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Mechanical Performance of Blended Fly Ash-based Geopolymer Concrete with GGBS and Metakaolin

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HIGHLIGHTS

- The mechanical strength of Geopolymer concrete increase with an increase SiO2/Al2O3 ratio.
- The substitution of GGBS with fly ash will increase the strength of concrete and reduce its workability.
- Increasing the molarity of NaOH led to increased compressive, tensile, and flexural strength.
- The workability increases with the fly ash content and decreases as NaOH concentration increases.
- The substitution of metakaolin with fly ash will reduce the strength and workability.

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ABSTRACT

One of the most user-friendly alternatives to ordinary concrete is geopolymer concrete(GPC), which achieves the same result. GPC is a unique substance made by activating source materials with a high concentration of silica and alumina. As a result, geopolymer binders use less raw resources and emit less carbon dioxide. For these reasons, most academics are focusing on these sorts of resins to develop eco-friendly housing. This article reports on an experimental investigation that examined the Mechanical Performance of Blended Fly Ash based Geopolymer concrete at 7,28 and 360 days made with two different activator solution molarities and varying R (SiO_2/Al_2O_3) ratios. Positive findings were seen at a larger percentage of GGBS (36%) with a concentration of a sodium hydroxide solution of 10 M and an R ratio of 2.75, compared with other proportions. The test findings indicate that increasing the concentration of sodium hydroxide (NaOH) solution and R enhances the compressive strength and decreases water absorption of geopolymer concrete.

1. Introduction

Ordinary Portland cement (OPC) is the world's most commonly used building material after water. However, cement manufacturing emits a huge quantity of carbon dioxide (CO_2) into the atmosphere, contributing considerably to greenhouse gas emissions. Every ton of OPC produced emits one ton of CO_2 into the environment [1]. As a result, sustainable alternatives to traditional cement must be developed, exploiting the cementitious capabilities of industrial by-products such as fly ash and powdered, granulated blast furnace slag, as well as natural materials like Kaolin [2,4]. On the other hand, the quantity and availability of class F fly ash (FA) and ground granulated blast furnace slag (GGBS) throughout the globe opens up the possibility of using these by-products as a partial substitute or performance enhancer for OPC. Davidovits used the term"geo-polymer" to describe a ceramic-like alternative cementitious material. Geopolymer technology is one of the newer solutions for reducing the usage of Portland cement in concrete. Geopolymers are green materials that don't produce greenhouse gases during polymerization. Combining a pozzolanic chemical or an aluminosilicate source material with strongly alkaline solutions may create a geopolymer [5]. Cement may be replaced by materials high in silica and alumina, such as fly ash and powdered, granulated blast furnace slag [6,7]. Fly ash, metakaolin, and GGBS react with alkaline solutions to make a cementitious material that produces no CO2 and improves the mechanical and durability of geopolymer concrete.

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Palomo et al. [8] investigated geopolymer concrete made with class-F fly ash. They utilized four different solutions with a mass ratio of around 0.25 to 0.30 of alkaline activator to fly ash. The molar ratio of SiO_2/K_2O or SiO_2/Na_2O solution was around 0.63-1.23. Compressive strength was determined after 24 hours of curing at 65oC, i.e., more than 60 MPa for the mixture, including sodium hydroxide and sodium silicate activators.

Xu, H., and van Deventer [9] researched and concluded that the geopolymer reaction requires a mass ratio of alkali solution to alumina-silicate of roughly 0.33. After 72 hours of curing at 35^{o}C, the highest compressive strength attained was 19 MPa.

Van Jaarsveld et al.[10] did studies employ a 0.39 mass ratio of alkali? The material utilized was 57% fly ash and 15% kaolin. 3.5 percent sodium silicate, 20% water, and 4% sodium or KOH were used to make the alkaline solution. Compressive strength of 75 MPa was obtained.

Hardjito and Rangan [11] investigated a geopolymer concrete composition. The sodium hydroxide (NaOH) concentration ranged between 8M and 16M. The mass ratio of sodium silicate to sodium hydroxide ranged between 0.4 and 2.5. Currently, the mass ratio of alkaline activator to fly ash is roughly 35%. To summarize, the increased molarity of NaOH results in the increased strength of compressive geopolymer concrete. When the mass Ratio of Na_2SiO_3 to NaOH is increased, the compressive strength of the geopolymer concrete increases. The compressive strength of geopolymer concrete was 67 MPa after 24 hours of curing at 600C.

Januarti Jaya Ekaputri et al. [12] investigated the mechanical properties of Jawa Power Paiton fly ash-based geopolymer concrete. The variables employed were the molarity of the activator solution and the Ratio of sodium silicate (Na_2SiO_3) to (NaOH). The best compressive strength was found at 10 M with a sodium silicate to sodium hydroxide ratio of 1.5. The strength of compressive attained was 48.59 Mpa.

Tabassum et al. [13] investigated the impact of sodium hydroxide solution concentration on geopolymer concrete mixture. NaOH concentration had a substantial influence on improving the qualities, with the optimal concentration of NaOH of 12 M giving improved strength properties of geopolymer concrete [14]. By 28 days, the highest compressive strength was 40.21 MPa.

Djobo et al. [14] discovered that the geopolymer system comprises C-S-H gels, (N, C)-A–S–H gels, C–(N)–A–S–H gels, and N–(C)–A–S–H gels depending on the Si, Al, Ca, and Na contents. The gels C-(N)-A-S-H and N-(C)-A-S-H correspond to gels with low Na and Ca concentrations, respectively, while N, C)-A-S-H is a hybrid gel with a chemical composition that is a combination of the C-(N)-A-S-H and N-(C)-A-S-H gels. N, C)-A-S-H is a hybrid gel with a chemical. As a result, GGBS-based GPC has better mechanical qualities than fly ash-based GPC.

Alkaline solutions, including NaOH and Na_2SiO_3, are acceptable alkaline activators for synthesizing GPC. Any alteration in the quantities of the weight of binders, the molarity of the NaOH solution, the Ratio of Na_2SiO_3/NaOH solution, or the curing temperature, Ratio of SIO_2/Al_2O_3, size of aggregate, the concentration of NaOH, Ratio of alkali solution /binder, water /solid Ratio and extra water will impact the compressive strength of the concrete [15, 17]. Previous research indicated that the desired compressive strength could be obtained using a NaOH solution containing M and a Na_2SiO_3/NaOH ratio of 2.5 [18,19]. Curing is also critical for achieving enough strength. Numerous studies have reported that the compressive strength of fly ash-based GPC specimens cured in an oven was greater than the compressive strength of ambient-cured specimens [20]. SiO_2 and Al_2O_3 in fly ash react with an alkaline solution during the polymerization process, forming the cementitious material. It was discovered that partial substitution of fly ash with GGBS effectively avoided oven curing conditions and increased compressive strength. Geopolymers derived from fly ash need an outer energy source in the form of heat curing to initiate the polymerization process. This may be a disadvantage for expanding the process to an industrial scale, while GGBS-based geopolymers do not need external energy and achieve adequate strength with ambient curing [19-21]. Due to the absence of a standard technique for creating needed strength fly ash and GGBS-based geopolymer concrete, an effort was made to establish a procedure for making GPC with goal strengths ranging from 20 to 60 MPa for outdoor curing using low molarity NaOH.

This work aimed to collect experimental data to evaluate and investigate the effects of molarity of alkaline activator solution (AAS) and different percentages of source material (different Ratio of R) on strength and water absorption by incorporation of ternary and binary binder. This binder is mixed according to the requirements for fresh and hardening properties of geopolymer concrete.

2. Materials and Methods

2.1 Metakaolin

Domestic Iraqi Kaolin clay from Al- Anbar Governorate (Dewekhla region) was used to make metakaolin in west Iraq. Initially, the Kaolin with an effective diameter of about1193nm was calcined in a furnace for one hour at temperatures of 750°C to obtain the optimum metakaolin. The burned metakaolin was cooled for 24 hours at room temperature, conforming to ASTM C618. According to X-Ray Fluorescence (XRF), the percentage of oxides and the source material's physical properties are shown in Table 1 and 2, respectively.

Table 1: The content of oxide in materials used

Series	SiO_2 (%)	Al_2O_3	Fe_2O_3	CaO	MgO	Others
Fly ash	61.21	27.02	4.423	0.00272	0.2938	7.0504
Metakaolin	57.04	39.96	1.806	0.5936	0.2142	0.3862
GGBS	37.2	10.31	0.9223	39.37	6.149	45.41

Table 2: Physical properties of materials used

No.	Test conducted	Fly ash	Metakaolin	GGBS
1	Effective diameter(nm)	1687.1	1610.3	278.1
2	Specific Gravity (Kg/m^3)	2.12	2.66	2.98
3	loss on ignition, corrected for oxidation of sulfide values %	0.68	6.12	0-2
4	Specific surface area (m^2/kg)	3052	4547	5800-6100
5	SO_3 %	0.129	0.24	1.55
6	Color	light – dark gray	off-white	light gray
7	Effective diameter(nm)	1687.1	1610.3	278.1

The X-ray diffraction (XRD) technique has been commonly used to analyze the mineralogical compositions of source materials used to manufacture geopolymer concrete, such as metakaolin, fly ash, and slag. Typically, this test is achieved by comparing d-spacings with standard reference patterns.

From Figure 1, the XRD examination of metakaolin burnt at 750 °C reveals the three highest peaks (8 and 7) obtained at (2θ), which are approximately 26.7810, 12.4672, and 25.1636 with intensity100,82and 78, respectively. Therefore, it may be inferred from the image below that metakaolin generally forms both amorphous and tiny crystalline phases, such as quartz, in its composition.

The observation was obtained that the amorphous phase achieves its highest approximately when 2θ is between (20-27), concluding that the amorphous phase exhibits feature similar to those of quartz crystal because it is near the ulterior peak of quartz crystal value. Also, another observation was obtained when comparing the two figures for Kaolin and metakaolin. All intensity of the peaks was reduced. Therefore, it can be inferred from the XRD results, leading to the conclusion that there is a reduction in uniformity of crystalline structure of atoms due to being subjected to non-uniform deformation during burnt [22].

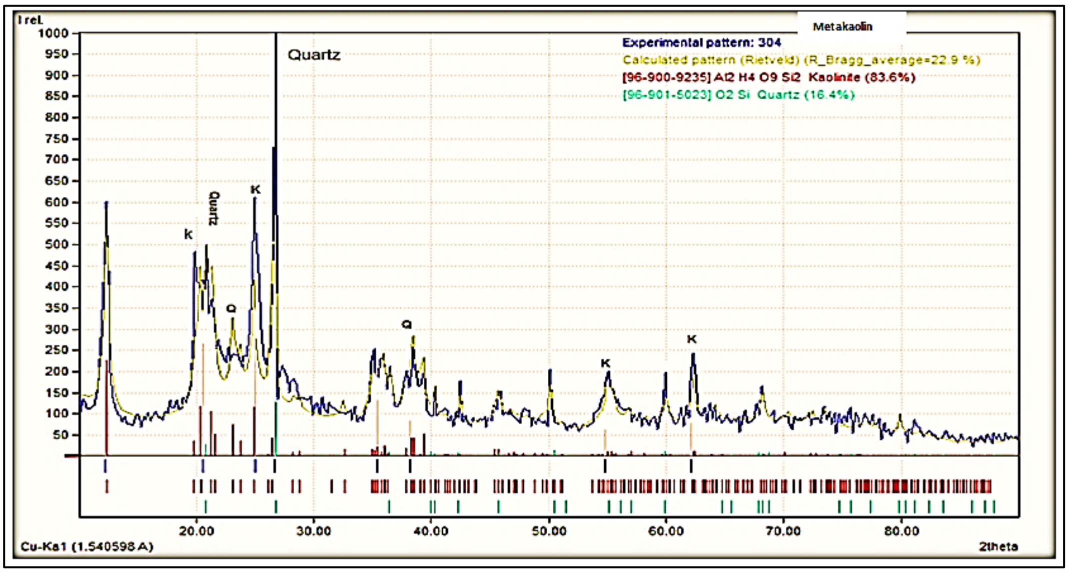

Figure 1: The X-Ray Diffraction (XRD) for Metakaolin burn at 750 °C

2.2 Ground Granulated Blast Furnace Slag (GGBS)

Turkish Ground granulated blast furnace slag (GGBS) was utilized in this study, generated during pig iron manufacturing. Based on X-Ray Fluorescence (XRF) results, the percentage of oxides is explained in Table 1. Also, the physical properties of slag used in this investigation are explained in Table 2.

From Figure 2, the XRD examination of GGB reveals that the peak at 30 corresponds to the highest concentration obtained at (2θ). Therefore, it may be inferred from the image that slag generally forms both amorphous and tiny crystalline phases, such as quartz, in its composition. Furthermore, the observation was made that the amorphous phase achieves its uttermost approximately when 2θ is between (20-27), leading to the conclusion that the amorphous phase exhibits characteristics similar to those of quartz crystal. After all, it is adducted to the uttermost peak of quartz crystal value, where the peak of quartz is presented as an inert or low reactive component in the sample crystal because the solubility of these components is very [22]. Also, it is hypothesized that GGBS's increased amorphous content may contribute to its much higher observed compressive strength. However, it is critical to note that the calcium concentration of GGBS seems more relevant in terms of strength development.

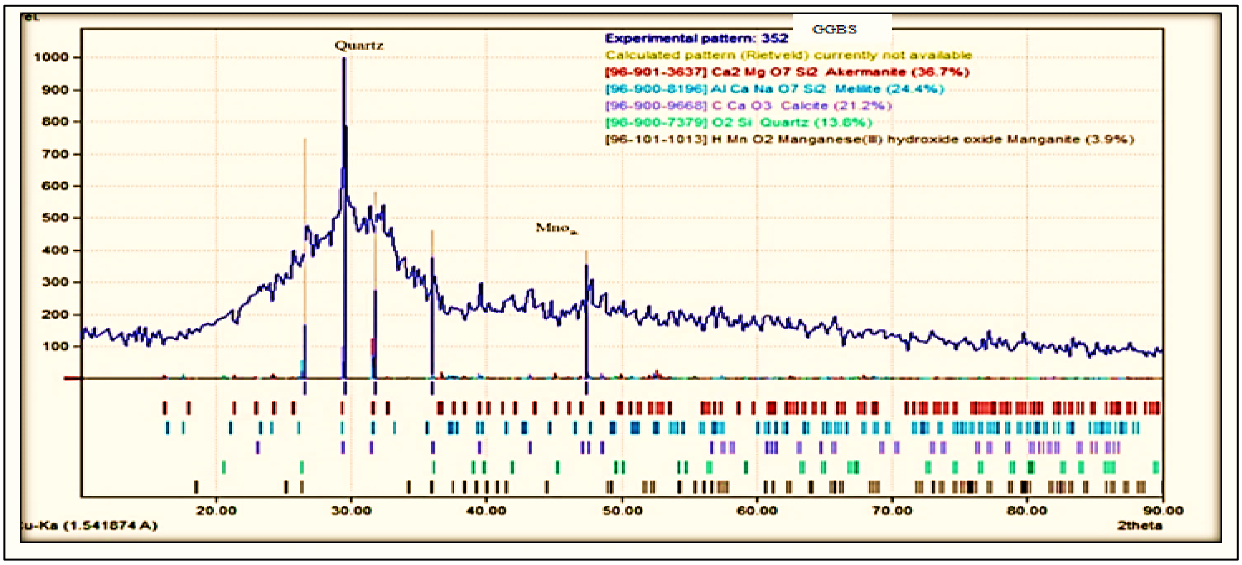

Figure 2: The X-Ray Diffraction (XRD) for GGBS

2.3 Fly Ash

A fine and glassy powder Hard coal fly ash from the Iskenderun power station was utilized, conforming with the requirements of BS3892 Part1 and BSEN450. Based on the X-Ray Fluorescence (XRF) test results, the percentage of oxides is explained in Table 1. Also, the physical properties of fly ash used in this investigation are explained in Table 2.

From Figure 3, the XRD test identified the crystalline phase of fly ash. It was found that a large part of ash was amorphous in accordance with [28]. Also, the figure reveals the three highest peaks (4, 2, and 10) obtained at (2θ), which are approximately 26.6445, 20.8667, and 40.8663 with intensity100,23and 12, respectively. Therefore, it may be inferred from the image that fly-ash generally shaped both amorphous and tiny crystalline phases, such as quartz, mullite, hematite, and amorphous phases, such as alumina.

Furthermore, the obtained observation was that the amorphous phase achieves its highest approximately when 2θ is between (20-30). This concludes that the amorphous phase exhibits feature similar to those of quartz crystal. This is because it is near the maximum peak value of quartz crystal). The peak of quartz is presented as an inert or low reactive component in the sample (crystalline phase) because the solubility of these components is very low due to it is high crystalline [22].

Since the glass and crystalline content in total mass must be determined, a high proportion of reactive Si and Al in amorphous phases in ash is a primary need for polymerization. Increased concentrations of the glassy component result in a faster reaction. In comparison, a larger crystalline concentration resulted in a significant decrease in Al-Si decline reactivity. Additionally, the reduced lime content of fly ash may inhibit the reaction, extending the setting time [1].

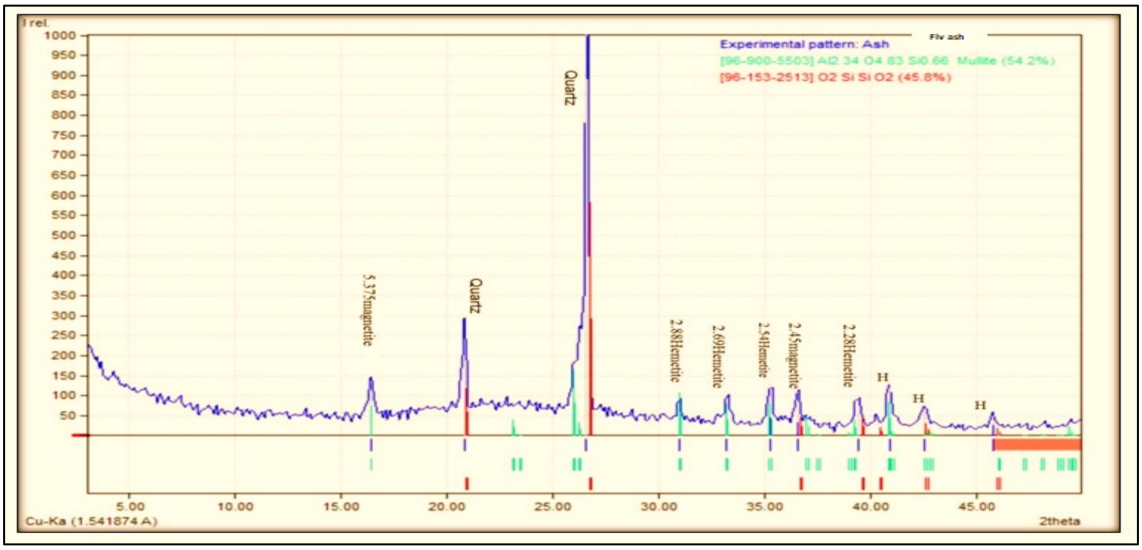

Figure 3: The X-Ray Diffraction (XRD) for fly ash

On the other hand, the hydration Modulus, HM = ($CaO + MgO + Al_2O_3$)/SiO_2 of kaolinite, metakaolin, fly ash, and GGBS were 0.706,0.714, 0.446, and 1.5, respectively. The GGBS has a high Hydration Modulus, which improves the polymerization process after barn Chang [23]. [($CaO+MgO$)/($Al_2O_3+SiO_2$)] kaolinite, metakaolin, fly ash, and GGBS had a basicity coefficient of 0.029, 0.0083, 0.0033, and 0.95 correspondingly (Bakharev 2000) [24]. The basicity of a material is defined as the ratio of its total basic components to its total acidic components. The reactivity of a material increases with its basicity, which is further enhanced by the addition of free-CaO. The initial strength of a concrete is determined by the binder employed. The more basic the fly ash and slag are, the greater the initial strength of compressive and hydraulic activity they have when activated with alkaline chemicals.

2.4 Coarse Aggregate

A crushed coarse aggregate of nominal maximum size 14 mm from the Al-Niba'ee region was used, confirming Iraqi specification No.45/1984 [25]. The chemical and physical properties of coarse aggregates are shown in Table 3.

Table 3: Chemical and physical properties of coarse aggregate

Physical Properties	Test Results	Limits of the Iraqi specification No.45/1984
Specific gravity (S.G.)	2.64	—
Absorption %	0.7	—
Sulfate content (SO3) %	0.096	≤ 0.1
Clay %	0 %	≤ 1.0
unit weight	1400	—

2.5 Fine Aggregate

Al-Ukhaider sand was utilized in this study, confirming Iraqi specification No.45/1984 [25]. The results show that sand gradation lies in the zone (2). The fine aggregate's physical and chemical properties are shown in Table 4.

Table 4: Physical properties of fine aggregate

Physical properties	Test result	Limit of Iraqi specification No.45/1984
SSD Specific gravity	2.60	Limit of Iraqi specification No.45/1984
Sulfate content	0.19	-
Absorption	0.75%	specification requirements ≤ 0.5% (max)
Fineness modulus	2.544	-

2.6 Used Chemicals to Manufacture Geopolymer Concrete

Sulphonated naphthalene formaldehyde-based superplasticizer (Flocretes SP33) was utilized to improve the workability of fresh geopolymer concrete, which has a specific gravity of about 1.17-1.21 at 25°C [26]. In addition, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) in pellet form (99.5 purity) were utilized as alkaline activators. The alkaline liquids were prepared using portable water. Table 5 explains the Physical properties of sodium silicate, NaOH, and superplasticizer.

Table 5: Physical properties of sodium silicate NaOH and superplasticizer used

NaOH *	Na_2SiO_3	Superplasticizer	Physical Properties
Specific gravity (S. G.)	1.17-1.21 at 25°C	1.534 – 1.551	1.21
SiO_2 %	0.7	32.00 – 33.00	32.00 – 33.00
Form	Dark brown liquids	Hazy	weight
Na_2O %	0 %	13.10 – 13.70	13.10 – 13.70

*The purity of NaOH used = 99.5.

3. Geopolymer Concrete Mixes Design and Mix Proportion

A competent code of practice and established technique are available for conventional concrete mix design. However, geopolymer concrete lacks a formal code of practice and no established technique. As a result, we must additionally develop a Geopolymer concrete mix based on the standard concrete mix design. Numerous mix proportioning techniques are utilized to achieve the necessary strength of concrete, depending on the kind of work, the materials' types, availability, and qualities, the field circumstances, and the workability and durability requirements. Rangan [27] offered a process for the mix design of geopolymer concrete using fly ash, while Anuradha et al. [28] gave amended recommendations for the mix design of geopolymer concrete utilizing the Indian standard code.

Anyway, most of proportioning is done according to trials. In this study, several trials of experimental mixes that performed satisfactorily in workability and strength were considered candidate mixes. After several trial mixes, the reference Geopolymer concrete mix was determined to perform a minimum compressive strength of 30 to 40 MPa for 28 days to obtain good compressive strength and evaluate the influence of R on strength development in compression flexure and splitting tensile strength for Geopolymer concrete. Several parameters chosen as a constant value for all mixtures to satisfy these performance objectives were described as follows. Tables 6 and 7 describe mixed proportion and percentage of replacement by fly ash and R of GPC.

Table 6: Description of mix design required for all mixes

Series	Description
1	The alkaline activator used included: a) The NaOH prills/1000 L (kg) = 26.88. for molarity 10 and 22.33for molarity 8 . b) Sodium Silicate solution (kg) =121.875. For two molarity. c) Water in NaOH solution/1000 L (kg) = 53.494. for molarity 10 and 58.22for molarity 8.
2	The ratio of Na_2SiO_3 /NaOH solution by mass = 1.5.
3	The ratio of Water /binder by mass = 0.3597.
4	The ratio of activator solution to binder by mass = 0.55.
5	The weight of Extra Water of 15.47 (kg/m3) for mixes with molarity 8 and 20.05(kg/m3) for mixes with molarity 10.
6	The Fine aggregate (kg/m^3) = 700.
7	Total Coarse Aggregate (kg/m^3) = 1100 where: a) Size 5-10mm (kg/m^3) = 660. b) Size 10-14mm (kg/m^3) = 440 .
8	Total source material by mass (kg/m^3) mass =404

*Sources material included (fly ash, metakaolin, and GGBS).

Table 7: The substituted mix proportion of fly ash-based Geopolymer concrete by GGBSand metakaolin

Mix Designation	FA, content (%)	MK, content (%)	GGBS, content (%)	R
Mix 1	70	30	0	2.01
Mix 2	100	0	0	2.26
Mix 3	66	10	24	2.50
Mix 4	64	0	36	2.74

The curing technique for Geopolymer concrete specimens was the same for all other mixtures. First, the steel molds were placed in the oven promptly after casting and kept there for 24 hours at the proper temperature. Next, the concrete specimens are removed from the mold and placed back into the electric oven for another 48 hours. After that, it is removed from the oven and placed in a laboratory at room temperature until the testing is completed as required. The curing temperatures vary depending on the type of source material employed, with fly ash-based Geopolymer concrete being cured at 60°C [29]. Figure (4a and b) shows the cured and dried specimens in the oven.


(a) (b)

Figure 4: (a and b) specimen cured with oven at 60 ˚C for 48 hours and then the ambient temperature

4. Results and Discussion

4.1 Fresh Properties of Geopolymer Concrete

4.1.1 Influence of different molarity and sio_2 /Al_2O_3 ratio on the slump test

The findings of fresh properties of different GPC mixes with the different R and NaOH concentration ratios are illustrated in the Table 8. Due to the stiffness of GPC consistency under fresh conditions, compaction is difficult to produce in GPC. Therefore, GPC is only practical when superplasticizers such as Naphthalene-based superplasticizers are added to the requisite dosage. In this experiment, the starting dosage was about 2.95% by mass of binder (sources material content). The conventional slump test was used to determine the workability of GPC. The slump values (shown in Table 8) were performed immediately after mixing according to ASTM C143-2004. The increase in slump occurs when the amount of fly ash (but not the amount of superplasticizer) is increased because the spherical fly ash granules boost the workability and lead to a higher slump %. Also, when GGBS was replaced with fly ash, it resulted in a higher slump value because of its GGBS particle angular shape.

When metakaolin was added to the mix or replaced by other material sources, a slump value was lower because of metakaolin's plate-like shape particle, which needed more water or superplasticizers to get the required workability. This might be explained by the increased surface area of slag and metakaolin particles. On the other hand, the finesses of slag are very high; it needs more water or superplasticizers to obtain the required workability.

In general, the slag and metakaolin mixes performed worse in fresh characteristics than the fly ash mix. GGBS and metakaolin absorbed the surplus water in the geopolymer system because of their larger surface area than fly ash. As a result, GPC concrete mixes with increasing percentages of slag and metakaolin were found to be more cohesive and sticky. In contrast, the fluidity and flowability of different combinations decreased as the quantity of slag and metakaolin rose. These effects of GGBS and metakaolin on GPC fresh characteristics were comparable to those of Andri [30]. He found that the workability of newly produced low-calcium fly ash-based geopolymer concrete reduced as the quantity of high-surface-area-particle-size source material increased.

Table 8: Details of slump test vs. superplasticizer quantity

Mix Designation	**R**	**Blended finesse (m^2/kg)**	**Molarity**	**Superplasticizer % of binder**	**Slump (mm)**
Mix1	2.012	3501	8	7.5	89
			10	7	95
Mix2	2.265	3052	8	3.72	120
			10	2.85	125
Mix3	2.5	3897	8	7	114
			10	6.8	105
Mix4	2.74	4095	8	4.25	105
			10	4.5	110

4.2 Hard Properties of Geopolymer Concrete

4.2.1 Mechanical strength

4.2.1.1 Compressive strength

It is critical to analyze the influence of mixed ingredients on the strength of GPC as a function of age. The mix design process entails choosing appropriate materials for a specific concrete and establishing relative proportions to achieve the desired strength and workability. For example, it is widely established that raising the alkaline content of concrete enhances its strength to a certain amount. Additionally, the strength of GPC is dependent on the binder percentage and the proportion of fine and coarse aggregate used in the mix.

The compressive strength of geopolymer concrete was evaluated at various NaOH solution concentrations and various R ratios.

Table 9 and Figures 5 to 7 show that the compressive strength increases as the age of concrete increases, increase of R ratio, and increase of NaOH concentration.

Compressive strength improves consistently over the course of seven days for all mixtures. Compressive strength increases gradually as cure time increases.

After 7, 28, and 360 days of aging, the findings indicate that mix 1 has a lower compressive strength than mixes 2, 3, and 4. For example, for the age of 7 days, the percentage of increase in strength for mixes 2, 3, and 4 achieved 90, 107, and 112.67%, respectively, for m=10 when compared to mix1, while the percentage of increase in compressive strength of mixes 2, 3 and 4 achieved of 120, 191, and 195% respectively, for m=8 when compared to mix1.

For the age of 28 days, the percentage of increase in strength for mixes 2, 3, and 4 achieved 100.44, 102.64, and 124.22%, respectively, for m=10 when compared to mix1, while the percentage of increase in compressive strength of mixes 2, 3 and 4 achieved of 73.57, 173.21, and 202.14% respectively, for m=8 when compared to mix1.

For the age of 360 days, the percentage of increase in strength for mixes 2, 3, and 4 achieved 75.19, 90.38, and 115.38%, respectively, for m=10 compared to mix1. While the percentage of increase in compressive strength of mixes 2, 3, and 4 achieved of 164.16, 177.97, and 199.57%, respectively, for m=8 when compared to mix1.

Consequently, the ultimate strength of compressive geopolymer concrete was attained at 28 days with a NaOH content of 10 molarity rather than 8 molarity. Also, the GGBS blended GPC mixes achieved greater compressive strengths at an early stage of curing. The findings indicate that increasing the proportion of GGBS in the GPC mixes resulted in enhanced strength of compressive values. This is due to the formation of rich Calcium Silicate Hydrate gel [31]. Moreover, the high silica content in GGBS results in a higher Si/Al ratio. Hence a stronger geopolymeric matrix is formed due to producing more sodium aluminosilicate zeolitic phases, and both zeolitic Geopolymers originate from $NaO-Al_2O_3-SiO_2-H_2O$ gel phases. Still, the respective reaction pathways are governed by available/reactiveSiO_2 and Al_2O_3 in the reaction environment [32]. Therefore, the results obtained in this category correspond to the previous findings in this concern [33,35].

Table 9: Compressive strength with various mixes of Geopolymer concrete

Mix Designation	R	Molarity	Compressive strength (MPa) Age (days)			28-day Splitting tensile strength, MPa 28 days	28-day Flexural strength, Mpa 28 days
			7days	8days	360days		
Mix1	2.012	8	10	14	14.1	0.85	0.97
		10	21.3	22.7	26	1.85	2.44
Mix2	2.265	8	22	24.3	37.3	2.15	3.5
		10	40.5	45.5	45.55	2.5	3.5
Mix3	2.5	8	29.1	38.25	39.2	2.57	3.8
		10	44.1	46	49.5	2.9	4.07
Mix4	2.74	8	29.5	42.3	42.3	2.63	3.9
		10	45.3	50.9	56	3.13	4.25

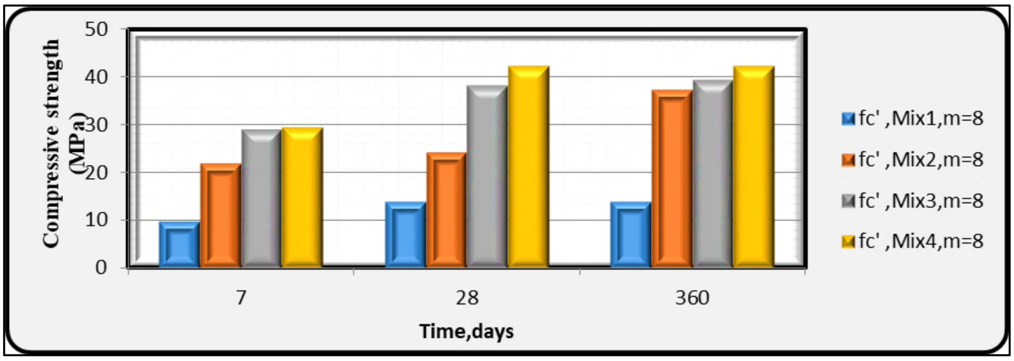

Figure 5: Relationship between compressive strength (MPa) and different times for different R ratios with molarity 8

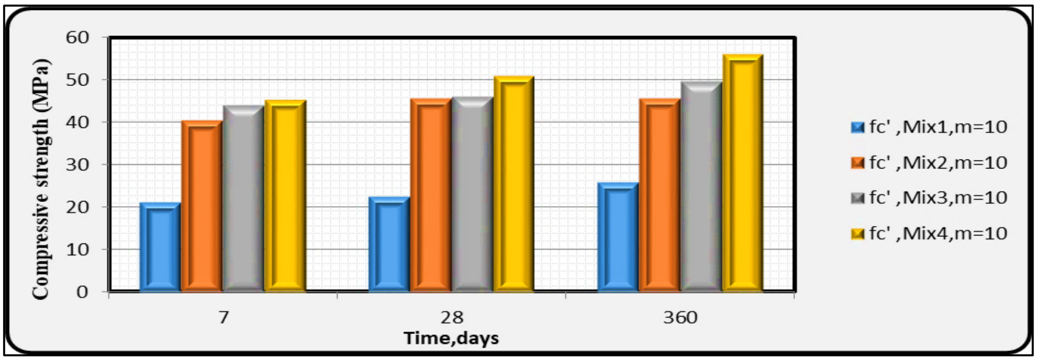

Figure 6: Relationship between compressive strength (MPa) and different times for various R ratios with molarity 10

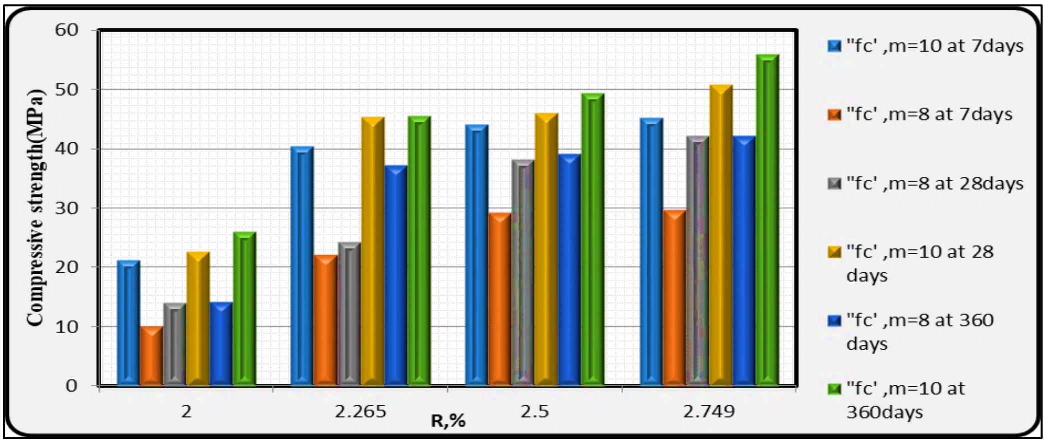

Figure 7: Relationship between compressive strength (MPa) and different R Ratios on various days

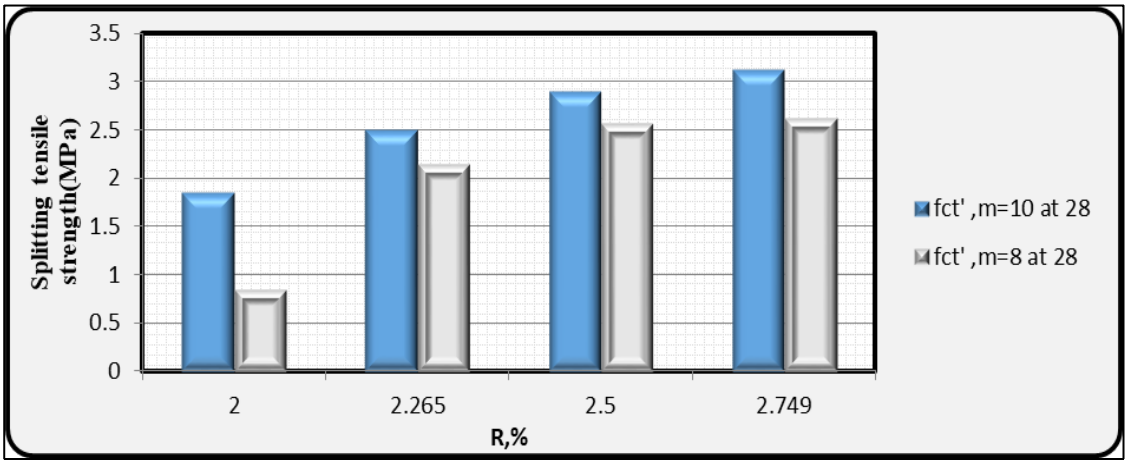

Figure 8: Relationship between tensile strength (MPa) of geopolymer concrete and different percentages of R for two molarities at 28 days

4.3 Tensile Strength

As with ordinary Portland cement concrete, the splitting tensile strength of geopolymer concrete is just a fraction of the compressive strength. The variance in the outcomes is shown in Table 10 and graphically in figure 8. The splitting tensile strength of specimens with various proportions is determined at the age of 28, and a graph (8) between R and splitting tensile strength is drawn. The specimen demonstrates an increase in tensile strength when 36% GGBS is substituted. The results suggest that mix 1 has a lower splitting tensile strength than mixes 2,3, and 4.

For the age of 28 days, the percentage of increase in strength for mixes 2, 3, and 4 achieved 35.135, 56.75, and 69.18%, respectively, for m=10 when compared to mix1. While the percentage of increase in splitting tensile strength of mixes 2, 3, and 4 achieved of 152.82, 202.35, and 209.41%, respectively, for m=8 when compared to mix1.

GPC concrete has a substantially lower tensile strength than it does compressive strength. This is due to the cracks propagating as a result of tensile stresses. Microcreaking, especially in the interfacial transition zone, governs concrete failure under tension [36].

4.4 Flexural Strength

Table 9 and Figure 9 summarise the flexural strength of geopolymer concrete with a % replacement. It was found that the strength of these samples rose as the aging duration increased, which is a trend that is comparable to the compressive strength finding. The findings indicate that mix 1 has a lower flexure strength than mixes 2,3 and 4. For the age of 28 days, the percentage of increase in strength for mixes 2, 3, and 4 achieved 43.44, 66.8, and 74.18%, respectively, for m=10 when compared to mix1. While the percentage of increase in flexural strength of mixes 2, 3, and 4 achieved 260.82, 291.75, and 303%, respectively, for m=8 when compared to mix1.

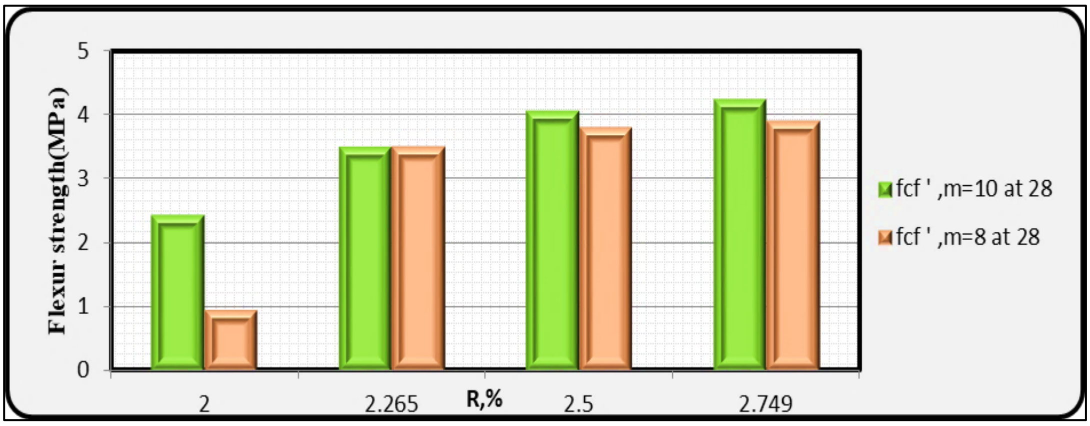

Figure 9: Relationship between flexure strength(MPa) of geopolymer concrete and different percentages of R for two molarities at 28 days

4.5 Ultrasonic Pulse Velocity Test and Dynamic Modulus Elasticity

The Ultrasonic device is used to measure the waves' speed for Geopolymer specimens in accordance with ASTM C597-02[37].

The ultrasonic pulse velocity (UPV) measurement values for all mixes at different curing ages are presented in Table10 and graphically in Figure10. The test results show that the velocity and dynamic modulus elasticity for all mixed specimens increase with NaOH and R concentration.

Table 10: Ultrasonic pulse velocity and dynamic modulus elasticity for different types of GPC

Name of mix	R	molarity	Density(Kg/m3)	Pulse velocity (m/sec)	Ed(GPa)
Mix1	2.012	8m	2164	3672	33.8924
		10m	2260	3717	38.1944
Mix2	2.265	8m	2218	4081	40.8817
		10m	2227.6	4286	44.5802
Mix3	2.5	8m	2218	4089	42.2261
		10m	2236.2	4166	44.3311
Mix4	2.74	8m	2274	4149	45.1193
		10m	2317	4201	46.369

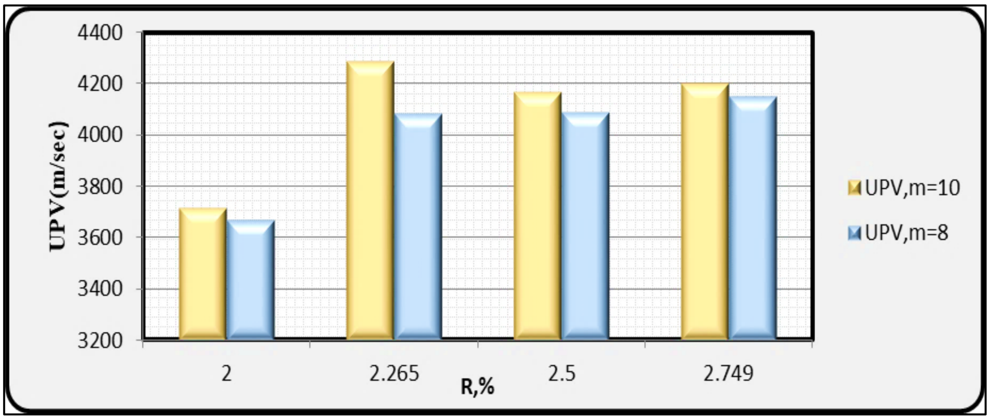

Figure 10: Development of UPV for all mixes

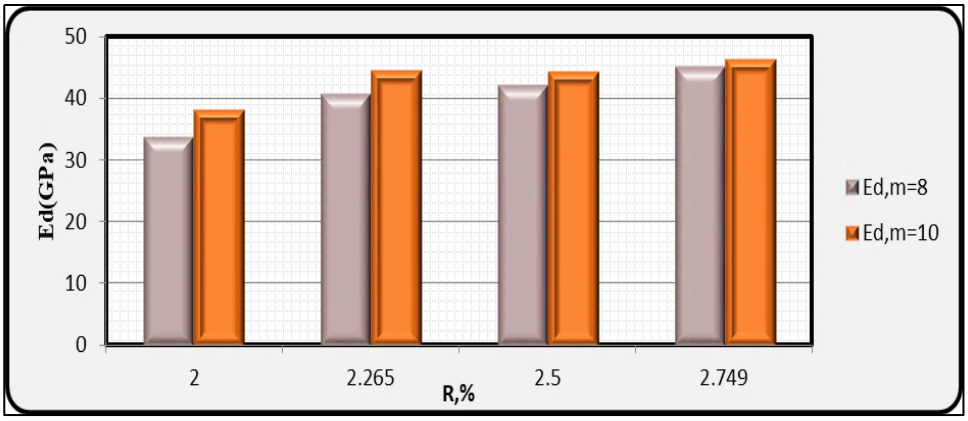

Figure 11: Relationship between dynamic modulus (GPa) of geopolymer concrete and different percentages of R for two molarities at 28 days

Also, the reading rate was collected to compute the dynamic modulus of elasticity according to equation (1), as indicated in Table 10.

By ultrasonic test, dynamic modulus elasticity may be estimated by the equation (1) below:

$$E=\rho V^2(1-2\mu)(1+\mu)/(1-\mu) \quad (1)$$

Where:E: dynamic modulus of elasticity.ρ: density .V: velocity of the pulse. μ: Poisson's Ratio.

Geopolymer concrete has a Poisson's Ratio that ranges between (0.16 and 0.19[38,39], and therefore the term $((1-2\mu)(1+\mu))/(1-\mu)$ ranges between (0.91 and 0.94, which is considered as (0.92) in all computations.

Figure 11 illustrates the relationship between the dynamic modulus (GPa) of geopolymer concrete and different percentages of R for two molarities at 28 days. It concluded from this figure that the Ed increase with the increase in R ratio and concentration of NaOH due to an increase in density and UPV of the specimen.

4.6 The Penetration Depth of Water under Pressure (Permeability)

The permeability test of geopolymer concrete was achieved according to (BS EN 12390-8:2009) [40] by measuring the penetration depth (mm) of Water into GPC samples under pressure for all mixes. This test aims to determine how easily water flows into the geopolymer material. Eight concrete cube specimens with dimensions of 150 mm are cast, the result of two duplicate samples for each mix as shown in Table 11.

Table 11: Details of absorption under the pressure test

Name of mix	R	Molarity	depth of penetration in (mm)
Mix1	2.012	8	150
		10	130
Mix2	2.265	8	135
		10	45
Mix3	2.5	8	110
		10	75
Mix4	2.74	8	38
		10	42

The geopolymer concrete sample is cured in an oven for 48 hr and then at the ambient temperature until 28 days and then connected to a particular instrument and subjected to water at a pressure of 500 bar. The sample is split perpendicularly to the face when the water under pressure is applied. The maximum penetration depth is recorded after identifying and tracing the water profile. Although there is no physical justification, concrete is considered impermeable based on deductions from experiments and tests if penetration depth is less than 20-30 mm [41].

A fast polymerization rate generally results in a pore-filled geopolymer matrix with poor permeability [42]. Based on the data obtained, it is known that the water absorption under pressure tends to decrease as the SiO_2/Al_2O_3 ratio increases. Water absorption is lowest in geopolymers with a SiO_2/Al_2O_3 ratio of 2.75.

In such circumstances, the polymerization reaction is inhibited, resulting in a slight geopolymer gel formation and a high porosity of the geopolymer matrix. Furthermore, under pressure, water absorption by Geopolymer decreases as the Si/Al ratio increases. This study found that raising the Si/Al ratio affects the formation of a homogenous microstructure, which reduces water absorption. In other words, the greater polymerization process was hindered, resulting in a less homogenous geopolymer structure.

5. Conclusions

The findings of the current investigation are as follows:

1) It has been shown via extensive experimental tests on fly ash, metakaolin, and GGBS-based GPC that the substitution of GGBS by fly ash will increase the strength of compressive concrete, regardless of the curing method used. Contrary the substitution of metakaolin with fly ash will reduce the compressive strength of concrete.
2) The reference Geopolymer concrete mix was determined to perform a minimum compressive strength of 30 to 40 MPa for 28 days to obtain good structural compressive strength and to evaluate the influence of R on strength development in compression, flexure, and splitting tensile strength for Geopolymer concrete.
3) The strength of Geopolymer concrete rises with an increase in GGBS content up to 36 %. Hence it is advised to use as much GGBS as possible in GPC mixtures (up to 100 %).
4) Compared to lower molarity, increasing the molarity of NaOH as an alkaline activator seems to increase compressive strength.
5) A blend with 36% GGBS and 64% fly ash seems to have a higher compressive strength than other mixtures. This might be because the alkaline interaction between GGBS particles and the calcium in fly ash is enhanced.
6) The test result shows that increasing the Ratio of SiO_2/Al_2O_3 up to 2.75 can increase compressive strength, splitting tensile strength, and nd flexural strength while simultaneously reducing water absorption.
7) The workability of geopolymer concrete decreases with the increase of fly ash content of the mixture. In addition, it decreases as the concentration of NaOH in the alkaline activator solution increases.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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