linear according to this formula, and as such, shows that higher compressive strength indeed comes with stiffer, much more rigid materials. Therefore, the study finds that high binder content, lesser W/B ratios, and, consequently, resultant

geopolymer concrete are better in strength as well as in stiffness, suitable for use under load-carrying conditions.

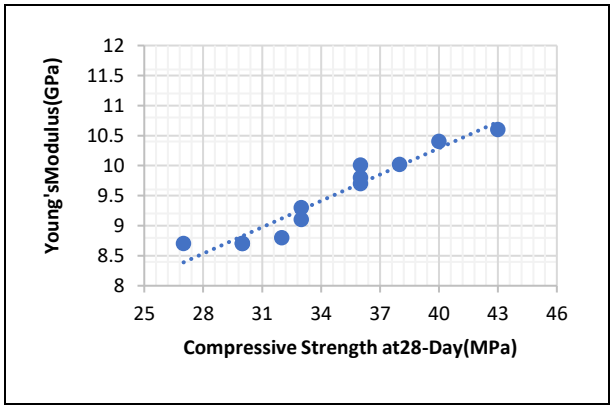


Fig. 11: Relationship Between the compressive strength and the Young's Modulus

3.5 Stress-strain Behaviour

At an aspect of the stress strain behaviour, one-part geopolymer concrete mixes indicated the good promise of toughness and energy consumption under load. Stress-strain curves for the Mix M12 indicated that maximum stress at an age of 28 days of 34.4 MPa was recorded much higher than in the case of Mix M1, whose corresponding value at age of 21.6 MPa. The strain data further indicate that the strain attained by as indicated in Fig. 11, compressive loading of the 12 mixes, M1 to M12 has moved forward with strength and ductility improvement which suggests optimized material compositions. Peak stress is experienced for M12 at a peak value of 607.9 kN when strain was about 0.003245. For M11 and M9 peak stresses values at strains 0.003077 and 0.00298, respectively have been observed at 565.49 kN and 537.21 kN. The better performance is, therefore, within these mixes in terms of higher compressive strengths and higher strain capacity, hence an indication of better ductility and energy absorption. While Mix M1 had the least peak stress recorded at 381.7 kN at a strain of 0.002483. This was more of a normal concrete standard performance characteristic. These mixes M2, M4, M5 and M7 were found to be responding in an intermediate manner; peak stresses fall in between 424.12 kN to 466.53 kN whereas their respective strain values are in between 0.002759 to 0.002901. These mixes depict a moderate strength as well as ductility properties. The mixes of M3, M6, and M8 whose stresses are ranging from the highest to 452.39 kN up to the lowest to 508.94 kN present better mechanical characteristics that is with more stiffness and with greater load-carrying capacity.

All mixtures exhibit nonlinear stress-strain behavior, which corresponds to an initial elastic stage with proportionality in the increment of the stress-stain applying as well as nonlinear deformation until the peak of the stress. Formulations for more complex forms of material formulation may then take into consideration that mixtures M9, M11, and M12 behave excellently since possibly they can optimize their strength-ductility ratio. These findings emphasize that mix optimization would play an essential role to be able to realize tailored mechanical properties for high-performance structural applications as clearly seen.

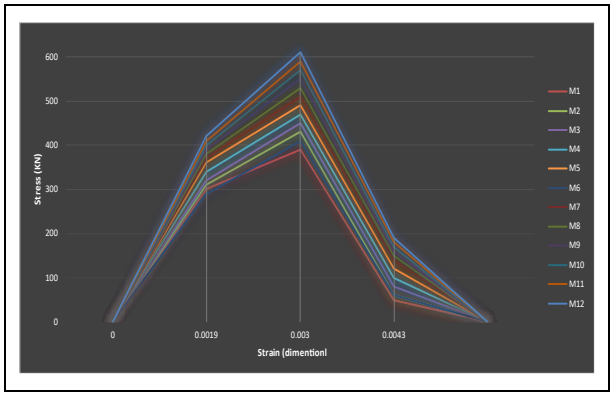


Fig. 12: A comparison of the stress-strain relationship

3.6 Scanning Electron Microscope (SEM)

One-part geopolymer concrete that was cured at room temperature reveals some significant microstructural variations as a function of activator and water content. The mixture with a higher water-to-geopolymer solids (W/GS) ratio clearly contains more unreacted particles compared to the mixture with the optimal W/GS ratio. This results in reduced gel formation, which explains the noticeable decrease in mechanical strength observed in Fig 13 when additional water was added. These results are consistent with previous studies. Excess water during polycondensation tends to evaporate, generating uneven internal pressure that weakens the matrix and increases the number of voids, ultimately leading to higher drying shrinkage rates. A denser and more uniform matrix is achieved in mixes with higher activator content. However, Fig. 13 shows the presence of longer micro-cracks, which can be attributed to the elevated Na_2O concentration. Higher activator dosages lead to increased heat during polymerization, which raises the concentration of ionic species, thereby restricting ion mobility and delaying the formation of stable structures. Despite the presence of these cracks, the formation of gelatinous products is still prominent in mixes with higher activator content, indicating a significant degree of reaction of fly ash and GGBS particles.

Fig. 13 illustrates that increasing the GGBS content results in a more compact and uniform matrix, contributing to improved strength, though some GGBS particles remain unreacted. This may explain the improved drying shrinkage performance compared to OPGM mixes with lower GGBS content, in line with

previous research findings. The gel products in high-GGBS mixes contain more calcium, along with aluminum and silica phases, suggesting the formation of C-(N)-A-S-H type gels, as supported by earlier studies.

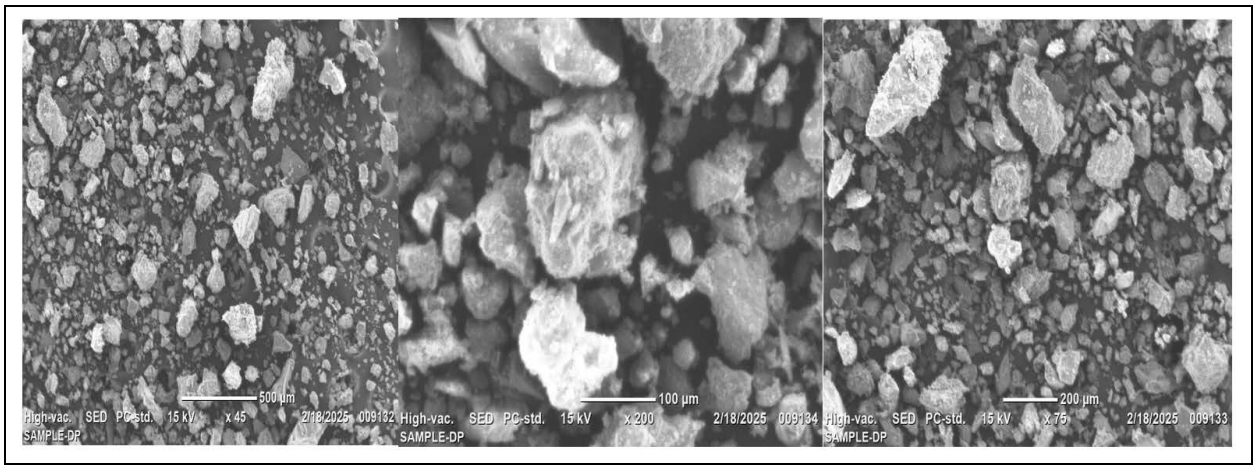


Fig. 13: SEM analysis

4. CONCLUSION

This study holds a high potential to slag and flyash based one-part geopolymer concrete as a novel material especially if cured in ambient conditions. A systematic mechanical property evaluation can reveal the details about how these essential mix factors such as binder quantity, water-to-binder ratio, and aggregate proportions affect the performance of this alternative sustainable option instead of the conventional Portland cement concrete.

The experimental result indicates the linear relationship between binder content and mechanical properties of the material. In fact, when the content of the binder increases from 350 kg/m^3 to 500 kg/m^3, a decrease in the W/B ratio from 0.45 to 0.35, compression strength, tension strength in the split test, and Young's modulus show significant enhancement. M12 reached the optimum binder quantity and the lowest W/B ratio, and compressive strength at 28 days was measured to be 43 MPa. Tensile splitting strength at the same age was measured to be 3 MPa. This trend clearly suggests that higher binder content is essential for porosity reduction in the geopolymerization process, the applied loads are carried by a denser aluminosilicate gel matrix that is formed.

SEM analysis confirmed these findings, where significant densification of the microstructure was found in samples with higher activator and binder content. High hydroxyl ion concentrations favored the dissolution of aluminosilicate precursors, resulting in an effective geopolymerization process and a dense matrix. Mixes with lower activator and water content showed incomplete geopolymerization with residual unreacted particles and microstructural weaknesses that directly affected the mechanical properties.

The stress-strain behavior of the material also further supports its capability of withstanding and dissipating loads. Mix M12 depicted more toughness and energy absorption, where higher values of stress and strain at the failure point compared with others were noticed. Young's modulus also portrayed a parallel trend indicating that as the binder content increases along with a decreasing W/B ratio, it has confirmed improved stiffness along with structural rigidity, the most important in load-bearing structures.

Binder quantity and W/B ratio are inversely related to the workability of mixes. While a low W/B ratio is found to enhance the strength properties by decreasing the porosity and promoting increased geopolymerization, it decreases slump values, which are the parameters for workability, thus reducing workable mixes. The above trade-off reveals the need for an optimized mix design wherein workability and mechanical performances have to be balanced.

Ambient curing was identified as a possible and sustainable curing method that allows for gradual geopolymerization under natural conditions without requiring exterior heating. This is an economically viable and sustainable design option in construction. The ambient curing process also allowed the material to continue developing strength and stiffness with time; thus, this improved upon the long-term performance of the material.

This extensive research justifies slag and fly ash based one-part geopolymer concrete as a high-performance, environment-friendly construction material. It achieves excellent strength, durability, and stiffness with low costs and sustainability, making it highly competitive with traditional concrete. One of the future research outcomes may involve optimizing

activator formulations, evaluating the long-term durability under varied environmental conditions, and scalability for industrial applications.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or non-for-profit sectors.

CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

REFERENCE

Chen, Y., Ortiz Rios, C. and Liou, F., Effect of aging time on mechanical and functional properties of graded Ti-Ni alloy joined by laser additive manufacturing, *Manuf. Lett.*, 3712–16 (2023). https://doi.org/10.1016/j.mfglet.2023.05.003

Chen, W., Pan, J. Zhu, B. Ma, X. Zhang, Y. Chen, Y. and Cai, J., Improving mechanical properties of 3D printable 'one-part' geopolymer concrete with steel fiber reinforcement, *J. Build Eng.*, 75, 107077 (2023). https://doi.org/10.1016/j.jobe.2023.107077

Doan, T., Arulrajah, A., Horpibulsuk, S. and Zhou, A., Low-carbon metakaolin precursor for one-part and two-part geopolymer activation of demolition wastes, *Constr. Build. Mater.*, 442137663 (2024). https://doi.org/10.1016/j.conbuildmat.2024.137663

Konduru, H. and Karthiyaini, S., Enhancing solidification in one-part geopolymer systems through alkali-thermal activation of bauxite residue and silica fume integration, *Case Stud. Constr. Mater.*, 21e03444 (2024). https://doi.org/10.1016/j.cscm.2024.e03444

Lin, Y., Wang, Y., Wan, S., Yang, C., Zong, Z., Qian, H., Xu, X., Elchalakani, M. and Cai, J., Experimental studies on behavior of one-part geopolymer composite slabs subjected to blast loading, *Structures*, 66106825 (2024a). https://doi.org/10.1016/j.istruc.2024.106825

Lin, Y., Yuan, Y., Wan, S., Ding, B., Yang, C., Zong, Z., Gu, X. and Cai, J., Flexural behaviour of reinforced one-part geopolymer concrete beams, *J. Build. Eng.*, 96110435 (2024b). https://doi.org/10.1016/j.jobe.2024.110435

Luo, X., Huang, L., Chen, Z., Li, Y., Zhou, Z. and Qu, Y., Alkali-fused lithium slag as a substitute for slag in one-part geopolymers: Mechanism of reactivity enhancement and microstructure, *Constr. Build. Mater.*, 442137696 (2024a). https://doi.org/10.1016/j.conbuildmat.2024.137696

Luo, X., Huang, L., Wei, L., Chen, M., Zhou, Z. and Zhang, T., A technique for preparing one-part geopolymers by activating alkali-fused lithium slag with solid sodium silicate, *Constr. Build. Mater.*, 435136817 (2024b). https://doi.org/10.1016/j.conbuildmat.2024.136817

Ma, B., Zhu, Z., Huo, W., Yang, L., Zhang, Y., Sun, H. and Zhang, X., Assessing the viability of a high performance one-part geopolymer made from fly ash and GGBS at ambient temperature, *J. Build. Eng.*, 75106978 (2023). https://doi.org/10.1016/j.jobe.2023.106978

Mahfoud, E., Ndiaye, K., Maherzi, W., Aggoun, S., Benzerzour, M., and Abriak, N.-E., Mechanical properties and shrinkage performance of one-part-geopolymer based on fly ash and micronized dredged sediments, *Dev. Built Environ.*, 16100253 (2023). https://doi.org/10.1016/j.dibe.2023.100253

Ramalingam, M., Narayanan, K., Masilamani, A., Kathirvel, P., Murali, G., & Vatin, N. I. Influence of Magnetic Water on Concrete Properties with Different Magnetic Field Exposure Times. Materials (Basel, Switzerland), 15(12), 4291.(2022). https://doi.org/10.3390/ma15124291

Samadi, M., Wong, L.S., Murali, G., Abdul Shukor Lim, N.H., Abdulkadir, I., Tan, S.Q. and Chan, Y.T., Sodium metasilicate-activated one-part geopolymer concrete: Impact strength assessment with bottom ash substitution and fiber reinforcement, *Case Stud. Constr. Mater.*, 21e03794 (2024). https://doi.org/10.1016/j.cscm.2024.e03794

Santos, I.D.S.D., Bao, S. and Huang, M., Mechanical and microstructural properties analysis of one-part geopolymer based on burnt coal cinder replaced by metakaolin, *J. Build. Eng.*, 76107265 (2023). https://doi.org/10.1016/j.jobe.2023.107265

Srinivasa, A.S., Yaragal, S.C., Swaminathan, K. and Rakesh Kumar Reddy, R., Multi-objective optimization of one-part geopolymer mortars adopting response surface method, *Constr. Build. Mater.*, 409133772 (2023). https://doi.org/10.1016/j.conbuildmat.2023.133772

Wan-En, O., Yun-Ming, L., Cheng-Yong, H., Abdullah, M.M.A.B., Li Ngee, H., Pakawanit, P., Wei Ken, P., Khalid, M.S., Md Razi, H., Lee, W.-H., Soo Jin, T., Shee-Ween, O. and Yong-Jie, H., Acid-resistance of one-part geopolymers: Sodium aluminate and carbonate as alternative activators to conventional sodium metasilicate and hydroxide, *Constr. Build. Mater.*, 404133264 (2023). https://doi.org/10.1016/j.conbuildmat.2023.133264

Yang, Y., Yan, X., Zhao, X. (Roy)., Mattila, A.S., Cui, Z. and Liu, Z., A two-wave longitudinal study on the impacts of job crafting and psychological resilience on emotional labor, *J. Hosp. Tour. Manag.*, 52128–140 (2022). https://doi.org/10.1016/j.jhtm.2022.05.014

Yong-Jie, H., Cheng-Yong, H., Yun-Ming, L., Al Bakri Abdullah, M.M., Yeng-Seng, L., Ern-Hun, K., Shee-Ween, O., Wan-En, O., Hui-Teng, N. and Yong-Sing, N., Strength optimization and key factors correlation of one-part fly ash/ladle furnace slag (FA/LFS) geopolymer using statistical approach, *J. Build. Eng.*, 63105480 (2023). https://doi.org/10.1016/j.jobe.2022.105480

Zhang, M., Yue, F. and Chen, B., Optimizing toughness and cost-effectiveness in one-part geopolymers via fiber reinforcement: A comprehensive investigation of PVA, PE, and glass fibers, *Constr. Build. Mater.*, 437136999 (2024). https://doi.org/10.1016/j.conbuildmat.2024.136999

Zhao, J., Xie, J., Wu, J., Zhao, C. and Zhang, B., Workability, compressive strength, and microstructures of one-part rubberized geopolymer mortar, *J. Build. Eng.*, 68106088 (2023). https://doi.org/10.1016/j.jobe.2023.106088

Zhao, Q., Ma, C., Lu, X., Huang, B., Chen, Z. and Lian, C., Effect of silica fume on the efflorescence, strength, and micro-properties of one-part geopolymer incorporating sewage sludge ash, *Constr. Build. Mater.*, 436136840 (2024). https://doi.org/10.1016/j.conbuildmat.2024.136840