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Research Article

Experimental and microstructural investigation of geopolymer concrete

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ABSTRACT

Ordinary Portland cement is the main binding agent in ordinary concrete and contributes to about 5 to 7 percent of all carbon dioxide emitted in the world. Also, the dumping of fly ash as a dangerous waste by thermal plants cause serious environmental problems. Geopolymer concrete has become a sustainable building block, using industrial byproducts, and has a promising future as an alternative of concrete. Several parameters were considered in order to determine the performance of Geopolymer concrete with some of them being water-to-binder ratio and the region of sand distribution under constant parameters to maximize the compressive strength. Geopolymer Concrete specimens were subjected to durability tests including rapid chloride penetration test, and acid resistance test. Also, microstructural studies were carried out through the X-ray diffraction. This analysis also gave analytical information regarding the phase and elemental structure of the geopolymer concrete as well as the elements of cesium, sulfur, nitrogen, carbon and cobalt. The findings can be added to the comprehensive interpretation of the material properties and performance of geopolymer concrete that can be used as an environmentally-friendly substitute in the construction industry. This paper has been rigorously researched on the phase composition of Geopolymer concrete material by X-ray diffraction test and the durability aspect by rapid chloride penetration test by use of 3-cells Rapid Chloride Penetration Test apparatus and comparison of experimental results with the conventional concrete.

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INTRODUCTION

According to the survey results, fly ash production is almost 780 million tons each year on the world-wide level [1]. The utilization rates however show that only some half of this entire size, which is estimated as being between 17 and 20 percent, is in fact utilized. India annually produces over 220 million tons of fly ash [2]. Geopolymer concrete (GPC) presents numerous environmental advantages [3]. GPC has the potential to save CO_2 emissions by up to 80% when compared to concrete made with regular Portland cement [4]. Approximately 70% of India's electricity generation relies on coal, resulting in significant fly ash production, which is often disposed of in landfills and ash ponds [5]. However, when combined with proper chemicals, the fly

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ash that can be used as a substitute of Portland cement in composite to create geopolymer concrete [6]. The manufacturing of cement contributes to almost 8% of the world's CO_2 emissions [7]. The ratios of alkaline accelerator to industrial waste fly ash and Na_2SiO_3/NaOH are essential to obtaining the necessary compressive strength of GPC [8]. The greatest degree of compression was identified by examining several ratios of these components; the highest values were obtained when the amount of alkaline activator to industrial waste fly ash ratio was among 0.5 and 0.30 [9]. Fine aggregate meeting grading zone-I specifications exhibits greater flow compared to zone-II, III, and IV, attributed to its inclusion of coarser sand particles. The grading of fine aggregate and water quantity have minimal effects on compressive strength in GPC with a consistent W-to-B ratio of 0.35 [10]. Larger coarse aggregates correspond to decreased compressive strength in GPC, likely due to increased micro cracks [11]. This suggests that changes in pore structure resulting from coarse aggregate size variations significantly influence strength development [12]. The duration and temperature of curing greatly influence the strength of hardened GPC. Remarkably, curing at room temperature results in substantial strength enhancements compared to curing at elevated temperatures [13]. Fly ash-based GPC represents a concrete variant which utilizes fly ash, a residue from coal combustion, as a primary constituent in lieu of traditional Portland cement. This eco-friendly alternative has garnered attention for its potential in curbing carbon emissions linked with cement production and for its capacity to repurpose industrial waste materials. The process of the formation of a geopolymer binder, which will hold the aggregates together, is largely dependent on the chemical reaction between fly ash and an activating solution, in the production of FGC (Fly ash Based geopolymer concrete). This is normally a solution made of alkali metal hydroxides or silicates which are used to catalyze the geopolymerization process.

Type F fly ash, which is rich in calcium and alumina and silica is widely used in the manufacture of FGC (Fly ash Based Geopolymer concrete). Combined with a silica fume activating solution, which consists of well dispersed particles of amorphous silica, FGC shows the possibility of achieving very high early compressive strength [14]. Experimental findings of geopolymer concrete mix between grade M20 to M40, using the proposed mix design method, show that the mixes have satisfactory workability and compressive strength [15]. Particularly, M30 grade is chosen to be cast with Type F fly ash being favored over Type C because it is more effective [16]. Grade P100 fly ash among the possibilities is selected between P10-100. The ideal conditions of curing the fly ash based mixes include high temperatures of above 30 °C to a maximum of 50 °C of at least 24 hours long [17]. A mix design approach to engineered dune sand concrete (DSC) based on close packing and mortar film thickness theories reached 50 MPa compressive and excellent workability, and both the results of performance and the variations in performance were associated with the difference in mortar film thickness. The DSC was characterized by the weak cement intensity and good eco-efficiency that indicates the success of the method in the balancing of mechanical, environmental, and economic forces [18]. One study examined self-compacting fiber-reinforced mortars (SCFs) with recycled brick powder (RBP) and two classes of cement and discovered that RBP enhances the durability and polypropylene fibers enhance the durability and strength. Flexural and compressive strength, porosity, and water absorbency of 32 SCFRM mixes were experimented upon [19]. One study evaluated the influence of different ratios of EPDMGR (ethylene propylene diene monomer granulated rubber) and test zones on the mechanical and durability characteristics of self-compacting concrete/mortars and that the ability to enhance flexural strength (up to 5% EPDMGR) was associated with the height of the porosity, whereas the compressive strength varied based on the location. The statistical analysis depicted that the independent variables affected properties, i.e., properties in dependence of EPDMGR ratio and element zone [20]. The authors assessed the effects of using 2-4 wt% silica fume (micro-silica and nano-silica) in place of white-Portland cement on the compressive and flexural strengths, and freeze-thaw resistance of the self-compacting mortars, discovering that these were improved. Nano silica significantly decreased the micro-cracks and pore size which increased the strength and durability due to its greater pozzolanic activity [21]. The research addresses the application of the waste tire aggregate (WTA), as an alternative to sand and cement in self-compacting concrete in an effort to achieve sustainability and resource savings. Findings suggest that concrete WTA does not lose its proper performance in terms of the different mechanical and durability tests, which can justify the use in civil engineering [22]. Evaluation of glass sand use in place of micro aggregates in micro-concrete with the contents of binders between 570 and 658 kg/m 3 is the subject of the study. Findings reveal that glass sand can be used to improve mechanical properties and durability, which in this case will justify its use in structural repair [23]. The paper investigates the effects of adding binder content to self-compacting concrete (SCC) on their fresh and hardened characteristics and found out that an increase in binder content enhances compressive strength whereas it also affects shrinkage and creep. It lays stress on the need to do more research on these effects [24]. The article discusses sustainable building through the use of pulverized fuel ash (FA) to produce lightweight aggregates and self-compacting concrete with a demonstration that FA can be used to form the environmentally-friendly material, which has the proper strength to serve as the structural material. The research mentions the opportunity of FA to minimize the environmental impact of construction [25]. The experiment compared fly ash/slag geopolymer concrete that incorporated different proportions of recycles of coarse aggregate (RCA) and it results that the highest proportion of 20% combined with 0.3 per cent of steel fiber, the results are an environmentally friendly type of concrete that had enough mechanical strength. Nevertheless, an increase in the level of RCA leads to a significant decrease in compressive, tensile, and flexural strength [26]. The fly ash (by product of coal power plants) generates cenospheres which add value to the concrete by making it stronger, less dense and more absorptive. Such properties render it useful in the development of lightweight composite materials [27]. Researchers are looking into using eco-friendly construction material such as sticky rice pulp, Samanea Saman pods, human hair as a way of improving the properties of concrete and minimizing environmental impact on the environment. These natural resources have the potential of providing sustainable cost effective building solutions [28]. This paper explores the impact of Nano Silica (n-SiO_2) and Nano Zinc Oxide (n-ZnO) in concrete and it is established that n- SiO_2 with 0.75 percent replacement is very instrumental in enhancing both compressive and tensile strength. Nano Silica is also better in durability with n-ZnO giving moderate benefits with n-SiO2 being better according to Ultrasonic Pulse Velocity (UPV) tests [29]. This paper examines the usage of copper slag and fly ash as a substitute of sand and cement in concrete and the best mixture of fly ash and copper slag is 5 percent fly ash and 20 percent copper slag which has better strength and durability. Also, incorporation of 5 percent nano silica and 5 percent micro silica also increases flexural strength [30]. The paper examines the application of cenospheres in place of cement in concrete revealing that the density decreased by up to 4.80 per cent and that compressive, flexural, and tensile strength increased with the inclusion of calcium lactate. Maximal changes in mechanical properties are obtained at replacement of cenosphere at 10 percent [31]. The article investigates the application of organic additives such as jaggery and sticky rice pulp in concrete to improve quality without increasing the amount of cement and CO_2 emissions and therefore provides a more ecological alternative to chemical additives. Such additives will not have adverse environmental impacts as they can enhance concrete properties [32]. The type of microstructural properties of geopolymer concrete examined in this paper through an XRD (X-ray diffraction) test is an advanced technique. XRD enables the researcher to study the crystalline arrangement of the material, and to determine the existing phases which gives technical evidence of its composition and probable performance possibilities.

MATERIALS AND METHODS

The materials that were used to make geopolymer concrete specimens of fly ash comprise of low-calcium fly ash as a binding binding substance, aggregates, alkaline solutions, water, and mixtures of them. In this study, low-calcium fly ash, with a particle fineness measured through the Blane apparatus as shown in Figure 1a, was purchased from the Thermal Power Plant located in the village of Eklahare Nashik in Maharashtra. The fly ash had a P100 of 638 m^2/kg, as demonstrated in Figure 1b. A successful mixture of geopolymer concrete was accomplished using low-calcium fly ash, with silicon and aluminum oxides comprising around 80% of the total material and maintaining a Si-to-Al ratio of roughly 2. The iron oxide content typically varies from 10% to 20% by weight, while the calcium oxide content is under 5% by weight. The loss on ignition, an indicator of the carbon content, reveals a minimal concentration of approximately 2% in the fly ash.

The Nashik laboratory analyzed the particle size of the fly ash using Blane's apparatus through an air permeability

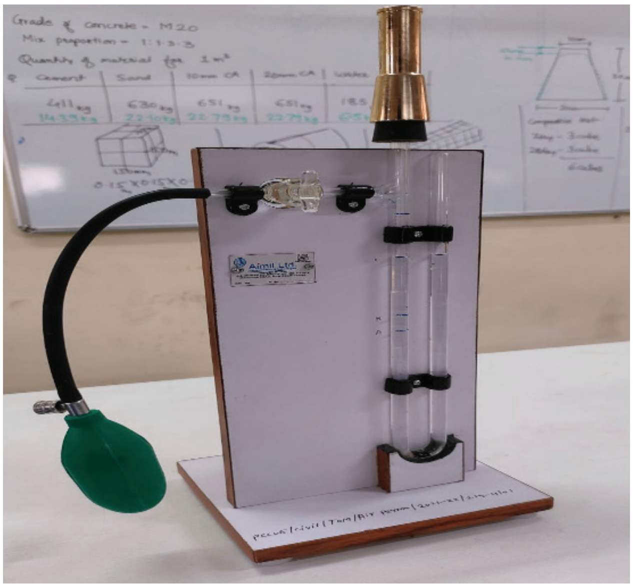


Figure 1a. Blaine's apparatus.

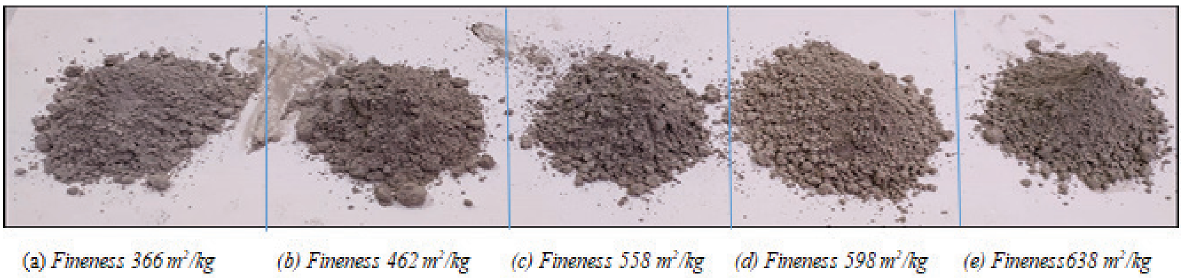


Figure 1b. Fly ash sample.

Table 1. Fly ash (chemical properties)

Sr. No.	**1**	**2**	**3**	**4**		**5**	**6**
Chemical Composition %	**$SiO_2 + Fe_2O_3 + Al_2O_3$**	**SiO_2**	**MgO**	**SO_3**	**Na_2O**	**Loss of ignition**	**Total chloride**
Sample-I	92.44	60	2	0.9	0.58	1.1	0.03
Sample-II	92.8	59.6	2	0.9	0.57	1.09	0.033
Sample-III	91	59	2	0.9	0.65	0.94	0.027
Sample-IV	93.19	58.7	1.9	0.9	0.49	1.3	0.027
Sample-V	93.42	58.3	1.7	0.7	0.56	0.8	0.024
Specifications as per IS 3812:1981	70	35	5	3	1.5	5	0.05

Table 2. Fly ash (physical properties)

Sr. No.	**1**	**2**	**3**	**4**	**5**	**6**
Physical properties of FA	**Fly ash Color**	**Residue retained on 45µm%**	**Specific surface area (Blaine), m2/kg**	**Specific gravity**	**Moisture content %**	**Autoclave expansion %**
Sample I	Light grey	15.38	366	2.25	0.25	0.029
Sample-II	Light grey	9.8	462	2.25	0.31	0.029
Sample-III	Light grey	6.72	558	2.25	0.34	0.028
Sample-IV	Grayish White	5.14	598	2.3	0.28	0.024
Sample-V	Grayish White	0	638	2.3	0.27	0.024
Specifications as per IS 3812:1981	---	34 (maximum)	320 (minimum)	---	2 (maximum)	0.8

test. The residue on the 45µm IS sieve was 0% for a sample fineness of 638 m^2/kg fly ash as shown in Figure 1b. The chemical and physical properties of fly ash are mentioned in table number 1 and table number 2 respectively. Coarse aggregates with maximum sizes of 20 mm and 12.5 mm were crushed and tested in accordance with IS: 383-1970[33]. Fine aggregates were divided into ZoneI, ZoneII, ZoneIII, and ZoneIV as shown in Table 3 along with its properties, each with corresponding fineness moduli. Crushed sand, with a fineness modulus of 3.2 and a specific gravity of 2.72, was primarily used as the fine aggregate. The fine aggregate was utilized in a dry state after sieving to a size smaller than 4.75 mm. various tests on specific gravity, water absorption, moisture content, and fineness modulus were conducted on both coarse and fine aggregates. Total 72 numbers of cubes were casted for different mix design to test on 7 days, 14 days and 28 days as shown in Figure 1c. Also M30 grade of concrete is while designing the mix design of geopolymer concrete.

Figure 1c. Ambient temperature curing system (36 cubes).

Table 3. Properties: Details of fine aggregate

Properties	Coarse aggregates	Fine aggregates			
		ZoneI	ZoneII	ZoneIII	ZoneIV
Specific Gravity	2.81	2.68	2.72	2.63	2.59
% Water absorption	0.45%	0.7%	1.5%	2.1 %	2.3%
% Moisture content	0.15%	0.79%	0.66%	0.50 %	0.43
Fineness Modulus	7.02	3.2	3	2.7	2.3

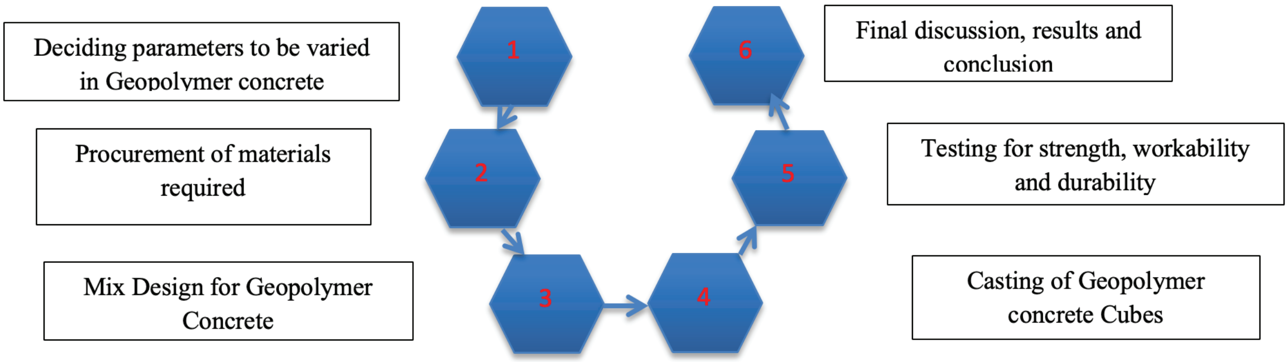


Figure 2. Methodology of experimentation.

In geopolymer concrete, agents like NaOH and Na_2SiO_3 are utilized as activators. It's advisable to mix these alkaline solutions at least 30 minutes before use. Moreover, a super-plasticizer can be added to enhance workability.

The experiment comprised establishing the water-to-binder ratio and sand zone parameters by casting cubes. Following parameter fixation, durability assessments were carried out, including the Rapid Chloride Penetration Test (RCPT) and acid attack evaluation. Subsequently, an experimental inquiry employing X-ray Diffraction (XRD) analysis which is conducted to thoroughly examine the properties of GPC. This comprehensive study encompasses the mix design, durability assessment, and microstructural investigation of GPC (Fig. 2).

The ratio of water to binder was systematically changed over a range with the increments of 0.3, 0.35, 0.4, 0.45 and 0.5. It was seen that a ratio of 0.3 gave satisfactory compressive strength to geopolymer concrete specimens. The increased strength was however accompanied by reduced workability therefore making the mixture less malleable and harder to work with. On the other hand, when the ratio was 0.5, the geopolymer concrete had an increased workability, which meant that it could be manipulated easily when the concrete was placed, but this was achieved at the expense of compressive strength. After weighing between these aspects, the best choice was 0.35 which gave a balance between sufficient compressive strength and workability of geopolymer concrete mix, as it appears in Table 4. Table 5

Table 4. Mix design chart for adjusting the fly ash to alkaline ratios

Fineness of fly ash (m^2./kg)	W-to-GPC ratio (kg/m^3)	Na_2Sio_3 solution (kg/m^3)	Coarse aggregate (kg/m^3)	Fly ash quantity (kg/m^3)	Sand (kg/m^3)	Extra water (kg/m^3)	NaOH (kg/m^3)	Total water (kg/m^3)
638.00	0.30	67.50	1340.39	450.00	690.51	34.10	67.50	108.35
	0.35	52.50	1323.04		681.56	50.40	52.50	108.35
	0.40	61.25	1284.86		661.90	40.74	61.25	108.35
	0.45	70.00	1246.68		642.23	31.08	70.00	108.35
	0.50	78.75	1208.51		622.57	21.43	78.75	108.35

Table 5. Mix design: For ZoneI, ZoneII, ZoneIII, ZoneIV

Fly ash fineness	Coarse aggregate	Fineness aggrgate zones	Extra water in Ltrs.	Fly ash quantity	NaOH	Total water in Ltrs.	Na_2SiO_3	Sand
638.00	1312.93	ZoneI	22.61	450.00	78.75	109.23	78.75	706.96
	1353.92	ZoneII	21.73		78.75	108.35	78.75	666.86
	1374.58	ZoneIII	21.07		78.75	107.69	78.75	646.86
	1394.94	ZoneIV	20.85		78.75	107.47	78.75	626.71

All dimensions are in kg/m^3, except fly ash fineness is in m^2/kg.

also lists also mix design of various zones of natural sand by maintaining fineness and quantity of fly ash constant.

In the cube casting process, it was done on fine aggregates of Zones I, II, III and IV, where the aim was to establish the best type of fine aggregate in order to maximize the compressive strength of geopolymer concrete (GPC). It was performed by first combining all solid ingredients before gradually adding sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. By adding water and the solutions of NaOH and Na_2SiO_3 to the dry mixture, the liquid phase of the mixture was obtained. Further four minutes thickening was then done to obtain homogenization of the mixture of geopolymers. The freshly blended fly ash-based GPC was of a greyish color and its workability was determined by the slump cone test according to the provision of IS: 1199-1959 [34]. Different proportions of mixing were cast which took into consideration the different ratios of fly ash-alkaline solution and the incorporation of fine aggregates of different zones. After casting, specimens were initially left to cure in an oven at 90 °C at 24 hours. The cubes were then demolded and allowed to cure under ambient room temperature (around 29 °C) 7, 14 and 28 days after the heat curing process. The curing process provided an opportunity to assess mechanical properties of the geopolymer concrete subjected to various curing time and an effect of aggregate zones.

RESULTS AND DISCUSSION

Effect of Water-to-Binder Ratio on Workability

As part of experimental investigations, the influence of altering ratios of water to geopolymer binder on the flexibility and compressive power of Geopolymer Concrete (GPC) has been investigated. This ratio is a percentage of the total water over the geopolymer binder, which is the fly ash, sodium silicate and sodium hydroxide solutions. Total water contains both intrinsic water in the mixture and any other water added to the mixture. Five ratios were researched namely 0.50, 0.45, 0.40, 0.35 and 0.30 and keeping a constant concentration of geopolymer binder at 450 Kg/m^3. Conventionally, when the water to cement ratio of a typical cement concrete is lowered, the compressive strength decreases. Nevertheless, in GPC, flexibility has been observed to be enhanced through reduction in the ratio of water to geopolymer binder.

It has been observed that as the ratio between water and geopolymer binder increases keeping all other factors constant, fluidity increases. Particularly, flow is built up in small steps. When the ratio attains 0.50, the slurry has the characteristics of flowing like self-compacting concrete. Further examination at ratios of 0.35 and 0.30 indicates that the mixture creeps over a long period of time yet it remains coherent and viscous. However, when the ratio is increased to 0.30, the mixture becomes sturdier to mix because of increased viscosity. Under ratios of 0.35, the details of its influence on compressive strength and malleability surface are provided. Although a lower water to geopolymer binder ratio of less than 0.35 might theoretically increase compressive strength, it might equally decrease malleability making the mixture harder to manipulate and place. Therefore, it is inevitable that construction intentions need to achieve a balance between the optimal compressive strength and sufficient malleability. More importantly, a careful mixing and correct curing are essential at lower water to geopolymer binder ratios to realize the potential of geopolymerization and attain the required properties of strength. Moreover, the characteristics peculiar to fly ash, sodium silicate, and sodium hydroxide solution in the geopolymer binder could also contribute to the reaction to changes in the water-to-geopolymer binder ratio.

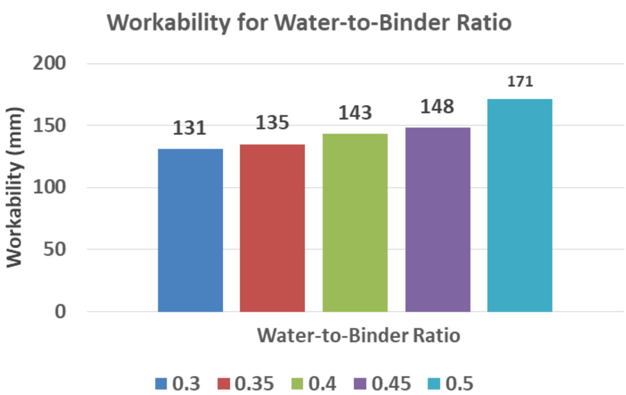


Figure 3. Effect of water-to-binder ratio on workability.

More research is justified to look into the implications of even lesser water-to-geopolymer binder ratios. The increase in the ratio of water to binder predisposes increased malleability to geopolymer concrete. The additional water provides additional lubrication between particles, which makes the mixture more liquid and easier to place just like traditional concrete. A progressive increase in the ratio of water to binder between 0.30 and 0.50 has shifted the malleability significantly; this can be indicated by the change of 131 mm into 171 mm (Fig. 3).

Effect of Water-to-Binder Ratio on Compressive Strength

The study involved the exploration of the effects of changing the water to binder ratio of geopolymer, all other experimental parameters remaining unchanged, on compressive potency of the geopolymer concrete. Results reveal a pattern that can be observed: the higher the ratio of water to geopolymer binder, the lower the compressive strength of geopolymer concrete. This is a function of the trend followed by the traditional cement concrete whereby the typical increase in water content normally results in a decrease in compressive strength. It implies that compressive strength of geopolymer concrete is inversely proportional to water to geopolymer binder ratio. This finding underscores the significant effect of water on the viscosity of the mixture, which is most probably, due to the role of water in reducing the viscosity. Figure 4 elaborates on compressive strength on 7^{th}, 14^{th}, and 28^{th} days, which unveils different results of different curing treatment procedures. In fact, with geopolymer concrete (GPC), the correlation between the water-to-binder (W/B) ratio and compressive strength is usually inverse, like the ordinary Portland cement concrete. The compressive strength of geopolymer concrete is normally reduced with an increase in the W/B ratio. The reason is that, the higher the W/B ratio, the more porous the structures and the less dense the matrix is, hence lowering the strength. It is worth noting that the compressive strength is highest at a water to binder ratio of 0.30. However, it is crucial to admit that water-to-geopolymer binder ratio of 0.30 provides a more compact mixture, which makes it more difficult to handle. In order to strike a balance between the mechanical strength and workability, water-to-geopolymer binder (W/B) ratio of 0.35 is offered. This ratio is supposed to enable sufficient workability at the mix and pouring stage and a dense microstructure, which is necessary in maximizing the compressive strength and the durability of the geopolymer concrete. The images used explain the correlation between the ratio of water and binder and the compressive strength of geopolymer concrete. Although the compressive strength of the water-to-binder ratio of 0.30 is the highest according to the data, the paste manueverability is limited by its high viscosity. On the other hand, a water to binder ratio of 0.5 provides superior plasticity but low compressive strength. Considering all these the ratio of water and geopolymer binder is selected as 0.35 in order to have a balance between the malleability and compressive strength.

It is evident that the strength of geopolymer concrete is highly affected by the water to binder ratio. Increase in water to binder ratio can result in reduction in compressive strength. Excessive water content in the amalgam may end up in a porous overall concrete structure, and this is very harmful to the entire strength of the binding matrix. A higher W/B ratio might contribute to a weaker Interfacial Transition Zone (ITZ) between the aggregate particles and the geopolymer binder. This circumstance can lead to reduced bond strength and consequently, diminished compressive strength. The compressive strength diminishes as the water-to-binder ratio escalates. Specifically, at a higher W/B ratio of 0.50, the compressive strength is lower (36.45 MPa) in contrast to the mix with a W/B ratio of 0.30 (46.64 MPa) (Fig. 4).

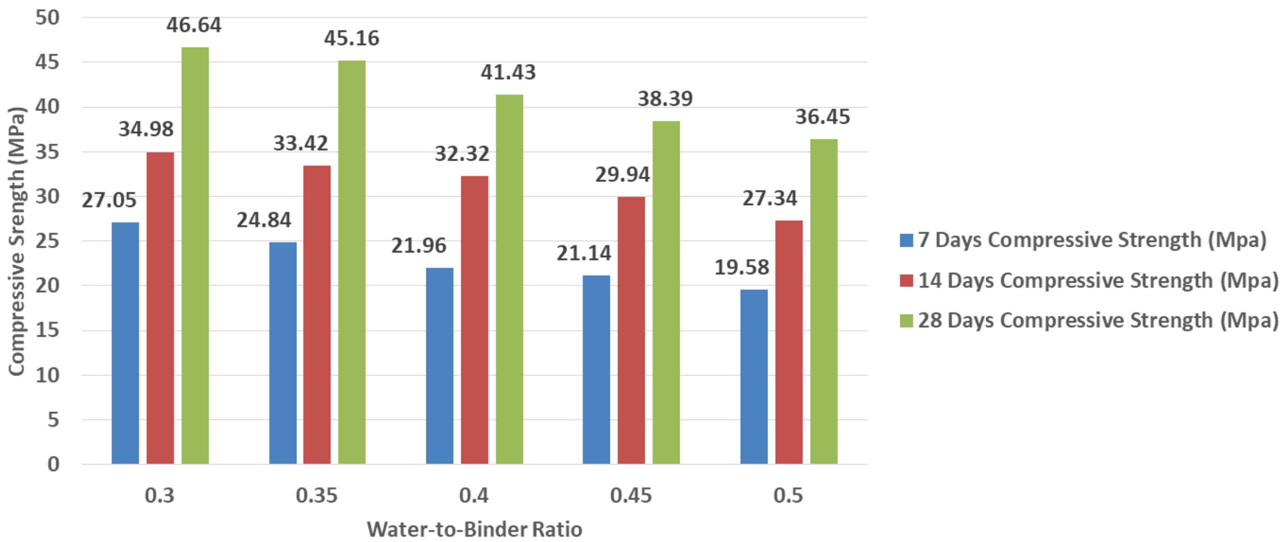


Figure 4. Effect of water to binder ratio on compressive strength of GPC.

Water-to-Geopolymer Binder Ratio vs Compressive Strength Mathematical Model

Step 1: Define Variables

x: Water-to-binder ratio (independent variable)

y: Compressive strength at different ages (dependent variable)

The compressive strengths for 7 days, 14 days, and 28 days can each be modeled as a function of the water-to-binder ratio.

Step 2: Observed Data Points

For 7 days (blue):

W/B = 0.30, y = 27.05 MPa

W/B = 0.35, y = 24.84 MPa

W/B = 0.40, y = 21.96 MPa

W/B = 0.45, y = 21.14 MPa

W/B = 0.50, y = 19.58 MPa

For 14 days (red):

W/B = 0.30, y = 34.98 MPa

W/B = 0.35, y = 33.42 MPa

W/B = 0.40, y = 32.32 MPa

W/B = 0.45, y = 29.94 MPa

W/B = 0.50, y = 27.34 MPa

For 28 days (green):

W/B = 0.30, y = 46.64 MPa

W/B = 0.35, y = 45.16 MPa

W/B = 0.40, y = 41.43 MPa

W/B = 0.45, y = 38.39 MPa

W/B = 0.50, y = 36.45 MPa

Step 3: Select a Regression Model

Given the nonlinear nature of the data that can be fitted a polynomial regression (typically quadratic or cubic) to each set of compressive strengths. The model can be represented as:

$$y=ax^2+bx+c$$

Where x is the water-to-binder ratio and y is the compressive strength.

Step 4: Perform Regression

Now calculate the coefficients a, b and c for each curve (7, 14, and 28 days) by fitting a quadratic regression to the data.

Here are the quadratic models for compressive strength as a function of the water-to-binder (W/B) ratio for 7, 14, and 28 days:

7 Days Compressive Strength:

$$y_7=52.706x^2-114.08x+96.0$$

14 Days Compressive Strength:

$$y_{14}=31.728x^2+39.28x-96.0$$

28 Days Compressive Strength:

$$y_{28}=62.315x^2-49.043x-6.571$$

Where:

x is the water-to-binder ratio and y is the compressive strength in MPa

These models represent the relationship between the water-to-binder ratio and compressive strength for each curing age. One can use these equations to predict the compressive strength for different W/B ratios within the tested range (0.30 to 0.50)

Effect of Zoning of Fine Aggregates on Workability

The water content and fine aggregate zoning are pivotal parameters influencing the workability of geopolymer concrete. According to the slump analysis, it can be stated that fine sand classified within the grading zone IV has a better workability than others. As a result, the relationship between water content and fine sand zoning in the grading zone IV, in particular, gains top priority in achieving workable geopolymer concrete formulations. It is worth noting that the sand that belongs to zone I will have coarser properties compared to those of sands in the other zones, i.e. zone II, III, and IV. This roughness equates to a lower surface area of zone I sand compared to those of its counterparts. As a rule the smaller particles require greater quantities of water to lubricate effectively. Comparing the performance of fine aggregates obtained in zone I and II (180 mm) to the performance of fine aggregates obtained in zone III and IV (161 mm) as indicated in Figure 5, the former has a better performance because it has relatively reduced surface area. The effect of fine aggregate grading on compressive strength after 28 days of curing is illustrated on the visual representation and presented in the form of the provided figure. It is noteworthy that geopolymer concrete samples that pertain to the grading zone I, II, III and IV reflect subtle differences in compressive strength. Interestingly, though the ratio of water to geopolymer binder is held constant at 0.35, the water content and fine aggregate grading cause minimal effects on compressive strength of geopolymer concrete. It is however notable that concrete composition that incorporate sand of grading zone II exhibit greater compressive strength as compared to sand obtained elsewhere.

Effect of Zoning of Fine Aggregates on Compressive Strength of Geopolymer Concrete

The effects of the various fine aggregate grading zones on the 28-day compressive strength of geopolymer concrete

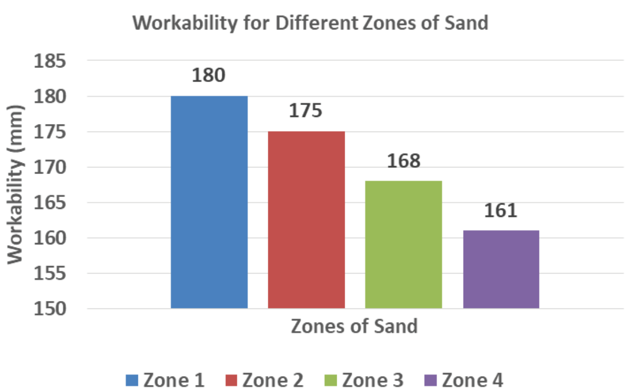


Figure 5. Effect of zoning of fine aggregates on workability.

indicate that varying grading zones may have effects on the strength of concrete. In most cases, geopolymer concrete prepared using fine aggregates obtained in different regions can exhibit different compressive strengths. As an example, concrete made using the fine aggregates of grading zone II may have a better compressive strength compared to concrete made using aggregates of other grading zones. This signifies that, choice of fine aggregate grading zones exudes much influence on the final strength properties of geopolymer concrete after a 28-day curing period. The findings reveal the presence of a regular pattern: the compressive strength is more apt to increase in accordance with the grading area of the fine aggregate. Amazingly, the highest compressive strength of 38.37 Mpa is on zone 4 in relation to the other zones.

Geopolymer Concrete (GPC) compressive strength with a standard water to binder (W/B) ratio of 0.35 is quite variable depending on grading properties of natural sand used as well as the specific dosage of water used. The sand within the grading zone IV exhibits superior compressive strength when compared to the one within zone I. This observation reveals the critical position of sand grading in dictating the strength of concrete. In addition, the amount of water in GPC is critical in the density. High water level usually results in low concrete density hence compressive strength is affected. The compressive strength of 38.37 Mpa, in this case, indicates that the GPC mix using sand in Zone IV has attained a greater level of strength compared to that which makes use of sand in Zone I as illustrated in Figure 6. The results indicate the complexity of interactions among the sand grading, water content, and the resulting compressive strength of GPC formulations.

Rapid Chlorine Penetration Test (RCPT)

Rapid Chloride Permeability Test (RCPT) is a fast method of determining the level of resistance of concrete to the entry of chloride ions. Using the technique, rapid data on the permeability of concrete to chlorides are generated, the lower the electrical conductivity, the lower the permeability and the greater resistance to chloride ingress, which implies enhanced durability. The effectiveness of the RCPT makes it to be typically used in the development of specifications and quality control. The RCPT equipment is usually made up of digital LED displays which give the voltages around the concrete specimen being studied. The test system is comprised of two diffusion chambers in which solutions of sodium hydroxide (NaOH) and sodium chloride (NaCl) are made with each solution having a concentration of 0.3 M. Concrete specimens are cast in molds with a diameter of 100 mm and a thickness of 50 mm with a constant water-binder ratio of 0.35 in the mix preparation. In the NaCl solution, 30 grams (or 3% by weight) of sodium chloride is dissolved in 1 liter of distilled water and the mixture is thoroughly stirreded to be fully dissolved. The solution is applied in the RCPT test following proper preparation. The RCPT apparatus measures the current flowing through the geopolymer concrete specimen every half hour whilst keeping the voltage constant to 59V. The table 6 shows the results of experimental data at different time periods, which develops the relation between current readings and change of temperature at various time periods, which lasts 360 minutes. Below is a little description of the crucial elements of the table 6: Time (min): This is the time in minutes elapsed throughout the experiment, and it starts at 0 and continues up to 360 minutes. C1, C2, C3 (mA): The columns are current measurements of three different cells which were

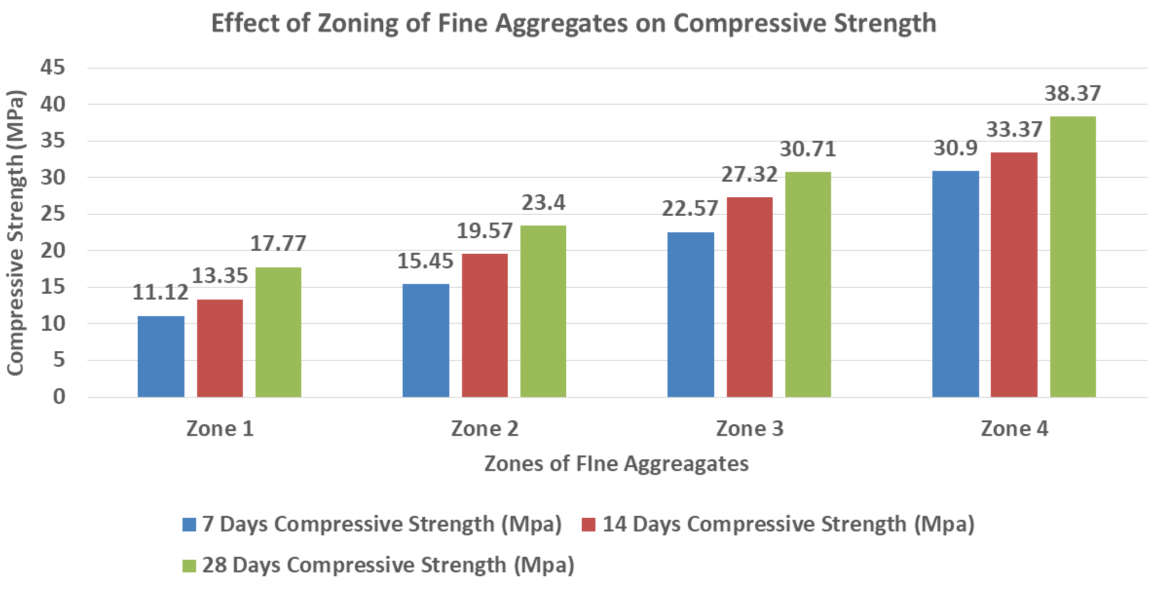


Figure 6. Effect of zoning of fine aggregates on compressive strength.

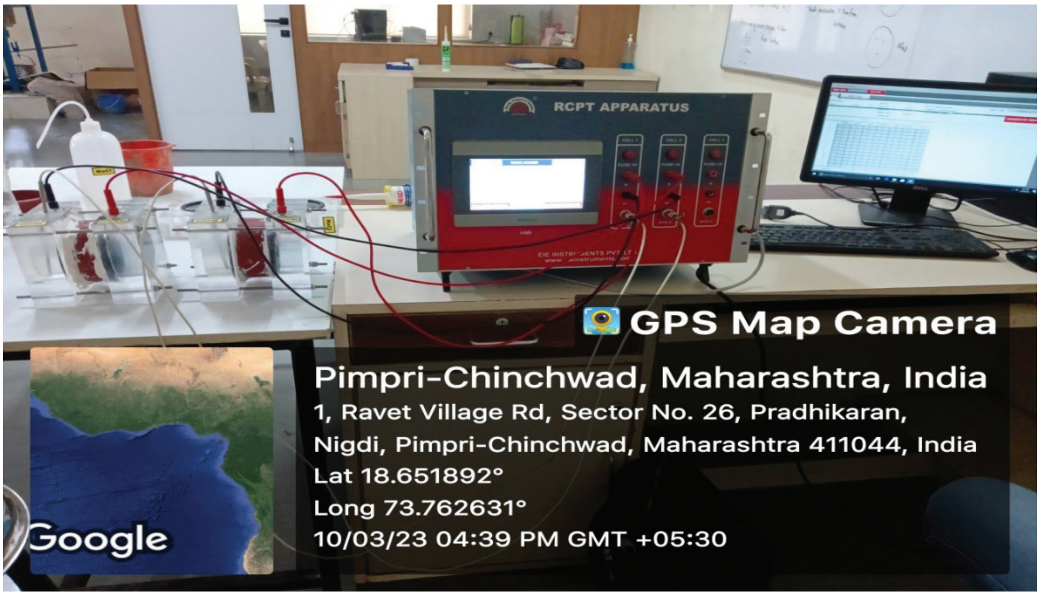


Figure 7. 3-cells RCPT apparatus.

Table 6. RCPT test readings

V	Time (min)	C1 (mA)	C2 (mA)	C3 (mA)	Temp1 °C	Temp 2 °C	Temp3 °C
59	30	79.5	76.3	79.5	86.3	83.9	76.1
59	60	89	89.4	86.2	54.6	44.4	49.3
59	90	110.3	125.2	112.5	79.3	59.5	67.8
59	120	130.4	140.4	132.9	91.8	84.3	78.7
59	150	132.8	159.9	152	101	98.7	100.6
59	180	189.1	189.9	193.4	100.6	96.8	100.4
59	210	226.3	196.4	202.4	99.6	95.2	96.6
59	240	240.9	228.9	216.2	93.5	94.5	98.5
59	270	256.6	240.9	240.1	88.4	93.1	100.2
59	300	289.8	269.6	249.4	97.6	92.6	98.3
59	330	299.2	289.5	264.4	86.3	91.8	98
59	360	309.5	316.7	310.3	85.0	90	97.5

recorded in each time interval as in Figure 7 (C1, C2, and C3) as in mill amperes (mA). Temp1, Temp2, Temp3 (°C): These are columns that show temperature values of three sensors at each time point, which were recorded in degrees Celsius (°C). Readings made are then used to determine the current through each cell after every 30 minutes. One of the popular techniques used to assess the ability of geopolymer concrete to resist chloride penetration is the analysis of its behavior depending on the current passed through the cell. This rigorous testing procedure assists in determining the concrete durability in chloride-rich environments like coastal areas or any other area that uses deicing salts, and thus helps to make decisions pertaining to materials and construction procedures and protective measures to counter the long-term structural integrity.

The chloride ion penetration is one of the crucial signatures of the maintenance of GPC since the construction of the concrete structure may be corroded and degraded by excessive chloride penetration. Based on the mean of the 03 cell samples of 3796.56 coulombs, it is evident that the average penetration of the chloride ion moderate into the Geopolymer sample was noted. The moderate chloride ion penetration indicates that the geopolymer sample exhibits a degree of resistance to chloride penetration but is not totally non-permeable.

X-Ray Diffraction Test (XRD)

X-ray diffraction (XRD) is an important method to analyze geopolymer concrete (GPC) both quantitatively and qualitatively. In this test, powder was taken out of the tested cubes. When dealing with the samples, it is imperative to make sure that they are not moist or that they are finely powdered. The powdered sample is put on a plate and inserted to the XRD machine where it is analyzed. The use of x-rays due to the high energy and short wavelength as compared to visible light is preferable in analyzing the crystal plane distance in crystalline materials. The results obtained from the XRD test are typically presented as a graph plotting intensity against the angle of refraction (2θ) as shown in Digure 8.

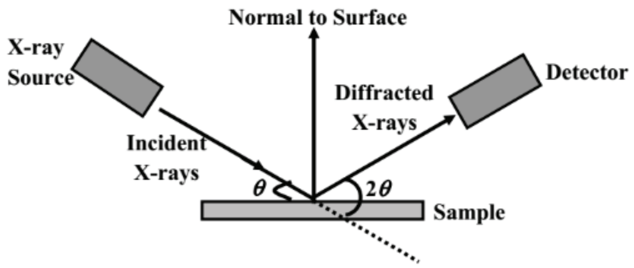


Figure 8. Schematic diagram of XRD setup.

Intensity indicates the chemical composition at specific points within the sample, while the angle of refraction represents the angle at which X-rays diffract from the sample after interaction. This graph shown in Figure 9 provides valuable information about the crystalline structure and composition of the geopolymer concrete sample.

Peak location is the maximum intensity around the hypothetical Bragg angle, and peak intensity is the magnitude of this maxima. Position of diffraction peaks is affected by variations in crystal structure. As a result, two substances with distinct crystal structures will yield various sets of XRD scan are observed.

Following the smooth graph obtained from the XRD test, the XRD patterns for GPC were displayed in Fig. 10. The primary crystalline phase identified was quartz as silicon dioxide, calcite as calcium carbonate. Sulphate phases such as mirabilite and arcanite were also detected. Portlandite in the form of calcium hydroxide at 2 thetas equal to 26.780 was present in the GPC sample. The existence of portlandite phase indicates the hardened state of the GPC which contributes to the solidification of the geopolymer concrete. Calcium hydroxide ($Ca(OH)_2$) can react with the aluminosilicate precursors in the geopolymer

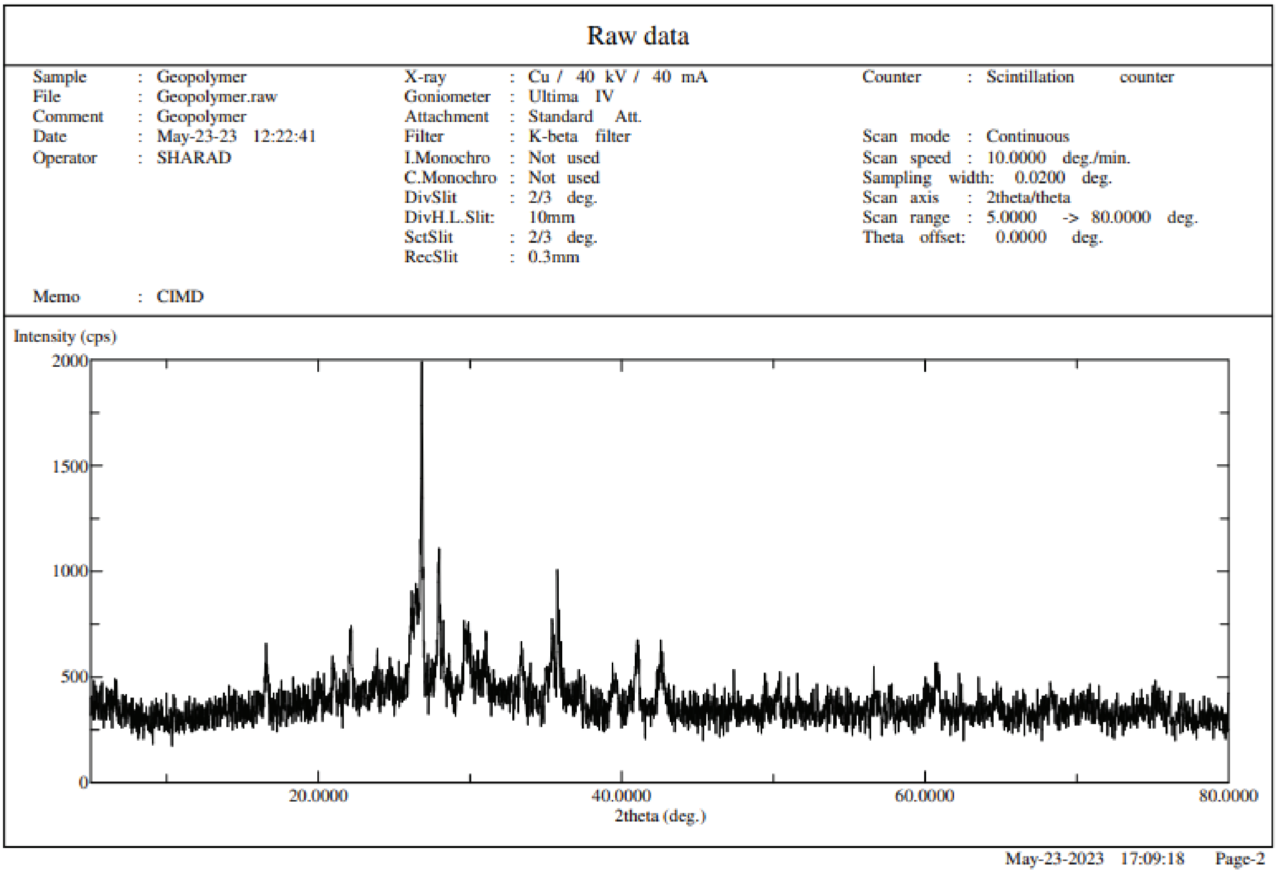
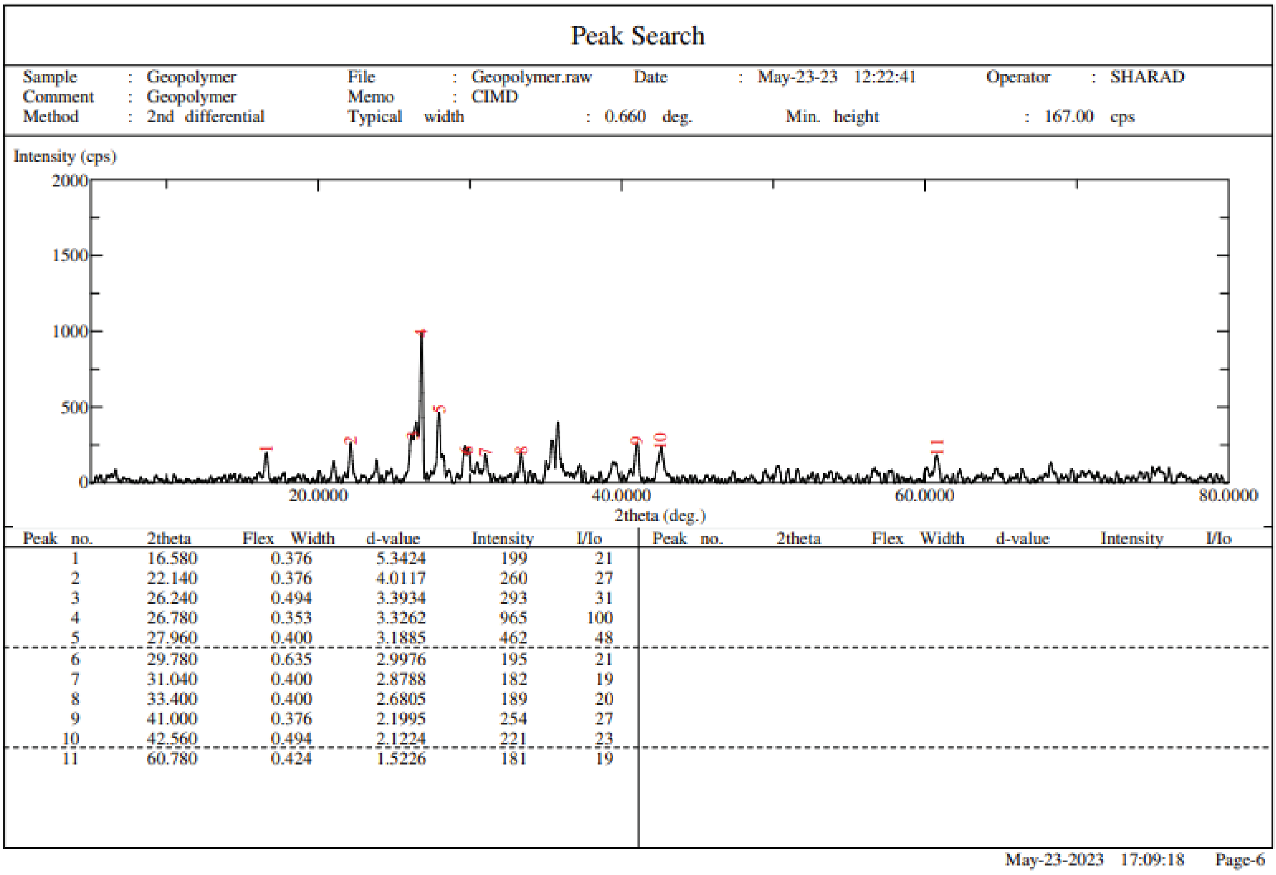


Figure 9. XRD test analysis of raw data.



Peak no.	2theta	Flex Width	d-value	Intensity	I/Io
1	16.580	0.376	5.3424	199	21
2	22.140	0.376	4.0117	260	27
3	26.240	0.494	3.3934	293	31
4	26.780	0.353	3.3262	965	100
5	27.960	0.400	3.1885	462	48
6	29.780	0.635	2.9976	195	21
7	31.040	0.400	2.8788	182	19
8	33.400	0.400	2.6805	189	20
9	41.000	0.376	2.1995	254	27
10	42.560	0.494	2.1224	221	23
11	60.780	0.424	1.5226	181	19

Figure 10. XRD test analysis of smoothing data.

matrix, leading to additional pozzolanic reactions. This can potentially enhance the strength and durability of the geopolymer concrete by forming additional calcium silicate hydrate (C-S-H) gel, which contributes to the overall matrix.

Co (NCS) 4Cs3 is a compound that is a combination of many elements such as Cesium, Sulphur, Nitrogen, Carbon, and Cobalt, all of which are found in a different amount. The highest quantity of Cesium (Cs) in the compound as indicated by the pie chart in Figure 11 is 49.4 percent whereas the lowest quantity amounts to Carbon (C) at 8.4 percent as indicated by the table below the pie chart.

The geopolymer concrete is prepared as a result of the polymerization of aluminosilicate materials under the influence of an alkaline activator. The cesium ions (Cs +) may react with this process in a number of ways: Cesium is involved in the chemical reaction of the geopolymerization process, which may change the way the three dimensional aluminosilicate network is formed. This has the potential of reinforcing the matrix according to the integration of cesium into the structure. Cesium can influence the development of N-A-S-H (sodium aluminosilicate hydrate) or C-A-S-H (calcium aluminosilicate hydrate) gels which is highly important in determining the mechanical strength of geopolymers. Geopolymer concrete can have sulfur in different forms, either as sulfates (e.g., gypsum - $CaSO_4 2H_2O$) or sulfides. The geopolymerization process involves the participation of these sulfur compounds in chemical reactions. The existence of the sulfur can influence the stability and formation of the N-A-S-H (sodium aluminosilicate hydrate) or C-A-S-H (calcium aluminosilicate hydrate) gels which are important in the strength of geopolymers. Nitrogen in the geopolymer concrete is capable of affecting

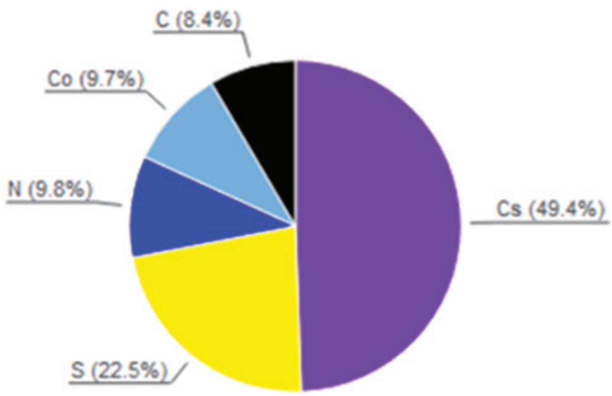


Figure 11. Phase composition.

the properties such as strength of the concrete, its durability and stability with regard to chemical stability. Nitrogen may be added to the geopolymer concrete in many different ways including nitrates, nitrites, ammonia, and other forms of nitrogenous compounds. These compounds are capable of influencing the alkalinity and chemistry as a whole of the geopolymer matrix. Nitrates (NO 3 -) and nitrites (NO 2 -) are oxidizers and may be involved in the reaction which may affect the setting and the hardening of geopolymer concrete. Carbon content of geopolymer concrete can affect its mechanical characteristics especially compressive, tensile, and flexural strengths to a significant extent. The consequences are very conducive to the type and quantity of carbon added, and its dispersion in the matrix. The carbon fibers tend to increase the mechanical properties and durability through reinforcement of material whereas carbon blacks and carbonates may alter porosity and density, which may influence strength and durability. Cobalt contains cobalt in geopolymer concrete may have various implications on the mechanical characteristics of the concrete because of the chemical and physical properties associated with cobalt. The effect is both positive and negative based on the form, concentration and distribution of cobalt in the geopolymer matrix. Cobalt ions (Co 2 +) are able to enter the geopolymer gel structure (N-A-S-H or C-A-S-H), which may alter the network connectivity and density. The introduction of cobalt compounds is also known to increase compressive strength by controlling the addition and refine the gel network and microstructure. Increased loading and density of the matrix decreases porosity and increases load-bearing capacity.

Cobalt, sulfur, nitrogen, carbon, and cesium Co(NCS) 4 Cs 3 compound, which can affect the characteristics of geopolymer concrete, interact during the process of geopolymerization. It is possible to have cesium altering the aluminosilicate network and this may enhance the matrix. The presence of sulfur, nitrogen and carbon can influence the development of the important gels (N-A-S-H or C-A-S-H), which influences the mechanical strength and the durability. The gel network can be modified using cobalt to improve the microstructure and compressive strength of the geopolymer.

CONCLUSION

- Parameters that were varied included; the alkaline activator to fly ash ratio and the various areas of sand in order to learn their effects on the strength of geopolymer concrete. A ratio of 0.35 for the alkaline activator to fly ash was found to provide good strength. Increasing the solution/fly ash ratio enhances workability, with a ratio of 0.50 considered more practical.
- In the case of a solution/fly ash ratio of 0.35, the fine aggregate grading and water content influence compressive strength. Zone 4 sand exhibits better conformity compared to Zone 1.
- From the Rapid Chloride Penetration Test test, average value of the 03 cells as 3796.56 coulombs, it is clearly indicated that the moderate chloride ion penetration into the Geopolymer sample if compare with the conventional concrete, Geopolymer concrete is more durable than the conventional concrete.
- Microstructural analysis using the X-ray Diffraction shows the phase constitution and the element constitution of geopolymer concrete, which consists of Cesium, Sulphur, Nitrogen, Carbon, and Cobalt. The above findings can be utilized to understand the performance and composition of geopolymer concrete. Also the existence of portlandite phase indicates the hardened state of the GPC which contributes to the solidification of the geopolymer concrete [34].
- Geopolymer concrete often has a higher degree of amorphous or poorly crystalline phases, which contributes to its superior resistance to chemical attacks like sulfate or chloride penetration. Normal concrete, with its crystalline calcium silicate hydrates (C-S-H), is more vulnerable to such degradation.
- The aluminosilicate framework in geopolymer concrete, observed in X-ray diffraction, typically provides better resistance to high temperatures compared to normal concrete, which can break down at elevated temperatures.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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