

Original Article

Fresh, Hardened and Microstructural Behaviour of Fly Ash based Geopolymer Mortar Modified with Ground Granulated Blast Furnace Slag

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Abstract - Geopolymer (GP) technology is an emerging, environmentally benign approach to concrete production utilizing waste materials and could provide a real alternative to Portland cement concrete. Conventional fly ash - based GPs generally require oven or steam curing to develop sufficient strength properties, and this curing requirement develops some limitations for cast-in-situ concrete applications. This present study focuses on developing GP mortar to achieve sufficient workability and strength properties in ambient temperature itself by replacing Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) for every 10% with low molar (3.5M and 5M) NaOH solutions. From the results, it was identified that in both 3.5M and 5M NaOH mixes, the GP mortar workability is inversely proportional to GGBS content. While studying the Compressive Strength (CS) for 90 days, the strength increases gradually up to a certain percentage of GGBS replacement (60% fly ash + 40% GGBS for 3.5M NaOH and 70% fly ash + 30% GGBS for 5M NaOH), and strength began to decrease after 28 days for further GGBS replacement. This decrease in strength after 28 days was validated by using Ultrasonic Pulse Velocity (UPV), Water Absorption (WA), porosity and microstructural parameters.

Keywords - Fly ash, Slag, Compressive Strength, Ultrasonic Pulse Velocity, Water absorption, Geopolymer mortar.

1. Introduction

One of the most common materials used in the construction industry is cement. Cement production involves several processes like grinding and calcination of limestone, which releases harmful gases like CO₂, NO₂, SO₂ into atmosphere. These releases of gases lead to global warming. Along with these environmental issues, the production of cement reduces a certain amount of energy [1, 2]. Recently, to reduce the use of conventional cement and to develop green concrete, GP has been developed [3]. Comparing to the production of cement, less than half an amount of energy is required for the development of GP binders [4]. In comparing to cost, GP binders are 10 to 30% lesser than conventional cement [5]. The GP matrix involves the industrial waste material, such as FA, obtained from thermal power plants. GPs are the inorganic by-products that consist of material rich in silica and alumina reacting with alkali activators to form a three-dimensional polymeric framework (Si-O-Al-O) [6-9]. Employment of these industrial wastes along with alkali activator solution provides a contribution to global warming reduction [10]. The matrix utilizes industrial waste products such as FA, which are derived from thermal power plants [11, 12]. The mechanical properties and sustainability of the FA-

based geopolymer system with different binder compositions and curing conditions have been investigated in earlier studies to a great extent. Li et al [13] used FA as a precursor with the use of 8M NaOH and subjected it to heat curing at 70°C for 24 hours, which yielded a significant improvement in the compressive strength of 85 MPa at 28 days. Similarly, Gopalakrishna et al. [4] used FA as a precursor with the use of 16M NaOH and a sodium silicate to sodium hydroxide ratio of 1.5, subjected it to heat curing at 60°C for 24 hours, which yielded a maximum compressive strength of 36 MPa at 28 days. Moreover, the same study reported a significant reduction in Embodied Energy (EE) of about 94% in addition to the mechanical properties, indicating the environmental and economic advantages of geopolymer systems. Furthermore, Sherwani et al. [14] revealed that the curing temperature plays a significant role in strength development, with an optimum curing temperature of 85°C for 24 hours yielding maximum compressive strength. In addition, Oz et al. [15] stated that the maximum strength properties could be attained when the GPC was cured at 100°C. To increase the pozzolanic reaction and to achieve the desired CS, a temperature curing for at least six hours is required for FA-GP mortar [16, 17]. The strength characteristics of FA-GP



mortar increase with respect to an increase in curing temperature and time [18].

The GGBS is also a waste by-product attained from the metallurgical industry during the manufacturing of steel [19, 20]. The alkali activator solutions were prepared by utilizing either sodium based, calcium based and lime-based hydroxide and silicates. Samantasinghar and Singh [21] reported on using a binder that contains 60% replacement of GGBS and activated with 8M NaOH solution and heat cured achieved the maximum compressive strength of 44 MPa at 28 days. In a similar study, Boumaza et al. [22] explored the impact of slag on the various properties of GP mortar and reported that the strength was lower at ambient curing; however, the strength found to be higher under 80 °C curing. From the previous works on GP, it was noted that the polymerization and strength improvements in GP matrix depend on type, nature and dosage of activators, raw materials and curing conditions to be adopted [8, 23]. Al-Otaibi revealed that in the development of GP matrix, type and dosage of alkali activator play a major role, and from this researcher's study, it was found that strength of GP matrix increases with an increase in silica modulus and alkali activator dosage [24]. From the study of Davidovits, it was reported that in metakaolin-based GP, potassium-based alkali activators showed double the CS comparing to sodium-based alkali activators [25]. From the microstructural studies conducted by Lloyd et al. [26], it was concluded that use of silicate-based activators results in a denser structure compared to sodium-based activators. Among precursors used in geopolymerization, FA and GGBS serve as binders based on calcium aluminosilicate.

Studies [27, 28] reported that the reaction mechanism of alkali-activated slag are found to be different from those of class-F FA-based geopolymer, which results in different reaction products. In FA-based geopolymerization, the primary binding phase produced is an amorphous, Sodium Silicate Hydrate (N-A-S-H) gel [9, 29]. On the other hand, alkali activated GGBS typically forms Calcium Silicate Hydrate (C-S-H) type gels. Moreover, Marjanovic et al. [30] found that the contribution of FA reaction products to flexural strength development is more significant, while the contribution of slag reaction products to compressive strength is more significant. Further, they reported that the GP mortars produced using GGBS show excellent early age strength but have also been found to exhibit premature setting and loss of workability [30]. Whereas FA-based GP mortars cured under ambient temperature exhibit delayed setting time and slow strength gain due to the less content of calcium hydroxide and reactive silica [31]. Vigneshkumar et al. [32] found that use of GGBS up to 50% with 50% FA activated with a higher NaOH concentration of 8M-16 M results in better mechanical properties. Lenin & Roselin [33] reported that a GPC mix 80% FA and 20% GGBS gives optimal strength and performance. This optimized 80:20 ratio

performs much better than conventional concrete and other proportions (90:10 and 70:30). Further, it was reported that the higher CS (62 to 66 MPa) can be achieved by curing the mortar at 60 °C -75°C for 24 hours [34]. With regard to sustainability and environmental aspects, Patil et al. [35] reported that the use of Fly ash-GGBS-based GPC can reduce the CO₂ emission by 18% compared to OPC concrete. Further, Polusani et al. [36] revealed that the GPC produced using FA and GGBS results in a significant decrease in environmental load, especially the Global Warming Potential (GWP), up to 45% lesser than the OPC concrete mix.

Most of the existing studies on FA-based geopolymer concrete reported in literatures [7, 30, 37-40] have been conducted on the synthesized product using heat or steam curing (60-75°C), thereby limiting its large-scale applications. Furthermore, most of these studies have focused on examining the early-age strength with the increase in GGBS content, while only limited studies explored the long-term performance at ambient curing, especially its durability properties and microstructural changes. Indeed, limited studies was carried out to investigate the use of a low molarity activator system with optimized FA-GGBS proportion to develop desirable strength and workability under ambient curing conditions. In this regard, the present study aims to formulate FA-GGBS-based geopolymer mortar with ambient curing in the presence of low molarity NaOH solution (3.5M and 5M), thereby examining its fresh, hardened, durability and microstructural properties.

2. Materials and Methods

The selection of FA and GGBS as binder is based on the complementary chemistry between FA (low calcium, slower reaction) and GGBS (high calcium, rapid reaction) that allows for synergistic geopolymerisation. Further, the low molar activators are chosen to lower the cost, safety risks and applicability in the field while maintaining acceptable mechanical and durability properties.

2.1. Materials for GP Mortar

2.1.1. Fly Ash (FA)

FA is a by-produced from thermal power plants. The FA used for this research work was sourced from Ennore Thermal Power Station, India. ASTM C618-12a [41] has proposed two classes of FA depending on its calcium content as Class-F and Class-C FA. In this research work, Class-F FA having low calcium was used.

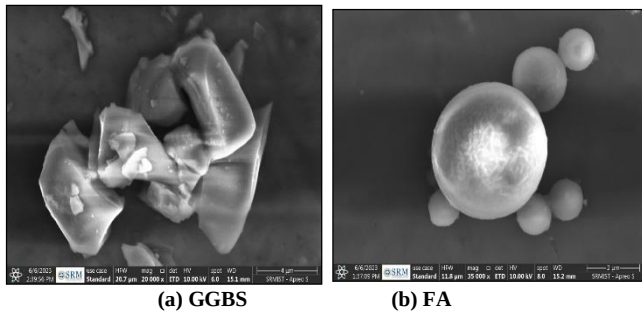
2.1.2. GGBS

GGBS is an industrial by-product from in steel manufacturing industries. In the current study, GGBS from JSW Cement Ltd. was used; the raw material used for manufacturing GGBS was of high calcium content. Physical and chemical properties of class-F FA and GGBS are shown in Tables 1 and 2, respectively. Surface morphology of FA and GGBS was studied using SEM, and it was found that FA

is spherical and hollow in nature, while GGBS is flaky, as shown in Figure 1(a) and Figure 1(b). From the Particle Size Distribution (PSD) curves and relevant standards, FA consists of 70% of particles finer than 45 μm , conforming to ASTM C 618 [41], whereas GGBS conforms to ASTM C989 [42] fineness requirements of less than 20% retention on a 45 μm sieve, as shown in Figure 2.

Table 1. Physical properties of FA and GGBS

Materials	Specific gravity	Specific surface area (m^2/kg)	Colour
FA	2.4	341	Grey
GGBS	2.89	405	Off white



(a) GGBS (b) FA
Fig. 1 SEM image

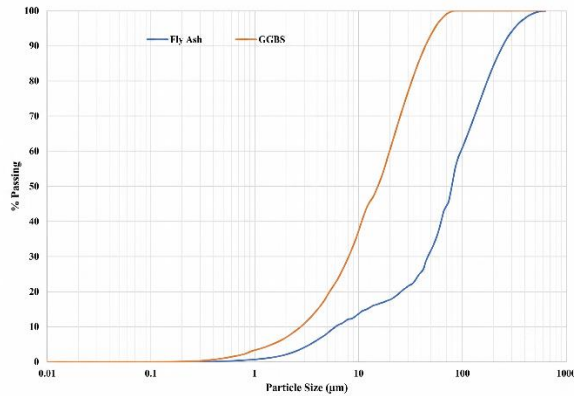


Fig. 2 PSD curve of FA and GGBS

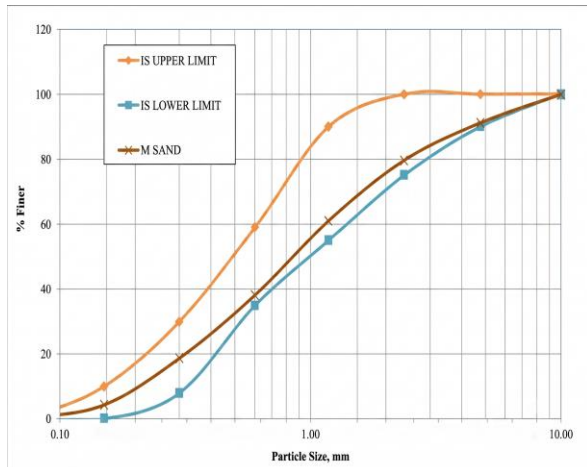


Fig. 3 PSD curve of M-sand

Table 2. Chemical composition of FA and GGBS (XRF)

Oxide	FA (%)	GGBS (%)
Fe_2O_3	10.87	1.40
CaO	2.51	55.36
SiO_2	55.61	28.74
Al_2O_3	26.93	9.62
SO_3	-	0.20
MgO	0.80	3.21
K_2O	1.65	0.17
Na_2O	0.40	0.18
LOI	1.23	1.12

2.1.3. Fine Aggregates

In this study, M-sand was employed as a fine aggregate. The M-sand was manufactured by crushing quarry boulders. The fineness modulus and specific gravity of fine aggregates was measured as 2.65 and 2.56. The PSD curve for M-sand is shown in Figure 3.

2.1.4. Alkali Activator Solutions (AAS)

Alkali Activator Solutions (AAS) used in this investigation was prepared by using SHS and SSS. SSS with silica Modulus (M_s) ($\text{SiO}_2/\text{Na}_2\text{O}$) of 2.0 with chemical proportion of $\text{SiO}_2 = 31\%$, $\text{Na}_2\text{O} = 15.5$ and $\text{H}_2\text{O} = 53.5\%$ has been used. SHS was prepared by liquifying NaOH (99% purity), which was available as pellets in water. The concentration of SHS used was 3.5 Molarity (3.5M) and 5 Molarity (5M). For the preparation of alkali activator solution, NaOH flacks were first diluted by using water to the required molarity of 3.5M and 5M NaOH solution and permitted to cool for 24 hours since the combination of NaOH with H_2O generated heat. After 24 hours of cooling, SSS was introduced into the prepared solution and permitted to react for 4 hours.

2.2. Mix Proportioning

Around 22 mixes were used for this study, in which 11 mixes were prepared by using 3.5M NaOH solution and another 11 mixes were prepared by using 5M NaOH solution. For each 3.5M and 5M NaOH solutions, FA and GGBS content have been varied for every 10% with constant sand content. The mix proportion of binder to sand ratio was kept as 1:0.3 because this mix proportion needs to be further extended to investigate in engineered GP composites. For 3.5M NaOH mixes, SSS/SHS ratio was taken as 0.25 with L/P ratio as 0.39, whereas for 5M NaOH mixes, SSS/SHS ratio was taken as 0.67 with L/P ratio as 0.43. The mix proportioning of 3.5M and 5M NaOH mixes are shown in Tables 3 and 4.

Table 3. Mix proportioning for 3.5 M mix

Mix ID	FA	GGBS	Sand	SSS/SHS	L/P
3.5M1	1	-	0.3	0.25	0.39
3.5M2	0.9	0.1	0.3		
3.5M3	0.8	0.2	0.3		
3.5M4	0.7	0.3	0.3		

3.5M5	0.6	0.4	0.3		
3.5M6	0.5	0.5	0.3		
3.5M7	0.4	0.6	0.3		
3.5M8	0.3	0.7	0.3		
3.5M9	0.2	0.8	0.3		
3.5M10	0.1	0.9	0.3		
3.5M11	-	1	0.3		

Table 4. Mix proportioning for 5M mix

Mix ID	FA	GGBS	Sand	SSS/SHS	L/P
5M1	1	-	0.3		
5M2	0.9	0.1	0.3		
5M3	0.8	0.2	0.3		
5M4	0.7	0.3	0.3		
5M5	0.6	0.4	0.3		
5M6	0.5	0.5	0.3		
5M7	0.4	0.6	0.3		
5M8	0.3	0.7	0.3		
5M9	0.2	0.8	0.3		
5M10	0.1	0.9	0.3		
5M11	-	1	0.3		

2.3. Specimen Preparation

For the mixing of mortar, high speed mortar mixer was used. First, FA was added along with M-sand and dry mixed for about 1 minute. Now, the 70% of alkali activator solutions prepared were mixed with dry mix containing FA and M-sand, and mixed for about 2 minutes. Then, GGBS was introduced into the prepared mixture and again mixed for 2 minutes. Finally, the remaining 30% alkali activator solutions were included in the mix and mixed well for another 2 minutes, as shown in Figure 4. Once the mixing was finished, the prepared mix were poured in the respective moulds and permitted to curing for 24 hours. After curing, the specimens were demoulded, and the specimens can be cured in the ambient temperature itself. Three specimens were made for each test.

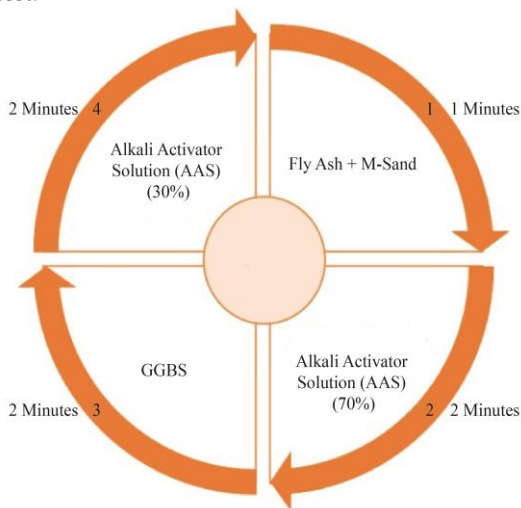


Fig. 4 Mixing procedure for GP mortar

3. Test Procedure

3.1. Mini Slump Test

The flowability of the GP mix was measured through the spread flow test, also referred to as mini-slump test. The flow diameter of the GP mortars was determined as per ASTM C1437 [43] specifications using a truncated conical test device measuring 70 mm top diameter, 100 mm bottom diameter and 50 mm height. The GP mortar was placed in four successive increments of 25 mm and subjected to regular tamping. The surface of the conical mold was levelled after filling. The mold was removed after one minute of dwell time, and the flow diameter of the GP mortar was measured in two perpendicular directions to obtain average flow value.

3.2. Density Test

The hardened density of the GP mix was calculated by measuring the weight of each specimen. Density is the ratio of mass to volume of the mortar mix.

3.3. Compressive Strength Test

According to ASTM C109-07 [44], CS testing of mortar specimens is done using a 50 mm cube dimension subjected to compression loading at a rate of 1.2 kN/s. The CS testing of the cube specimens of the 22 mixtures at 3, 7, 14, 28, 56, and 90 days was undertaken by using a 1000 kN compression testing machine. Three specimens were tested for each mix to determine the average CS.

3.4. Water Absorption (WA) Test

The WA of GP mortar, due to internal microcracks and porosity in different hardened states, was measured by a WA test. Cylindrical specimens (100 x 200 mm) with GP mortar to make cylinders of 100 x 100 mm according to ASTM C642 [45, 46]. The test procedure involved drying, water immersion, boiling, and water cooling. Initially, the specimens were dried in an oven for 24 hours, cooled at room temperature and weighed. After 48 hours, the specimens were then placed in water and weighed. The apparent mass in water was determined by boiling the same specimens in water for 5 hours, and then cooling and weighing using a wire.

3.5. Sorptivity Test

The captivity values of the geopolymer mortar specimens were obtained according to ASTM C1585 [47]. After curing (28, 56, and 90 days), the specimen was oven dried to a constant mass and sealed around all surfaces except the bottom surface. Specimens were submerged in shallow water (3-5 mm) the quantity of water absorbed by capillarity measured at frequent intervals. The sorptivity values were determined by plotting the cumulative water absorption with a plot of square root of time.

3.6. Acid Resistance Test

The acid resistance was measured by immersing geopolymer mortar samples under 5% H₂SO₄ solution. The initial weight was measured prior to the immersion.

Specimens were taken after exposure times (28, 56 and 90 days), cleaned, dried and weighed. Resistance to acid attack was determined as the percentage weight loss.

3.7. Rapid Chloride Penetration Test (RCPT)

This test was conducted using RCPT per ASTM C1202 [48]. Cured geopolymer mortar samples were cut to provide disc specimens (≈ 50 mm thick) and then vacuum saturated. The potential applied between NaCl and NaOH solutions was 60 VDC for 6 hours. Total charge passed (coulombs) was determined, and lower values were found to be better resistance to chloride ion penetration.

3.8. Ultrasonic Pulse Velocity (UPV) Test

UPV is the non-destructive test employed to find the presence of pores and internal cracks in the specimens. If there are not many pores and internal microcracks, then specimen has good density, uniformity and homogeneity, which results in higher pulse velocity. However, if there were pores and internal cracks in specimens, it results in lower pulse velocity. UPV test was performed on three mortar cube specimens of size 50 mm for 28, 56 and 90 days as per ASTM

C597-09 [49]. In UPV, pulse velocity is produced and transmitted through a transducer and are received by a receiver, which are placed on opposite sides of mortar specimens. The pulse velocity was obtained by finding the time elapsed between the time of pulse application and arrival on opposite side of specimen.

4. Results and Discussions

4.1. Workability Test Mini Slump Test

The flowability of 3.5M NaOH and 5M NaOH mixes were measured using mini slump test, and their results are displayed in Figure 5(a) and Figure 5(b), respectively. The flowability of prepared mortar mixes is influenced by their cohesive properties, consistency, and flexibility. While consistency can indicate workability, it was hard to assess the cohesiveness and flexibility of mortar mixes under field conditions. The flowability behaviour of new GP mortar mixtures was described by a small slump test. Flowability must be checked immediately after the GP mortar is mixed in the mixer. To allow for placement in the mould, the flow diameter of the fresh GP mortar should be maintained at a minimum of 150 ± 10 mm.

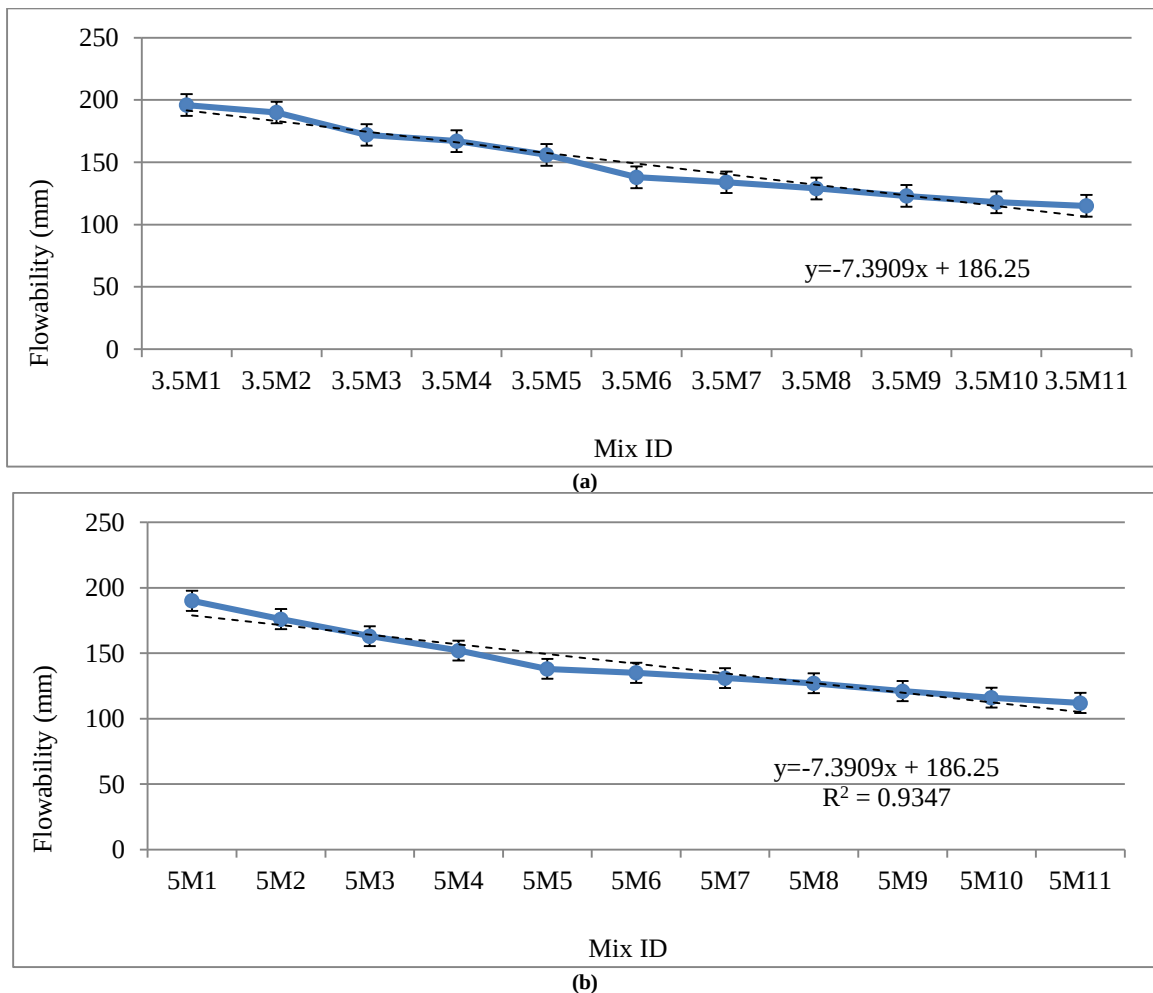


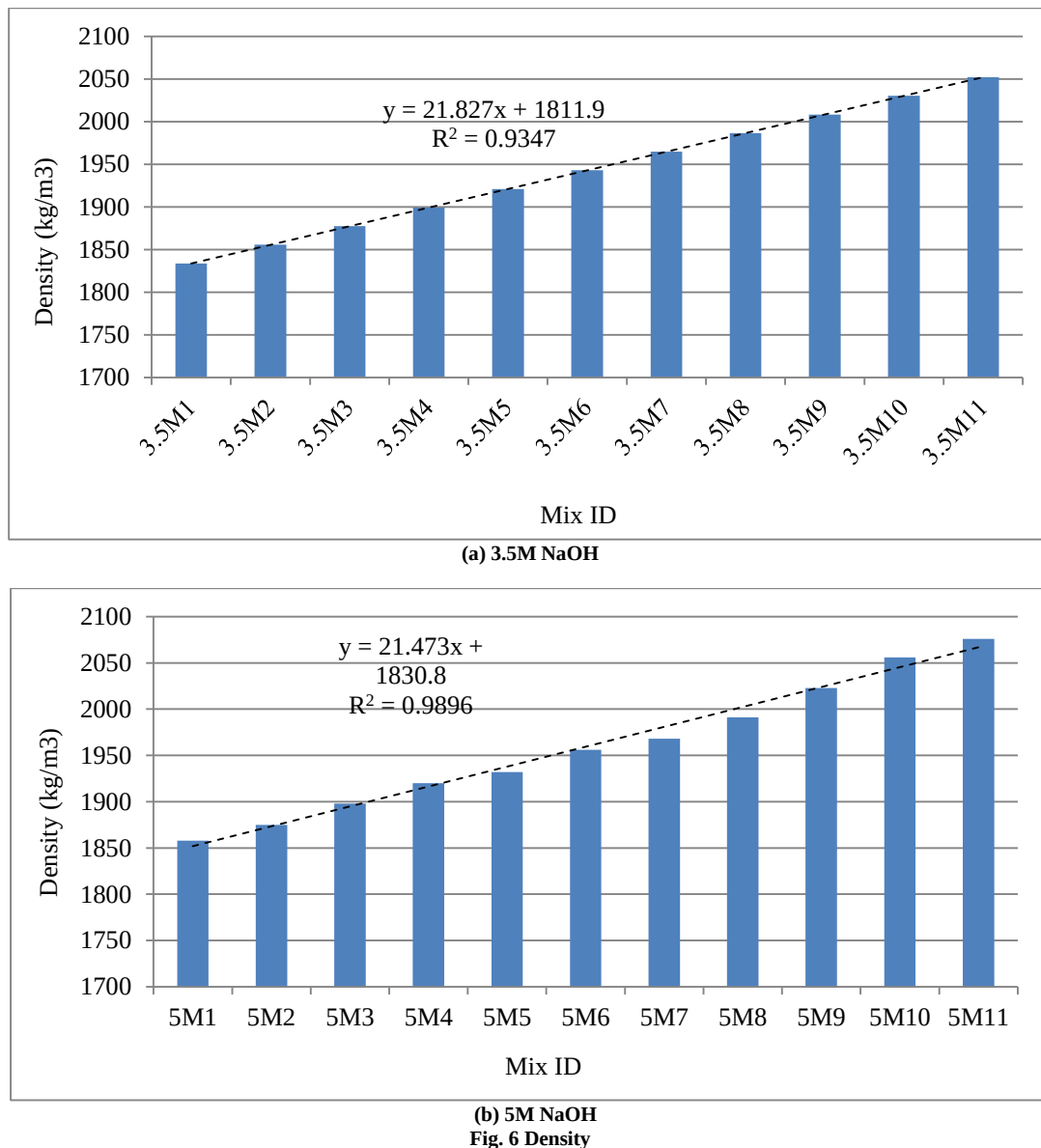
Fig. 5 (a) Flowability of 3.5M NaOH mix, and (b) Flowability of 5M NaOH mix.

In 3.5M NaOH, the Mix 3.5M1 has a higher flowability of 196 mm, which has 100% FA and 0% GGBS. The flowability of mixes from 3.5M1 to 3.5M11 decreases consistently with an increase in every 10% GGBS replacement instead of FA. The Mix 3.5M11 has a lower flowability of 115 mm, which has 0% FA and 100% GGBS. In a 5M NaOH mix, the mix 5M1 with 100% FA and 0% GGBS has the higher workability of 190 mm, whereas the mix 5M11 with 0% FA and 100% GGBS has the lowest workability of 112 mm. The similar trend obtained for 3.5M NaOH mixes was obtained in 5M NaOH mixes, i.e., flowability decrease on increase in GGBS content from 5M1 to 5M11 mixes. As per the suggestion from the previous researches on workability of GP mortar, for 3.5M NaOH mix, the mix 3.5M5 has the flowability of 156 mm with 60% FA and 40% GGBS, and for 5M NaOH mix, the mix 5M4 has

the flowability of 152 mm with 70% FA and 30% GGBS, which was categorized as moderate workability [50]. From studying the flowability of GP mortar, it was found that the flowability decreases with increases in the GGBS concentration. This scenario is because of high calcium in GGBS, which reacts quickly with alkali activator solutions to form C-A-S-H and N-A-S-H gel rapidly [51]. Further, the high R^2 value of 0.9602 and 0.9347 confirms the reliability of the linear regression models for forecasting flow behavior.

4.2. Physical Property of Mortar

Figure 6 represents the density of 3.5M NaOH mixes and 5M NaOH mixes. From the results, it was noted that the densities of both 3.5M NaOH mixes and 5M NaOH mixes increase with an increase in GGBS content.



This increasing trend observed in both 3.5M NaOH mixes and 5M NaOH mixes is because the density of GGBS is higher compared to density of FA. While comparing the density of 3.5M NaOH mixes with 5M NaOH mixes, it was found that density of 5M NaOH was higher comparing to 3.5M NaOH mixes, this is because the molarity of AAS used is higher. The high R^2 value of 0.9896 and 0.9927 validates the reliability of the regression models and confirms the strong linear dependence between mix constituents and density, making the developed correlations appropriate for predictive modelling in mix design.

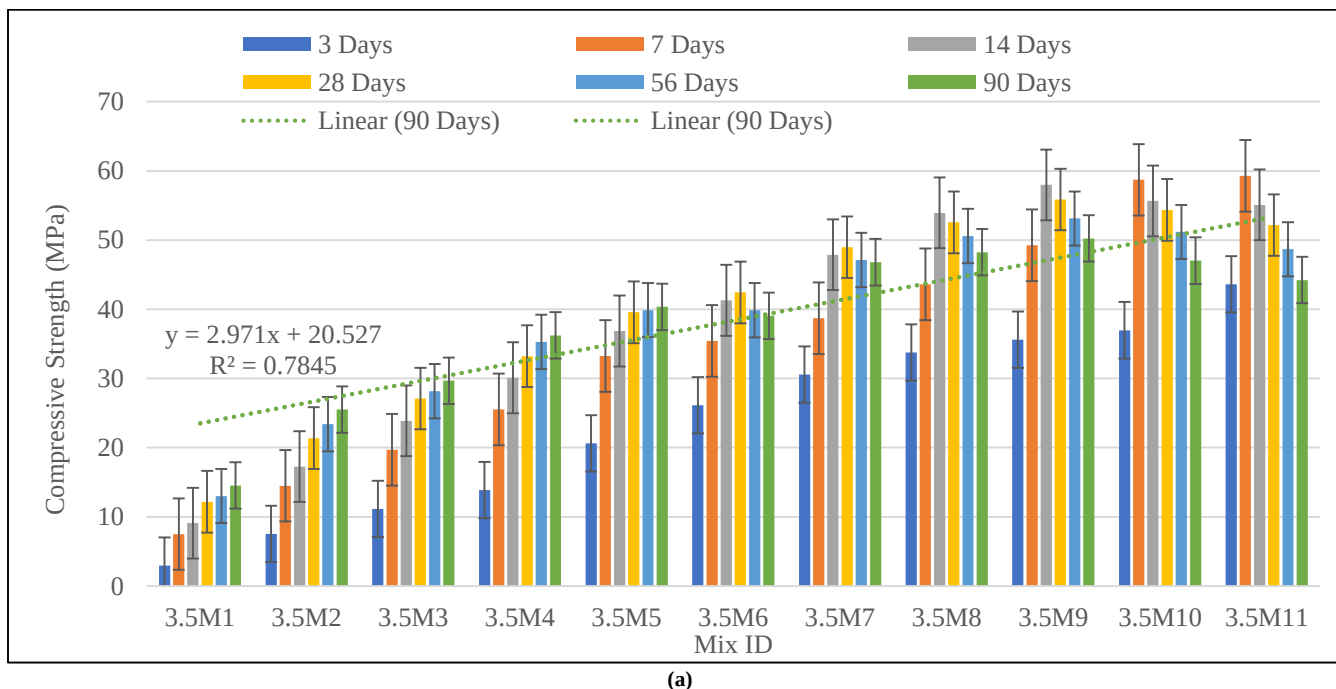
4.3. Mechanical Properties of GP Mortar

4.3.1. Compressive Strength (CS)

The CS of GP mortar for 3.5M NaOH mix and 5M NaOH mix at different ages was graphically illustrated in Figure 7(a) and Figure 7(b), respectively. The GGBS is one of the source materials used in the preparation of GP mortar, which can be activated by using alkali activator solutions. Without the activator, the strength development of GGBS dominant mix is extremely slow [25]. A detailed evaluation of the strength gain during the 3-, 7-, 14-, 28-, 56-, and 90-day periods shows an initial gain of strength followed by marginal loss after a certain period. Specifically, for the 3.5M NaOH mixes, the strength of 3.5M1 to 3.5M5 mixes shows continuous increase up to 90 days, while 3.5M6 and 3.5M7 mixes have a loss in strength after 28 days, 3.5M8 and 3.5M9 mixes after 14 days, and 3.5M10 and 3.5M11 mixes after 7 days. The 3.5M NaOH mix 3.5M5, containing 60% FA with 40% GGBS, satisfies the characteristic CS of M30. The maximum CS recorded was 59.28 MPa for the 3.5M11 mix in the 3.5M NaOH system at 7 days, while the 5M NaOH system, the 5M11 mix has a maximum CS of 75.13 MPa at 7

days. Further, it was observed that the increase in GGBS content results in an increase of CS.

In 5M NaOH mixes, the CS of mixes 5M1 to 5M4 continued to increase for up to 90 days. However, 5M5 and 5M7 mixes showed a reduction in strength after 28 days, whereas mixes 5M8 and 5M9 showed decreases after 14 days. Mixes 5M10 and 5M11 showed strength losses after 7 days. The standard CS of M50 was achieved in mix 5M4 (70% FA + 30% GGBS) for the 5M NaOH system. The strength improvement due to the increased GGBS content is presumably due to the formation of optimum aluminosilicate hydrate and C-S-H gel [29, 52]. The improvement in strength is due to the synergy between the GGBS and FA in the GP system. This synergy helped in developing C-A-S-H and C-S-H gels through hydration and polymerisation of GGBS along with polymerization of FA, as evidenced SEM image, as illustrated in Figure 12. On the other hand, a strength loss beyond the optimum GGBS content that aligns with the results of Wardhono et al. [53], who explained that loss in strength of GP systems after an optimum content of GGBS and FA takes place due to the hydration reaction of surplus calcium in GGBS, which causes the formation of $\text{Ca}(\text{OH})_2$, resulting in cracking and expansion. Hassan and Ismail [54] also presented a similar trend of strength loss with an increased GGBS content in FA-slag-based GP. The regression equations $y = 4.047x + 29.585$, $R^2 = 0.7057$ and $y = 2.971x + 20.527$, $R^2 = 0.7845$, indicate that approximately 70.57% of the variation in the strength is explained by a linear trend. The moderate R^2 value of 0.7845 and 0.7057 indicate that strength development is affected by both mix progression and complex physicochemical interactions in the system.



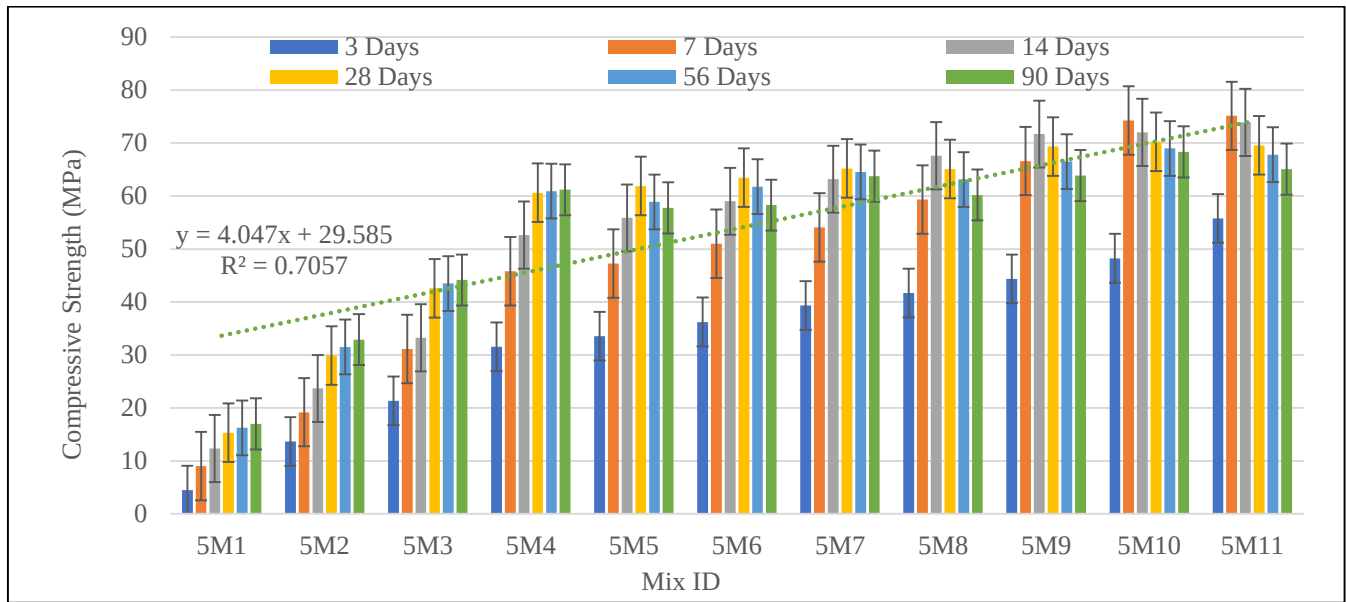


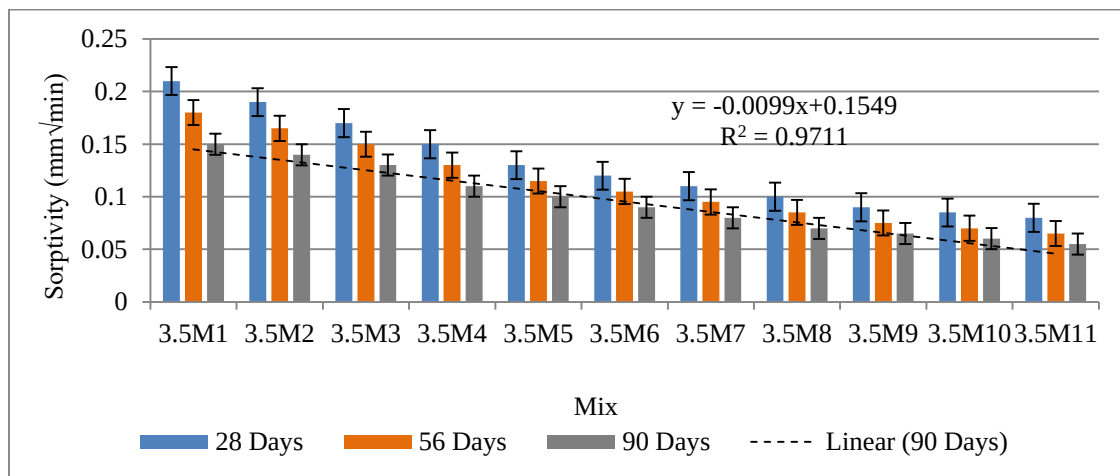
Fig. 7 (a) CS of GP mortar for 3.5M NaOH mix, and (b) CS of GP mortar for 5M NaOH mix.

4.4. Durability Properties of GP Mortar

4.4.1. Sorptivity

Figure 8 presents the sorptivity results of the GP mortar modified with GGBS, which reveals an increase in curing age causes a reduction in sorptivity value for both 3.5M and 5M mixes. The 3.5M mixes exhibited a sorptivity value range from 0.21 mm/ $\sqrt{\text{min}}$ to 0.08 mm/ $\sqrt{\text{min}}$ at 28 days, which was reduced to 0.15 mm/ $\sqrt{\text{min}}$ to 0.055 mm/ $\sqrt{\text{min}}$ at 90 days. This decrease in sorptivity is due to the continued geopolymerization and pore refinement, resulting in a more compact microstructure. Similarly, the sorptivity values of 5M mixes were found to be lesser than the 3.5 M mixes at all ages, whose values are ranges from 0.18 mm/ $\sqrt{\text{min}}$ to 0.06 mm/ $\sqrt{\text{min}}$ at 28 days and decreasing to 0.13 mm/ $\sqrt{\text{min}}$ to 0.035 mm/ $\sqrt{\text{min}}$ at 90 days. The better performance of the 5M mixes is due to higher alkali concentration, which enhances

the dissolution of aluminosilicate materials, thereby promoting the formation of a dense and well-connected gel structure. The increase in GGBS content results in a decrease on sorptivity due to the formation of calcium-rich hydration products that effectively block capillary pores. The 3.5M8-3.5M11 and 5M8-5M11 mixes had the least sorptivity, demonstrating higher resistance to water infiltration. The findings concluded that increased GGBS content and molarity led to a reduction in sorptivity and an enhancement in the durability of the mixtures, making them more appropriate for structures subjected to moisture and aggressive environments. The regression equation ($y = -0.0099x + 0.1549$, $R^2 = 0.9711$; $y = -0.0095x + 0.1314$, $R^2 = 0.9646$) shows a strong linear decreasing trend with high correlation.



(a)

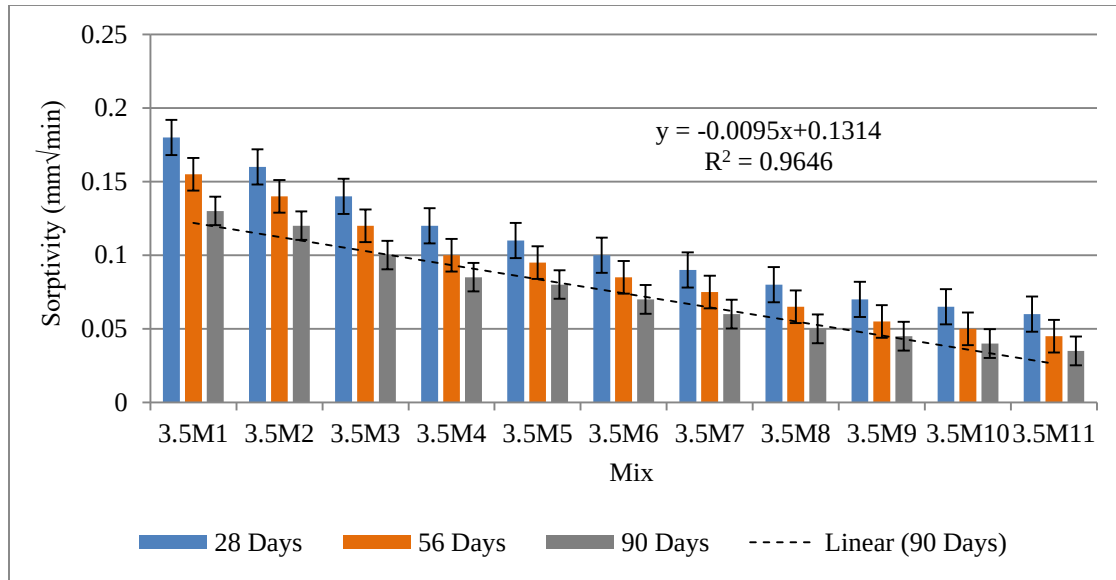
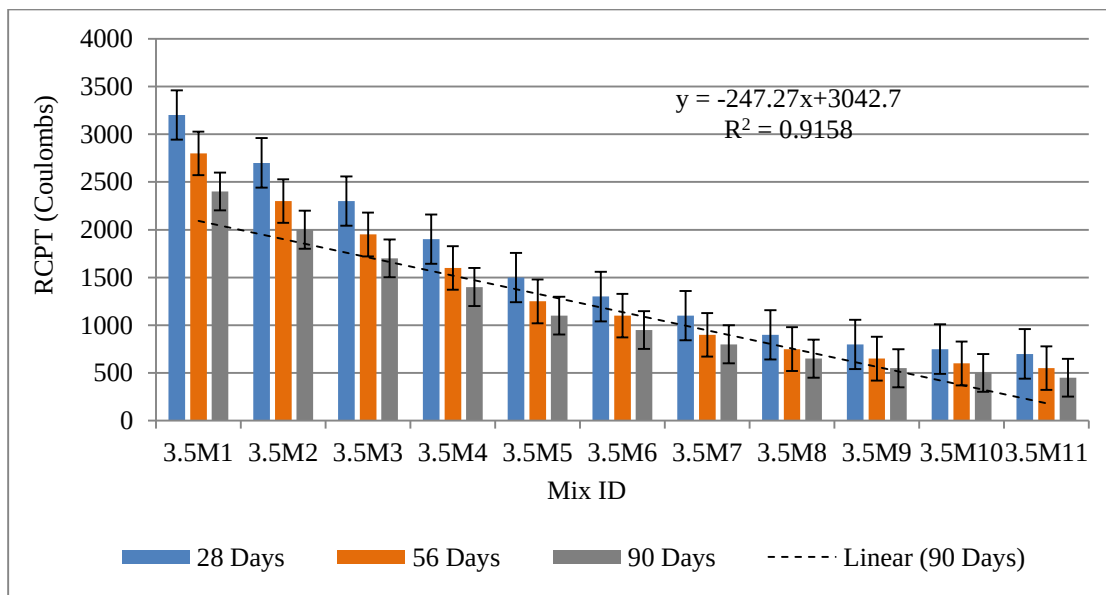


Fig. 8 (a) Sorptivity of GP mortar for 5M NaOH mix, and (b) Sorptivity of GP mortar for 5M NaOH mix.

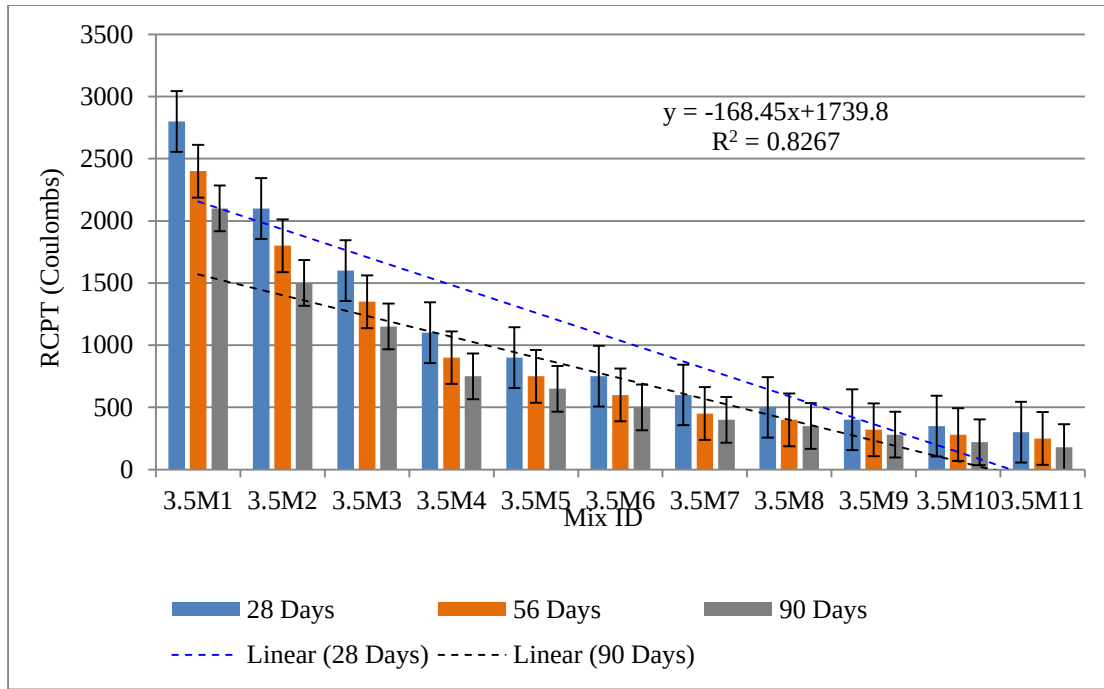
4.4.2. RCPT

Figure 9 presents the RCPT results of the geopolymer mortar modified with GGBS, which reveals a significant reduction in charge passed with increasing curing age and GGBS content for both 3.5 M and 5M mixes. At 28 days, the 3.5M mixes had chloride permeability values ranges from 3200 to 700, which falls under “moderate” to “very low” according to ASTM C1202 standards. These also reduced with further extended curing to 56 and 90 days, with most of the mixes falling into “low” and “very low” chloride ion permeability, reflecting progressive pore refinement and densification of the matrix. Similarly, the RCPT value for the 5M mixes was lesser than the 3.5M mix at all ages, with

values ranges from 2800 and 300 coulombs at 28 days. These are considered “very low” to “negligible” permeability (<1000 coulombs) for higher percentage mixes of GGBS. Further, the RCPT values were found to be reduced as 180 columns at 90 days, thus falls under “negligible” chloride ion penetration. It was found that the 5M8-5M11 mixes showing excellent resistance to chloride ingress, which make them very well suited for aggressive exposure conditions. The better performance in 5M mixes is due to the better dissolution of aluminosilicate phases and accelerated formation of dense N-A-S-H and C-A-S-H gels, which results in a finer pore structure as evidenced SEM image as illustrated in Figure 12.



(a)



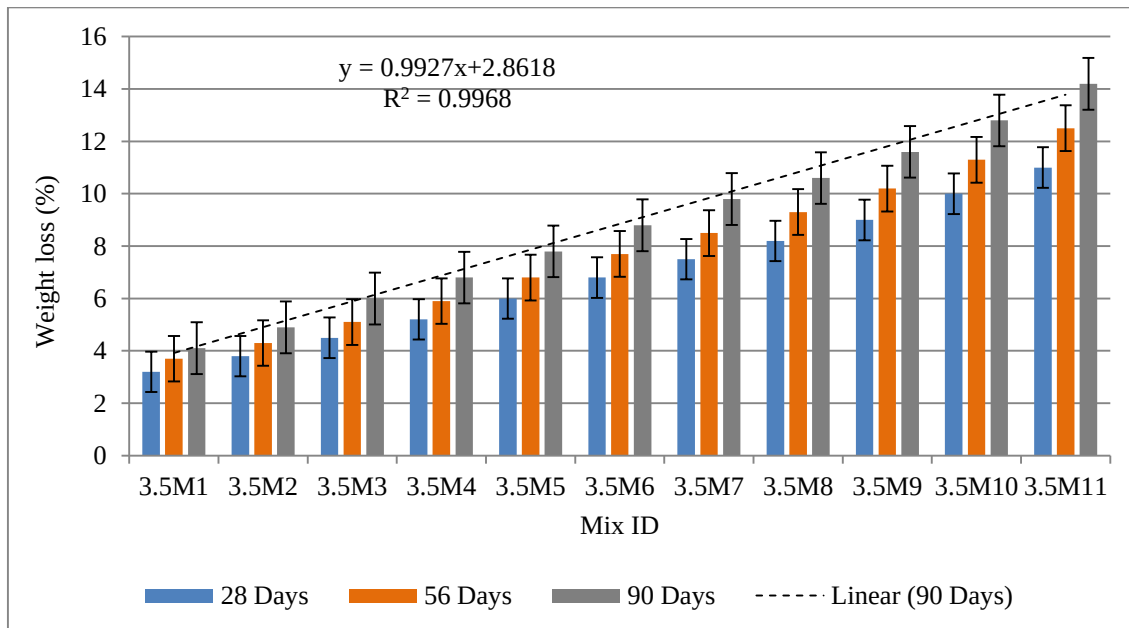
(b)
Fig. 9 (a) RCPT of GP mortar for 5M NaOH mix, and (b) RCPT of GP mortar for 5M NaOH mix.

Further, the high percentage of GGBS makes a substantial contribution to the reduction in permeability due to the formation of calcium-rich hydration products, which close the capillary pores. The linear regression ($y = -247.27x + 3042.7$, $R^2 = 0.9158$; $y = -168.45x + 1739.8$, $R^2 = 0.8267$) demonstrates a significant negative correlation, indicating that optimized mix composition effectively increases resistance to chloride ingress. The findings concluded that both higher molarity and GGBS content have significantly

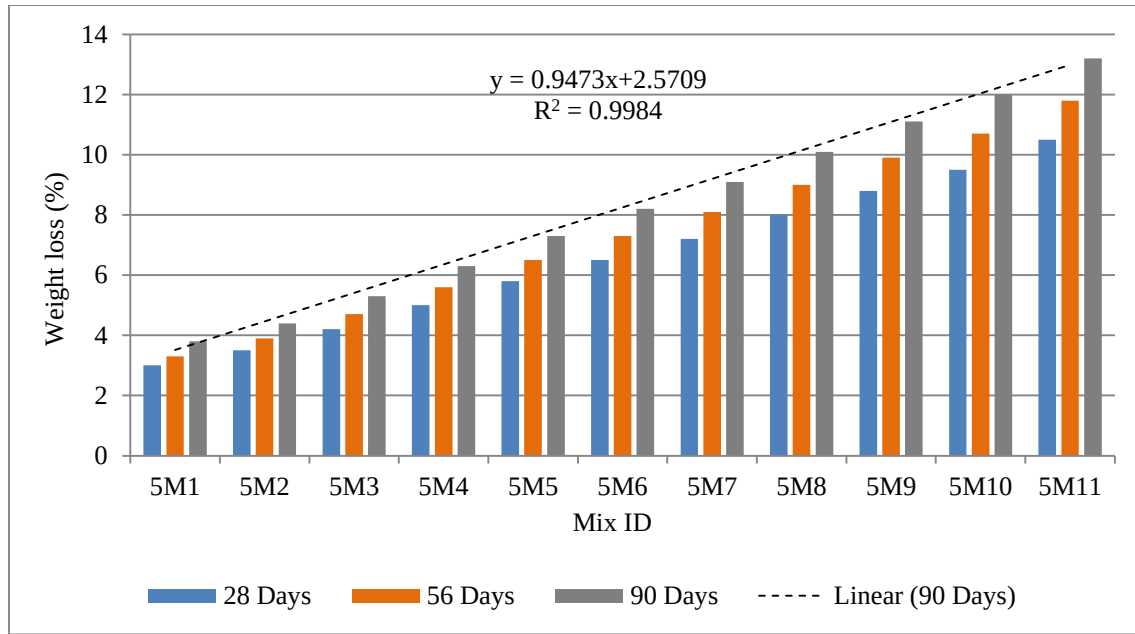
enhance the durability properties in terms of chloride ion penetration.

4.4.3. Acid Resistance

The weight loss under acid exposure shows that for both 3.5M and 5M mixes, the weight loss increases as the curing time increases, indicating degradation of the binder matrix over time, as presented in Figure 10.



(a)



(b)
Fig. 10 (a) Weight loss of GP mortar for 5M NaOH mix under acid exposure, and
(b) Weight loss of GP mortar for 5M NaOH mix under acid exposure.

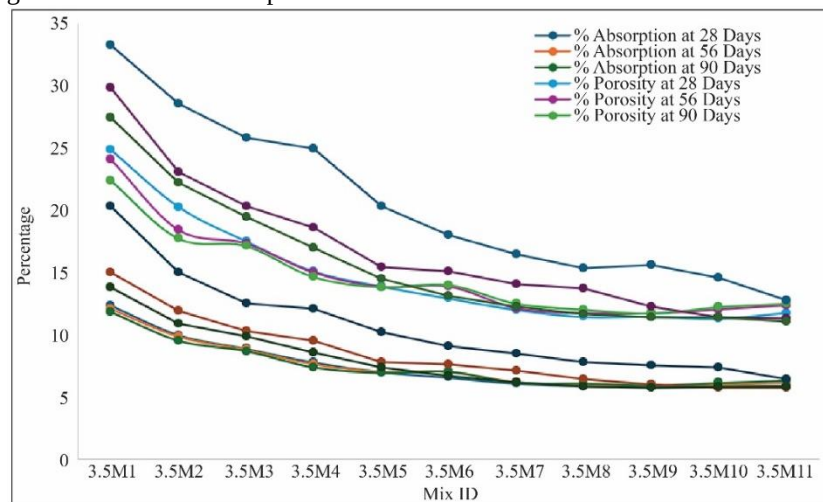
At 28 days, the 3.5M mixes exhibited weight loss ranging from 3.2 % to 11%, which is about 4.1% to 14.2% higher than at 90 days, due to the continuous dissolution of aluminosilicate gel and leaching of calcium compounds under prolonged acidic attack. Similarly, the 5M mixes had slightly lower weight loss, ranging from 3.0% to 10.5% at 28 days and 3.8% to 13.2% at 90 days. The improved performance of the 5M mixes is a result of higher alkali concentration, that increases geopolymerization and forms a denser and more stable matrix with reduced permeability to acidic solutions. The weight loss is found to be increases as the GGBS content is increased for both 3.5M and 5M mixes.

Mixes such as 3.5M9-3.5M11 and 5M9-5M11 mixes exhibited a higher degradation due to the presence of

calcium-rich phase, which are more susceptible to acid attack.

4.4.4. Water Absorption Test

WA denotes the capacity of the GP mortar specimens to absorb water and is represented as a percentage calculated from the weight difference between fully saturated samples and those dried in an oven. The porosity of the mortar specimens, the main factor responsible for the mechanical behaviour of the GP mortar, governs the WA of the GP mortars. WA and porosity of the GP mortars developed with 3.5 M NaOH and 5 M NaOH were determined at 28, 56, and 90 days, and their results are given in Figure 11a and Figure 11b, respectively.



(a)

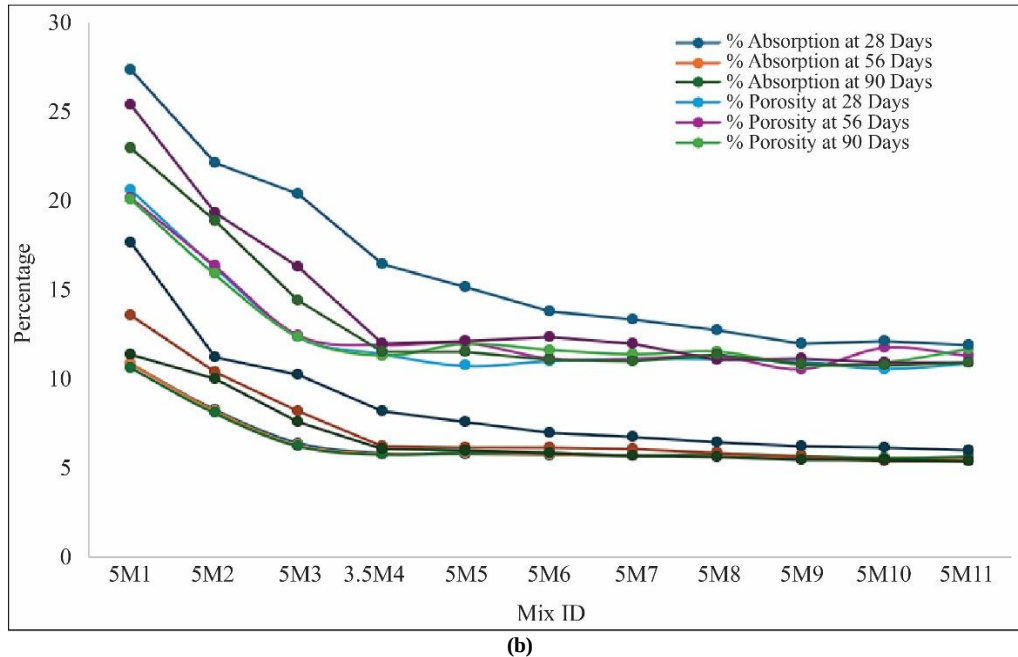


Fig. 11 (a) WA and porosity of 3.5M NaOH Mix, and (b) WA and porosity of 5M NaOH Mix.

From the results, it was found that in 3.5M NaOH, from 3.5M1 mix to 3.5M5 mix, the WA and porosity decrease with an increase in GGBS content and an increase in curing days. Whereas in mix 3.5M6 and 3.5M7, the WA and porosity decrease up to 28 days and begin to increase after 28 days. However, in mixes 3.5M8 and 3.5M9, the WA and porosity increase after 14 days and also in 3.5M10 and 3.5M11 mixes, the WA and porosity increase after 7 days.

For the optimal mix 3.5M5 (60% FA + 40% GGBS) with in 3.5M NaOH, the WA and porosity were relatively low, as 7.03% and 13.90%, which contributed to its enhanced mechanical strength. Similarly, in the case of 5M NaOH, from 5M1 to 5M4 mix, WA and porosity are recorded to decrease with the increase in GGBS concentration and curing duration.

From 5M5 to 5M7 mixes, WA and porosity decrease for up to 28 days and increase thereafter. Whereas in 5M8 and 5M9 mixes, WA and porosity increase after 14 days; and in 5M10 and 5M11 mixes, the respective parameters increase after 7 days, beyond which they are measured.

Optimum formulation 5M4, comprising 70% FA and 30% GGBS, results in WA and porosity in 5M NaOH system as 5.78% and 11.40%, respectively, while attaining the required strength. The results obtained reveal that the WA decreases as the level of GGBS replacement increases up to an optimum replacement percentage due to the calcium in GGBS reacting with FA to form C-A-S-H gel, as evidenced SEM image as illustrated in Figure 12. Beyond the optimum proportion of GGBS, its further replacement results in increased WA due to the unreacted calcium present in GGBS

hydrating to form Ca(OH)_2 as confirmed by EDS analysis, which causes expansion and cracking. The same result can also be demonstrated by porosity data: an increased number of pores corresponds to increased porosity and vice versa. The observed trend of WA and porosity, therefore, correlates well with the trend obtained in the CS tests.

4.4.5. Ultrasonic Pulse Velocity (UPV) Test

UPV was employed to study the internal structure of the GP mortar. The UPV technique has been identified as one of the promising techniques for mortar quality assessment. UPV gives an idea about internal microcracks, defects, and pore content inside the mortar.

Tables 5 and 6 illustrate the average UPV values at 28, 56, and 90 days for three specimens per mix for mix 3.5 M NaOH and mix 5 M NaOH, respectively. By comparing the ultrasonic pulse transmission through the GP matrix, it is evident that an increase in GGBS content improves the internal structure and density of the GP matrix by providing a clear path for the passage of ultrasonic pulses, which results in higher velocities. It should be noticed that UPV rises with a rise in GGBS content to a certain value and then decreases when further GGBS content is increased. Based on curing days, the UPV increase with increase in curing days indicated the formation of denser and stronger internal structure. In 3.5M NaOH, from 3.5M1 mix to 3.5M5 mix, the pulse velocity increases with increase in curing days, indicating the pores are lesser. Whereas in mix 3.5M6 and 3.5M7, the pulse velocity decreases after 28 days, indicating the formation of pores.

However, in mixes 3.5M8 and 3.5M9, the pulse velocity decreases after 14 days, and also in 3.5M10 and 3.5M11

mixes, the pulse velocity decreases after 7 days, indicating the presence of a greater number of pores and internal cracks. Similarly, for 5M NaOH, from 5M1 mix to 5M4 mix, the pulse velocity increases with an increase in GGBS content and curing days. However, in mixes 5M5 to 5M7, the pulse velocity decreases after 28 days due to the formation of pores. Similarly, for 5M8 and 5M9 mixes, the pulse velocity decreases after 14 days and for mixes 5M10 and 5M11, the pulse velocity decreases after 7 days itself due to more

number of pores and internal cracks. From the results obtained, it was concluded that with increase in GGBS content beyond a certain percentage will drastically increase the internal pores and cracks within the matrix, which leads to decrease in UPV. The results obtained in UPV are in a similar trend with results of CS, which proves that if strength decreases, pulse velocity also decreases due to the formation of pores and internal cracks.

Table 5. UPV of 3.5M mixes

Mix	UPV (m/s)					
	3 day	7 day	14 day	18 day	56 day	90 day
3.5M1	758	1052	2568	3098	3208	3353
3.5M2	1089	2548	3024	3273	3311	3445
3.5M3	2319	2896	3357	3459	3581	3622
3.5M4	2463	3482	3540	3611	3752	3880
3.5M5	2900	3526	3629	3753	3869	3946
3.5M6	3568	3681	3769	3892	3811	3701
3.5M7	3601	3719	3905	3972	3928	3900
3.5M8	3715	3816	4195	4155	4019	3951
3.5M9	3793	4006	4390	4211	4123	4008
3.5M10	3814	4412	4202	4197	4098	3918

Table 6. UPV of 5M mixes

Mix	UPV (m/s)					
	3 day	7 day	14 day	18 day	56 day	90 day
5M1	869	2566	3125	3296	3468	3614
5M2	2986	3102	3312	3517	3619	3709
5M3	3250	3587	3614	3729	3826	3958
5M4	3598	3725	3821	3933	4051	4149
5M5	3625	3861	3958	4186	4020	4003
5M6	3781	3986	4031	4219	4092	4129
5M7	3825	4123	4186	4299	4126	4191
5M8	3911	4468	4528	4368	4182	3911
5M9	3956	4568	4598	4456	4228	4231
5M10	3970	4762	4612	4561	4402	4398
5M11	4171	4799	4659	4468	4311	4268

4.5. Microstructural Analysis

Scanning Electron Microscopy images of geopolymer mortars prepared with 3.5 M and 5 M NaOH activators, as shown in Figure 12.

The main microstructural aspects that could be identified are gel formation, unreacted fly ash particles, partially reacted GGBS and FA, microcracks, and pore formation.

The aluminosilicate gel that forms through polymerization in GP. In both the 3.5 M and 5 M NaOH concretes, the 100% FA-based GP mixture had N-A-S-H gel formation due to alkali-activation.

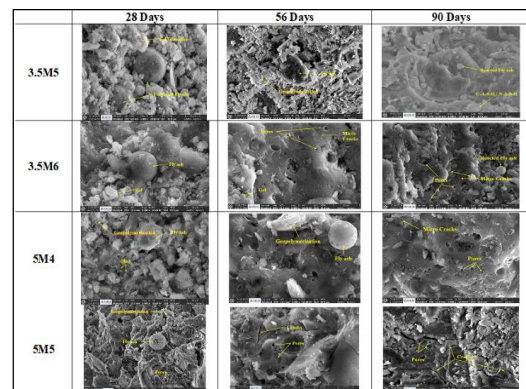


Fig. 12 SEM image of various GP mortar mixes

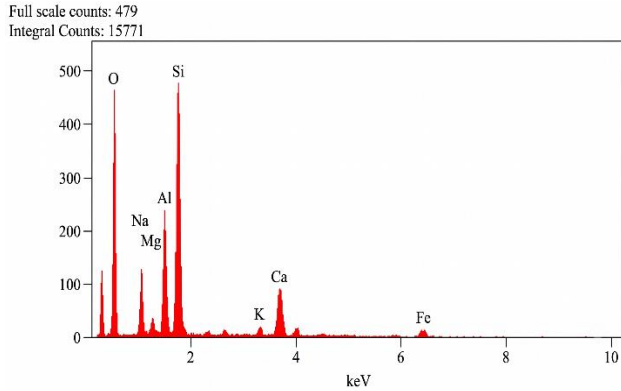


Fig. 13 EDS of GP mortar mixes

However, the increase in pH (>12) following the introduction of GGBS into the mixtures promotes the substitution of calcium for sodium within the gel, thus resulting in the formation of C-(A)-S-H type gel along with N-A-S-H type gel. The existence of Ca, Si and Al in the EDS analysis confirms the presence of calcium and aluminosilicate components in the matrix, suggesting the potential for mixed gel formation as illustrated in Figure 13. Hence, GP concretes have gels corresponding to N-A-S-H, C-S-H, and C-A-S-H.

In the microstructure of GP concrete specimens cured with 3.5 M and 5 M NaOH, a well-reacted matrix is identified with a large number of pores and unreacted FA particles. The incorporation of GGBS induces a noticeable change in the microstructure. A denser microstructure was realized with GGBS addition owing to an improvement in C-A-S-H gel formation, which may explain the increased CS up to an optimum percentage of GGBS replacement.

Beyond the optimum, the excess matrix calcium introduced by further GGBS replacement in 3.5M5 and 5M4 mixes leads to the formation of $\text{Ca}(\text{OH})_2$, microcracking, and an increase in porosity. The moderate R^2 value of 0.5677 and 0.6813 indicate that UPV is affected by both the mix composition and complex microstructural features like pore connectivity, moisture state and the existence of microcracks.

4.6. Sustainability and Environmental Assessments

The ICE database V3.0 was used to determine the Embodied Energy (EE) and Embodied Carbon (EC) of the mortar mixes, and their results are presented in Tables 7 and 8.

The EE and EC were calculated by multiplying the quantity of each material (kg/m^3) by the EE (MJ/m^3) and EC ($\text{kg CO}_2/\text{m}^3$) coefficients from the ICE database v3, then summing each materials contribution to give an EE and an EC per cubic meter of mortar. The analysis was conducted over a cradle-to-gate system boundary, which encompasses raw material extraction, processing, and material production.

Table 7. EE and EC of GP mortar for 3.5M

Mix	EE (MJ/m^3)	EC ($\text{kg CO}_2/\text{m}^3$)
3.5M1	1450	135
3.5M2	1520	142
3.5M3	1590	149
3.5M4	1660	156
3.5M5	1740	165
3.5M6	1820	174
3.5M7	1900	183
3.5M8	1980	192
3.5M9	2050	200
3.5M10	2120	208
3.5M11	2200	215

Table 8. EE and EC of GP mortar for 5M

Mix	EE (MJ/m^3)	EC ($\text{kg CO}_2/\text{m}^3$)
5M1	1650	155
5M2	1750	165
5M3	1850	175
5M4	1950	185
5M5	2050	195
5M6	2150	205
5M7	2250	215
5M8	2350	225
5M9	2450	235
5M10	2550	245
5M11	2650	255

It was observed that increasing the GGBS content and molarity of the GP mortar results in increases in EE and EC. The 3.5 M mixes exhibit EE value ranges from 1450–2200 MJ/m^3 and EC from 135–215 $\text{kg CO}_2/\text{m}^3$; while 5M mixes exhibit higher EE values in the range of 1650–2650 MJ/m^3 and EC values in the range of 155–255 $\text{kg CO}_2/\text{m}^3$.

The increase in EE and EC was primarily due to the energy intensity of GGBS and alkali activators. The mixes containing either a high proportion of GGBS or FA have different environmental impacts, with GGBS-rich mixes showing higher environmental impacts (EE and EC) while the FA-rich mixes show lower environmental impacts.

The findings concluded that the performances of the mixes with moderate GGBS content are optimal and sustainable.

4.7. Comparative Evaluation with Recent Studies

The performance of the proposed FA-GGBS geopolymer system is critically assessed based on the recent state-of-the-art studies, based on the compressive strength and curing conditions as summarized in Table 9.

Table 9. Performance evaluation against state-of-the-art studies

Reference	Parameters	Results
Boumaza et al. [22]	Binder: Volcanic Tuff+ BFS; BFS used at 30% replacement level; heat cured at 80°C, 48 hours	Maximum CS of 15.03 MPa was obtained at 28 days using heat curing.
Samantasinghar and Singh [21]	Binder: Fly ash+slag; GGBS used at 60% replacement level; Activator: 8M NaOH; heat cured at 29°C.	A maximum CS of 44 MPa was obtained at 28 days using heat curing.
Li et al. [13]	Binder: Fly ash; Activator: 8M NaOH; heat cured at 70°C for 24 hours.	A maximum CS of 85 MPa was obtained at 28 days using heat curing.
Gopalakrishna et al. [4]	Binder: Fly ash; Activator: 16M NaOH; $\text{Na}_2\text{SiO}_3/\text{NaOH} = 1.5$; heat cured at 60°C	A maximum CS of 36 MPa was obtained at 28 days using heat curing.
Gopalakrishna et al. [4]	Binder: Fly ash; Activator: 16M NaOH; $\text{Na}_2\text{SiO}_3/\text{NaOH} = 1.5$; heat cured at 60°C	The EE was reduced by 94%
Proposed study	Binder: Fly ash+GGBS; Activator: 5M NaOH; ambient curing.	Maximum compressive strength of 70.26 MPa was achieved at 28 days under heat curing.

The comparison clearly showed that the present study could outperform or be comparable to the others under more practical conditions. Boumaza et al. [22] found that under elevated temperature curing (80°C for 48 h), the maximum compressive strength was only 15.03 MPa at 28 days. The poor performance under ambient conditions emphasizes the lack of applicability of VT-based systems. Conversely, the proposed study shows much higher strength of 70.26 at 28 days under ambient curing, indicating significant enhancement in the reactivity of the binder and the efficiency of geopolymerization. Similarly, Samantasinghar and Singh [21] obtained the maximum strength of around 44 MPa with 60% GGBS and 8M NaOH with ambient conditions. In contrast, the present study demonstrates the maximum strength of 70.26 at 28 days using a highly reactive FA-GGBS mix, thus resulting in significantly improved strength due to the enhanced geopolymerization and calcium-driven hydration. The very high compressive strength was reported by Li et al. [13], where heat curing was performed at 70°C. While the strength is higher than the strength reported in this proposed study, this requires elevated temperature curing. The proposed study also delivers high ambient curing strength and is a more viable and energy-saving option. The maximum strength of 36 MPa observed by Gopalakrishna et al. [4] using high NaOH concentration (16M) and curing at 60°C was still much lower than that obtained strength of 70.26 at 28 days itself in the present study, thus showing that optimizing the binder composition is more significant than only increasing the concentration of the activator. It was concluded that the proposed FA-GGBS geopolymer system is superior in every aspect in terms of achieving high compressive strength with moderate molarity under ambient

curing conditions. The comparable or improved strength obtained with the ambient curing method at a lower molarity (3.5M) in this present study is mainly due to the increased reactivity introduced by the GGBS, which compensates for the lower alkalinity and eliminates the need for heat curing. This shows that it has practical application, it is energy efficient, and it can be a sustainable alternative to conventional and existing geopolymer systems.

5. Conclusion

Based on the experimental investigations, the following conclusions were derived,

- The slump flow test revealed that the flowability of the prepared GP mortar decreases with the increase in the content of GGBS at both 3.5M and 5M NaOH mixtures.
- Among the established recommendations regarding the workability of GP mortar, it was indicated that the minimum flow should be 150 ± 10 mm. Thus, the 3.5M NaOH mixture with the designation of 3.5M5, with 60% FA and 40% GGBS, has attained a flowability of 156 mm. On the other hand, its corresponding 5M NaOH mixture was labelled as 5M4, demonstrating a flowability of 152 mm with a 70% FA and 30% GGBS composition, which falls into the category of moderate workability.
- Density measurements confirm that the density of each mix increases with the addition of GGBS; this results directly from the higher intrinsic density of GGBS compared to FA.
- The maximum CS of GP mortar was recorded for the 3.5M5 mixture (60% FA + 40% GGBS) and the 5M4

mixture (70% FA + 30% GGBS) in the 3.5M NaOH and 5M NaOH systems, respectively, because beyond 28 days, CS of other mixes decreases with increased content of GGBS.

- The CS of GP mortar increases with the increased GGBS content up to an optimum dosage and, beyond this, decreases because of the $\text{Ca}(\text{OH})_2$ that formed inside the matrix causes internal fissuring in the specimens.
- This optimum composition, based on CS, was validated by tests for WA, porosity, and UPV. The tests showed increased WA and porosity, along with a decrease in UPV, to signify internal cracks and voids within these mixes.
- The results obtained are validated by using microstructural analysis, which indicates that an excess of GGBS leads to increase in pores and microcracks.

The findings reveal that an optimum FA-GGBS ratio can be used to produce ambient-cured GP mortar for field construction that can achieve a lower energy consumption and CO_2 emission. The early strength and durability support structural use, while scalability is feasible using industrial by-products. However, workability control and mix optimization become important for large-scale implementation. The flexural strength was not experimented in this study, which will be a limitation of this study. Future study will focus on examining the flexural behaviour of FA-GGBS-based

geopolymer mortar to provide a more comprehensive understanding of its structural performance. Furthermore, future work will incorporate FTIR/XRD/NMR analyses for more definitive phase identification and validation of gel transformation mechanisms.

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Author Contribution

Jegan M: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Resources, Writing - Original Draft; Annadurai R: Supervision, Writing – Review & Editing, Validation; Kannan Rajkumar P R: Validation, Writing – Review & Editing.

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