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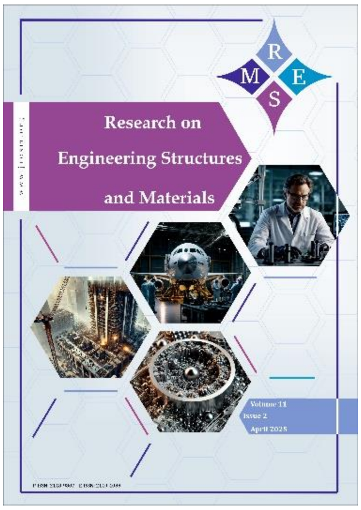

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Research Article

Durability and microstructure of ternary binder geopolymer concrete: A comprehensive study

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Abstract

Geopolymer concrete (GPC) is emerging as a promising, eco-friendly alternative to traditional cement concrete due to its lower carbon footprint and enhanced durability. A key challenge with geopolymer concrete is its dependence on heat activation at varying temperatures, which restricts its practical applications. In this study, the impact of various molarities of NaOH (2 to 10 M) on the sorptivity, sulfate attack resistance, and microstructure of geopolymer concrete (GPC) made with ternary binders is investigated. Ternary binders of Fly Ash, GGBS, and Nano silica are utilized in the proportion of 49:48:3 for all the molarities. Concurrently, Plain Cement Concrete (PCC) of equivalent grade is assessed for comparative analysis. The study found that GPC with a 10 molar concentration exhibits less weight loss and strength degradation, at 1.24% and 12.26%, respectively, when immersed in a sulfate solution. The sorptivity test reveals that GPC with 10M had the lowest water absorption, measuring only 0.14mm compared to the other mixes. The formation of (N-A-S-H) was observed in all samples, indicating a compact and dense microstructure of the geopolymer matrix. This study finds an alternate binder to traditional cement concrete with lower molar concentration, that can exhibit better performance in durability characters.

1. Introduction

Concrete production poses environmental challenges, primarily due to the significant carbon emissions generated during cement manufacturing [1]. To address these challenges, ongoing research and development efforts are exploring sustainable alternatives, such as geopolymers and recycled concrete, to mitigate the environmental impact of concrete production and promote eco-conscious construction practices [2]. Geopolymer concrete (GPC) stands out as a symbol of innovation and advancement in the building industry amid the growing emphasis on environmental responsibility. Geopolymer concrete (GPC) transforms conventional building methods by adopting the principles of sustainable development and the circular economy, utilizing industrial byproducts such as fly ash and GBBS [3]. These alternative materials sourced from industries help reduce industrial waste and minimize carbon footprints. The transformative geo-polymerization process imbues these materials with remarkable properties, endowing the resulting concrete with exceptional strength and durability [4]. In contrast to traditional concrete, geopolymer isolation is a unique chemical process that occurs in geopolymer concrete (GPC) [5]. During this process, alkaline activators react with alumina and silica-rich materials such as fly ash and GBBS, initiating polycondensation reactions [6,7]. These reactions lead to the formation of a three-dimensional network, known as the geopolymer gel, which is the primary reason for

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enhancing the structural integrity of the concrete [8,9]. Meanwhile, geopolymer concrete (GPC) exhibits exceptional mechanical properties and also resilience to harmful environmental conditions. The combination of different precursors helps refine the geopolymer matrix, resulting in an enhanced performance. GGBS enhances early strength gain, while fly ash contributes to long-term strength development [10–12]. However, the pores present in the binary geopolymer blends lead to a reduction in the efficiency of geopolymer concrete (GPC) in harsh ecological conditions [13,14]. Hence, including ternary binders in geopolymer formulations optimizes mechanical properties, workability, and durability while promoting sustainability. This makes them a superior choice for modern construction applications, ensuring long-term performance and environmental benefits.

The incorporation of nanoparticles in GPC has sparked considerable interest in recent studies due to their prospective advantages in augmenting mechanical properties and overall durability. Researchers are keenly studying the distinctive features of these nanoparticles to maximize the efficiency and longevity of geopolymer concrete structures [3]. This novel subject has the potential to revolutionize the construction industry by utilizing nanoparticles in geopolymer concrete (GPC), which can help fill pores and create a compact geopolymer structure. Meanwhile, geopolymer concrete exhibits greater strength at 60°C than at 80°C, despite the slower polymerization process. However, curing it at ambient temperatures (27°C ± 2°C) remains a challenge, with limited literature on the use of geopolymers for this purpose [3]. The addition of nano-silica as a binder in conventional and geopolymer concrete (GPC) provides a compact and dense mixture, which enhances strength and resistance to adverse environmental conditions [15]. Nano silica is a material composed of 95 percent SiO2. Due to its smaller size of less than 1 μm, it occupies a larger surface area, which helps it fill the nanopores. Due to its pozzolanic nature, the NS is involved in accelerating the formation of geopolymer gels and portlandite in the geopolymer concrete (GPC), which can promote strength development by its compactness [16].

In geopolymer, a high alkaline medium is required as a monomer for the dissolution of oxides (such as SiO_2, Al_2O_3, and CaO) present in the precursors. The molarity and type of activators have a significant influence on geopolymers, which are renowned for their exceptional durability and sustainability advantages. Changes in NaOH molarity provide geopolymer concrete (GPC) mixes a complex layer that influences key properties, including workability, setting time, and, most crucially, durability [17,10]. Adjusting the concentration of NaOH allows for targeted modifications to be made to the geopolymer formulation. The study conducted by [16] examines the performance of GPC at various molarities of NaOH and different curing temperatures. It demonstrates that the compressive strength increases with increasing molarity and curing temperature. The study concluded that samples made with 16M yield better performance in terms of strength. However, higher concentration leads to inefficient strength development in later ages. The GPCs made with 12 M NaOH concentration had the greatest strength. Increased concentrations of NaOH inhibited the polycondensation by accelerating the dissolving of silica and alumina. The resistance of GPC in an acidic environment increases with the molarity of the sodium hydroxide (NaOH) solution [18]. The results of GPC specimens after immersion in sulfuric acid showed a weight loss of 2.03% and a strength loss of 1.81%, respectively, indicating a better performance of GPC samples in acidic conditions. According to [19], the production of crystalline phases within the aluminosilicate network determines the stability of geopolymer materials in acidic environments. This indicates that more crystalline phases lead to better stability in hostile environments. The alkalinity of the binder itself serves as the foundation for the concept of acidic attack [20]. The primary cause of acid damage is an interaction between acidic and alkaline components within the binder network. The primary reason why alkali-activated material is more durable than an OPC binder is due to its low Calcium concentration. Heat-cured geopolymer concrete test specimens exhibit surface degradation, and after one year of exposure, a mass loss of approximately 3% occurs due to a sulfuric acid solution. FESEM and EDX investigations revealed that the performance improvement was attributed to the formation of crystalline structures. The better performance was due to the promotion of high NASH gel products [21]. It confirms that the concentration of alkaline liquids plays a vital role in the performance of GPC. Additionally, the pores in any type of concrete should be a more significant concern in terms of its performance [22].

Hence, there is a need to fill the pores, and this study incorporates nanomaterials to reduce the pores available in GPC and investigate the quantity of alkaline medium in the activation process and durability of geopolymer concrete (GPC). Therefore, nano silica has been used as a replacement binder with a fixed weight of 2%. This study also investigates the durability and microstructural behavior of geopolymer concrete (GPC) as the molarity of NaOH is varied.

2. Materials and Methods

The materials used in this study included FA, GGBS, nano-silica, alkaline activators, fine and coarse aggregates, and admixtures. This research involves the casting process, curing, and evaluation of samples according to standard procedures.

2.1. Materials

2.1.1 Fly Ash

Fly ash is a fine powder composed primarily of spherical, glassy particles generated as a byproduct of coal combustion in power plants. The primary constituents of fly ash are silica, alumina, and iron oxide. Due to its pozzolanic properties, fly ash can react with lime to form cementitious compounds. According to IS 3812 (Part I) [23], the current investigation utilized Class F Fly Ash. Fly ash with a specific gravity of 2.1 is used.

2.1.2. GGBS

A by-product of iron production, it is cementitious in nature. GGBS is a waste by-product of the steel industry, and its principal components are CaO, SiO_2, Al_2O_3, and MgO. In the present study, the GGBS manufactured by the JSW Cements Company is utilized. GGBS has a specific gravity of 2.4.

2.1.3 Nano Silica

The main component of nano-silica is silicon dioxide (SiO_2), which can be either crystalline or amorphous. The nanoparticles of silica utilized in this study are 17 nm in size. In polymer compounds, nano silica is used as a filler to enhance mechanical and durability performance.

2.1.4 Fine Aggregate

This project utilized sand from a nearby location with a specific gravity of 2.55 and a Zone II classification, as per IS 383-1970 [24].

2.1.5 Coarse Aggregate

In this investigation, locally obtainable aggregate having a specific gravity of 2.60 was utilized.

2.1.6 Alkaline Solutions

Sodium hydroxide and sodium silicate were used as alkaline activating solutions in the current research work. The resulting fluids react with fly ash and other cementitious materials rich in silica and alumina. Before use, NaOH pellets must be dissolved in water at the required concentration. The sodium hydroxide used has concentrations of 2, 4, 6, 8, and 10 M. After combining the sodium hydroxide and water glass solution, it was allowed to settle for one day. The ratio of NaOH to Na_2SiO_3 is 1:2.5 [25]. The sodium silicate solution contains SiO_2-33.92% and Na_2O-16.33%. The NaOH pellets used for making NaOH solution in each molarity of (GPC) mix for a total of 100 percent is, i.e., for 2M – 8.1%, 4M – 15.1%, 6M – 21%, 8M – 26.23%, 10M – 30.37% and the remaining percentage is diluted with water.

2.1.7 Admixture

Conplast SP 430, a water-reducing additive, is used to improve workability.

2.2. Methodology

The current study utilized GPC mix proportions from earlier studies [23–25] to define the GPC composition. Materials are originally sourced and then quantified in batches. The aggregates were initially added to the pan mixer, followed by batched FA, GGBS, and Nano silica, and the mixture was then vigorously mixed. The additive and alkaline mixtures are then added and blended with the ingredients in the mixer. The mixing process was repeated until an evenly distributed and homogenous mixture was obtained. The test items used were cube specimens measuring 150 mm for acid attack and 100 mm for sorptivity. The cast specimens were removed from the mold and left to cure for 28 days at ambient temperature. Table 1 shows the mix proportion of GPC and PCC mix. As per ASTM C1898-20 [26], the acid attack test was performed in the concrete cubes of size 150 mm^3. For conducting the sorptivity test, 100 mm cubes, as mentioned by Liu et. al [27], are cast, demoulded after 24 hours, and placed for ambient curing, the temperature ranging between 27^{0}C to 30^{0}C, and the test was performed as per ASTM C1585-04 [28] standards.

Table 1. The details of the mix proportions are given in this table for 1 m^3 of concrete.

Mix	Binder (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
Fly ash + GGBS + NS	443	656	1264	44.2	110.8	-	8.86
PCC	368	707	1136	-	-	186	-

3. Results and discussions

3.1. Durability

3.1.1 Sulfate Attack

Table 2 presents the weight loss and strength loss resulting from the immersion of specimens in acids. The graph in Fig. 1 compares the percentage weight loss for the various concrete compositions listed in Table 2. According to the figure and table above, PCC mix cubes lost 8.22% of their weight after 28 days of immersion in 5% H_2SO_4. When compared to other mixes, the PCC mix sheds more weight. The GPC-10M mix sheds less weight, i.e., 1.24%, than all other mixes. The percentage of weight loss of GPC-8M and GPC-10M are comparably near to each other.

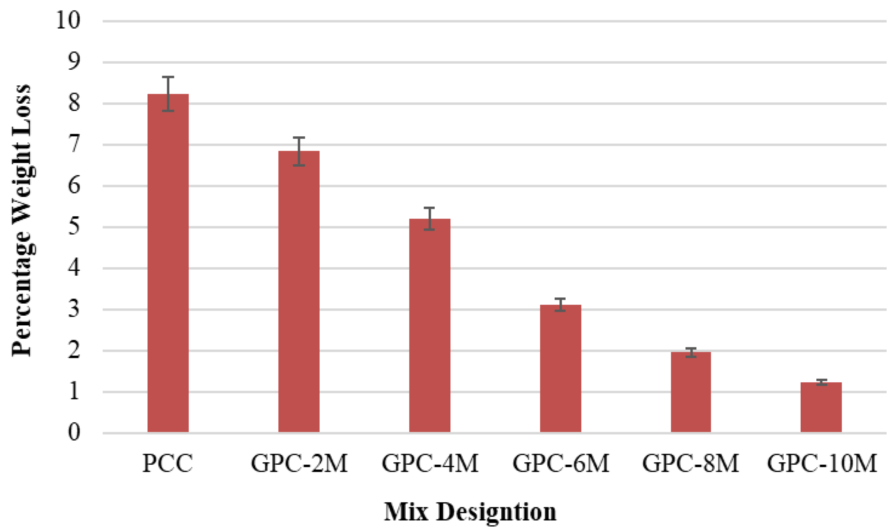

Fig. 1. Percentage weight loss of different concrete mixes.

The graph in Fig. 2 compares the percentage loss in compressive strength for the various concrete combinations listed in Table 2. The image and table above show that PCC mix cubes lose 26.81% of their compressive strength after 28 days of immersion in 5% H_2SO_4 and lose 54% of their strength compared to GPC-10M. PCC mix loses greater compressive strength when compared to other mixtures. The GPC-10M mix loses less compressive strength, i.e., 12.26%, than all other mixes.

Table 2. Percentage Loss in weight and Strength of Specimens after Immersed in H_2SO_4 Solution for 28 days

Mix Designation	Initial weight in kg	Final weight in kg	Percentage weight loss	Initial compressive strength in MPa	Final compressive strength in MPa	Percentage Loss in strength
PCC	8.16	7.48	8.22	48.52	35.49	26.81
GPC-2M	8.17	7.60	6.84	27.13	20.28	25.22
GPC-4M	8.17	7.74	5.21	34.49	26.35	23.60
GPC-6M	8.18	7.92	3.12	39.12	31.44	19.58
GPC-8M	8.18	8.01	1.96	44.71	38.08	14.82
GPC-10M	8.18	8.07	1.24	50.30	44.13	12.26

This demonstrates that increasing the molarity of NaOH in GPC mixes, as well as adding Nano Silica, improved resistance to sulfate attack. As a result, GPC concrete has demonstrated superior resistance to sulfate attack than PCC mix. The positive effect of nano-silica on pozzolanic activity led to the development of Si-Al bonds, which increases the strength of the binder paste. The nanoparticles of nano silica increased the packing capacity of the geopolymer matrix by filling the pores of the binder paste, lowering acid permeability in concrete specimens while modestly boosting durability. GPC varies from PCC such that it has very little calcium content, making it more resistant to acid assaults. Its aluminosilicate gel, formed during geo-polymerization, forms a solid, impermeable structure that serves as a barrier to acidic chemicals.

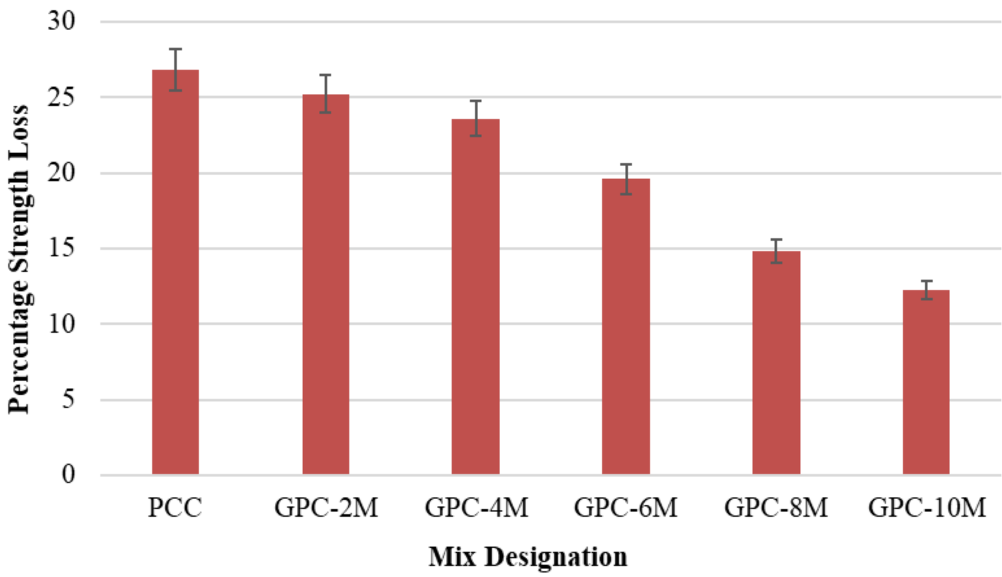

Fig. 2. Percentage strength loss of different concrete mixes.

The decreased porosity of GPC reduces acid intrusion, reducing possible chemical reactions and increasing overall durability. PCC samples primarily consist of calcium silicate compounds, when exposed to sulfuric acid, these compounds can undergo chemical reactions leading to the formation of gypsum (calcium sulfate) and other soluble compounds. This results in the degradation of the PCC matrix and the weakening of the concrete. When more NaOH is used, it helps break down the raw materials more effectively, which leads to the formation of a strong and well-connected aluminosilicate network, also known as N-A-S-H gel. This network plays a key role in protecting the concrete. It creates a dense, tightly packed structure that makes it harder for harmful sulphate ions to get inside. Because the material has fewer pores and pathways, there's less chance for sulfates to react with the concrete and cause damage like cracking or expansion.

3.1.2 Sorptivity

The absorption values of the sorptivity test on a 100 mm cube specimen at various time intervals are shown in Table 3. The absorption results of the sorptivity test are shown in Table 3 and Fig. 3. It can be seen that the incorporation of Nano Silica resulted in less absorption than that of the PCC mix. At 28 days, compared to the other mixes, the GPC-2M mix has a higher absorption value (i.e., 0.38mm). The water absorption of the GPC-2M mix is 80.95% more than the PCC mix at 28 days. The GPC-10M mix has absorbed less water than the other mixes.

Table 3. Absorption values for different concrete mixes with respect to time.

Time	Absorption (I) Values in mm					
	PCC	GPC-2M	GPC-4M	GPC-6M	GPC-8M	GPC-10M
0 Minutes	0	0	0	0	0	0
30 Minutes	0.03	0.08	0.05	0.03	0.04	0.03
60 Minutes	0.05	0.13	0.09	0.05	0.05	0.03
2 Hours	0.07	0.17	0.14	0.08	0.06	0.05
4 Hours	0.10	0.21	0.18	0.12	0.08	0.07
6 Hours	0.12	0.26	0.22	0.15	0.10	0.08
1 Day	0.14	0.29	0.25	0.18	0.13	0.10
3 Days	0.16	0.32	0.27	0.21	0.15	0.11
7 Days	0.19	0.34	0.29	0.23	0.16	0.12
14 Days	0.20	0.36	0.30	0.25	0.18	0.13
28 Days	0.21	0.38	0.31	0.26	0.19	0.14

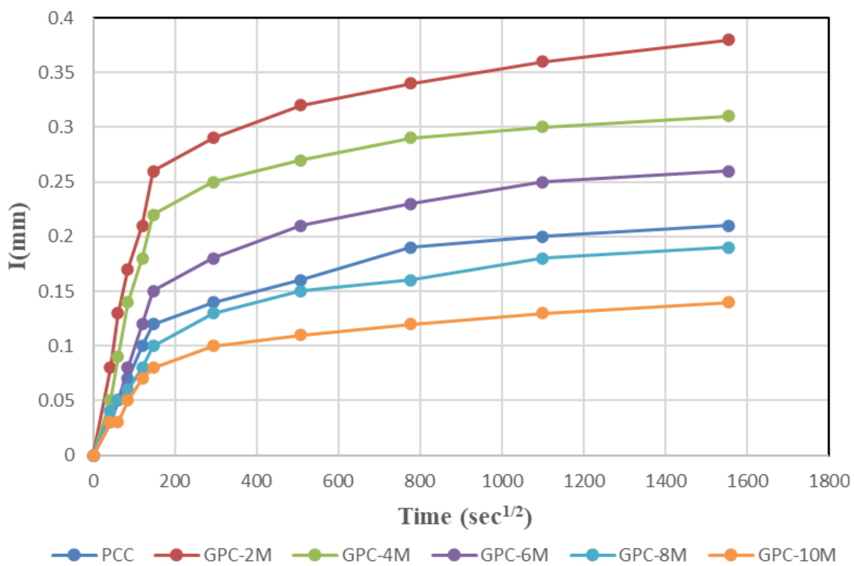

Fig. 3. Variation of water absorption values of different concrete mixes with time

The graph shows that the absorption values for all mixes increased with time. It states that the capacity of water to penetrate the concrete cube rises with the time it is immersed in water. GPC-10M has the lowest absorption value (0.14 mm) after 28 days, whereas PCC has the highest value (0.21mm). However, the mixes GPC-6M and GPC-8M also have lower absorption values than the PCC mix at 28 days. The results show that sorptivity decreases as the NaOH molarity increases. This means the concrete absorbs less water when more NaOH is used. The reason behind this is that higher NaOH concentration helps break down the raw materials more effectively, which leads to better formation of a binding gel called N-A-S-H. This gel fills the spaces inside the concrete, making it denser and less porous. As a result, the concrete becomes more resistant to water absorption. From the experimental results, it was found that Geopolymer concrete at higher molarities has lower porosity than PCC concrete mix. The probable reason for this effect is that the geo-polymerization method forms a three-dimensional network of aluminosilicate gel, resulting in a more compact and less porous structure. This decreased porosity slows the water flow through the concrete, making it more resistant to water penetration.

3.2. Microstructure Analysis of Concrete

3.2.1 Field Emission Scanning Electron Microscopy (FESEM)

FESEM (Field Emission Scanning Electron Microscopy) is a useful method for investigating the microstructure and surface morphology of various materials, including concrete. FESEM scans a sample's surface with a high-energy electron beam, producing a different signal like secondary electrons, backscattered electrons, and distinctive X-rays. These signals help analyze surface characteristics at a microscopic level, providing insights into the material's composition and structural integrity.

For FESEM analysis, core concrete samples were collected to reflect the relevant region and then split into smaller pieces. These components were ensured to fit on SEM stubs. The surface was prepared for examination by removing any impurities or loose debris using compressed air or a mild solvent. It was ensured that the surface was free of any impurities that might interfere with imaging or analysis. The samples were carefully dried to prevent artifacts during analysis. This allowed for the analysis of the cement paste structure, including the detection of hydration products, voids, and the distribution of different components such as calcium hydroxide, calcium silicate hydrate, and un-hydrated cement particles. These parameters are crucial for evaluating the concrete strength, porosity, and durability variations over a period of time.

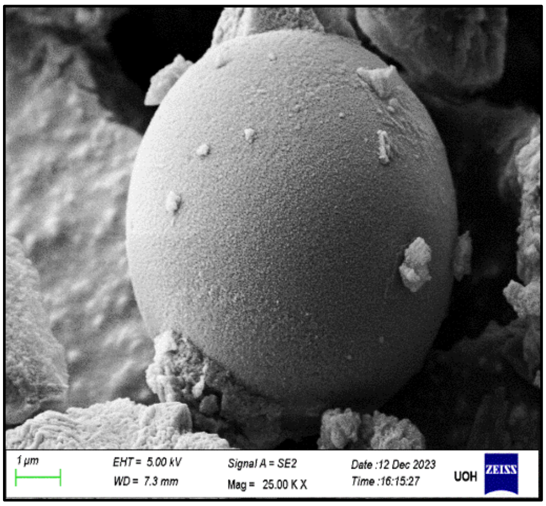

Fig. 4. FESEM image of Flyash

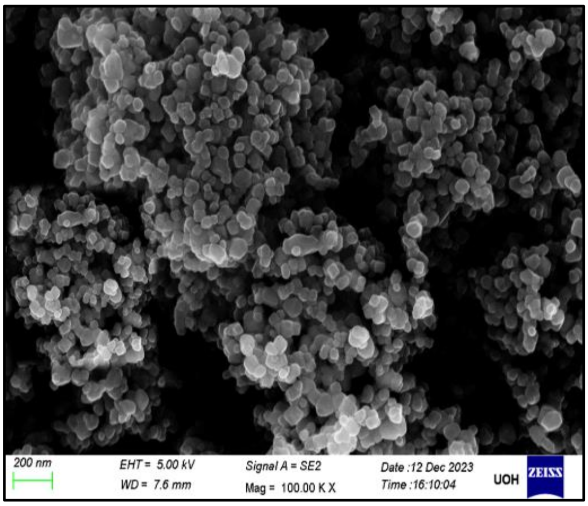

Fig. 5. FESEM image of Nanosilica

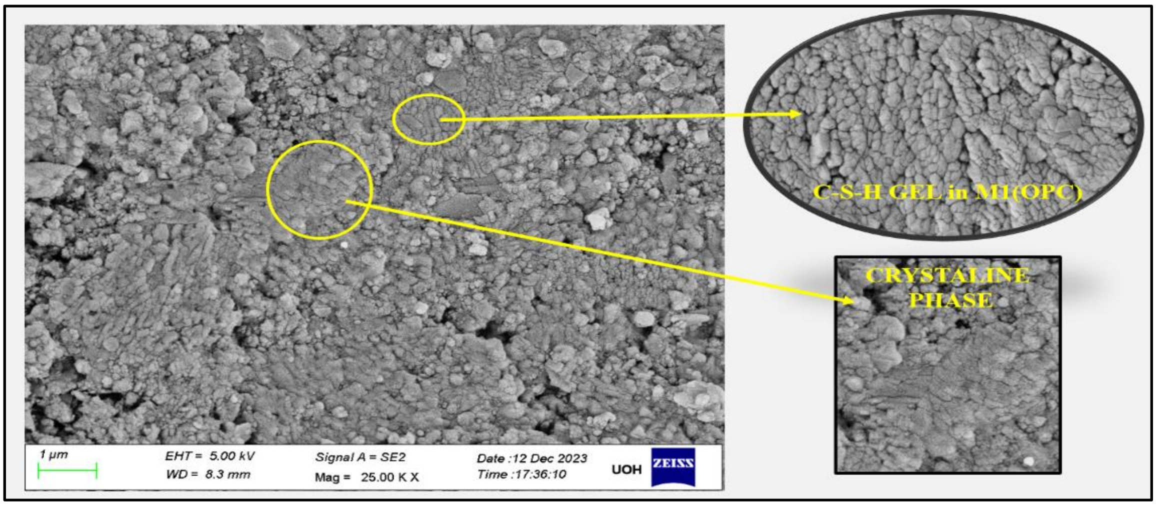

Fig. 6. FESEM image of PCC mix

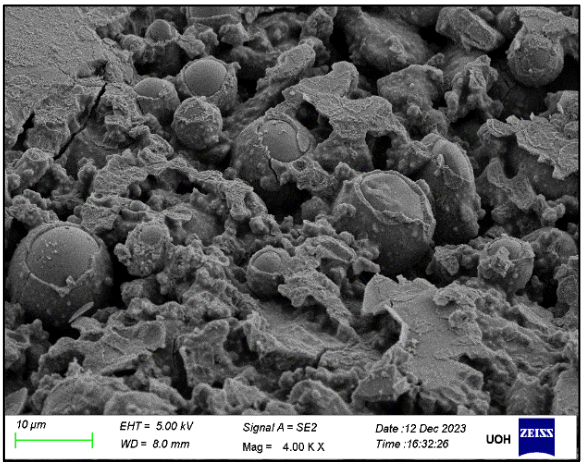

Fig. 7. FESEM image of GPC-2M mix

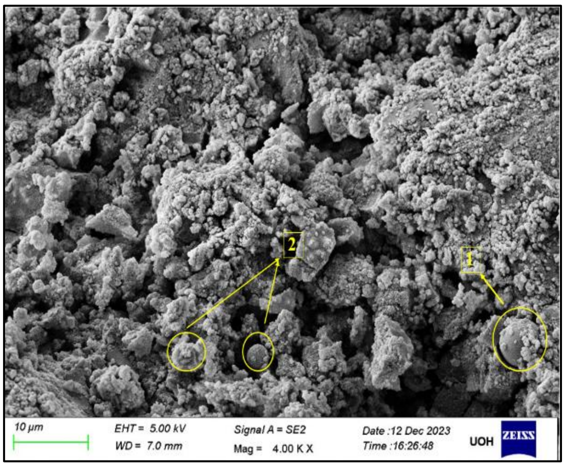

Fig. 8. FESEM image of GPC-4M mix

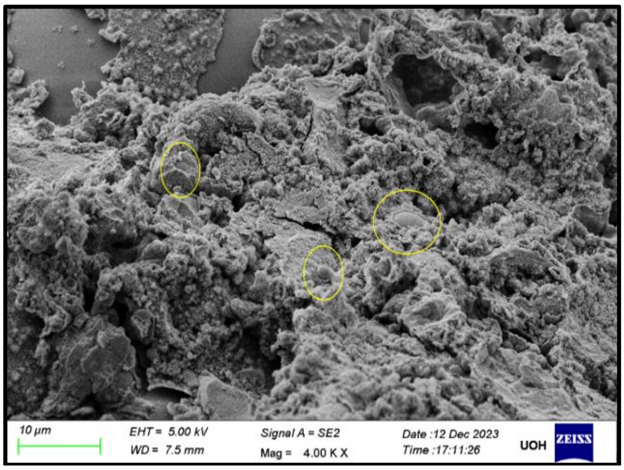

Fig. 9. FESEM image of GPC-6M mix

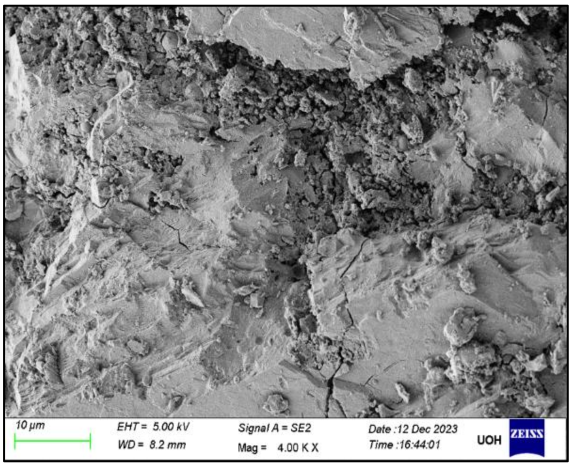

Fig. 10. FESEM image of GPC-8M mix

Fig. 4 and 5 show the FESEM image of fly ash and Nano silica particles. Lower alkali concentrations result in insufficient breakdown of Si and Al ions, leading to the formation of few Si- Al bonds, resulting in less N-A-S-H gel formation and more unreacted particles, which leads to less amorphous phase formation. The presence of unreacted fly ash particles is more significant in the low molar concentration samples, and large voids are observed in Figures 6-8. These samples have exhibited quicker crack development and less compressive strength. Samples with a low NaOH molarity are less dense because of their loose matrix. A high cross-sectional area of components is observed from Fig. 12 at 4M concentration because of less production of N-A-S-H gel, which is caused by more unreacted particles.

In contrast, at higher alkali concentrations, the disintegration of Si and Al ions is adequate. The formation of Si-Al bonds results in more N-A-S-H gel formation, and more particles are reacted and mixed. High-molarity solutions accelerated the geo-polymerization process. The presence of unreacted fly ash particles is low, and small voids are observed in high-molarity samples (Fig.11 and 13). Samples with a high NaOH molarity are denser because of their compact matrix. The zone encircling the unreacted particles seems compact despite the fact that few microfractures were identified in the region from Fig. 9 & 10. The interlocking morphology of the hydrated gel with the remaining unreacted particles leads to dense microstructure and decreased crack propagation in Fig 11. Further, the presence of increased molarity promoted the crystalline phase formation in GPC 8M 10M, resulting in a dense matrix. As depicted in Fig. 12 and 13, the reduced cross-sectional area of components in higher molarities has significantly improved geo-polymerization. Additionally, the presence of Nano Silica in the Pozzolanic activity caused the formation of Si-Al bonds and raised the density of the binder paste by filling the pores, all of which resulted in marginally better mechanical and durability qualities. These structural refinements contribute to superior mechanical and durability in geopolymer concrete.

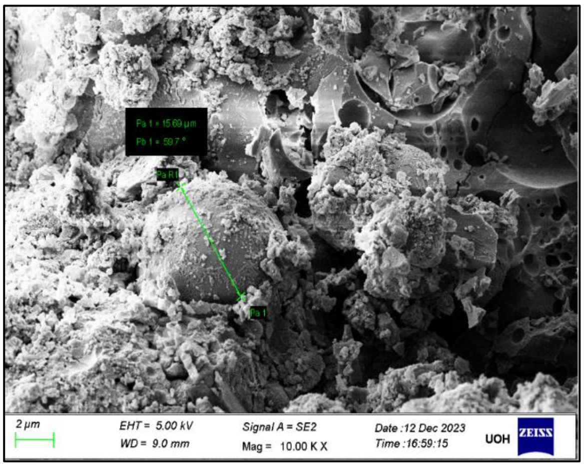

Fig. 11. FESEM image of GPC-10M mix

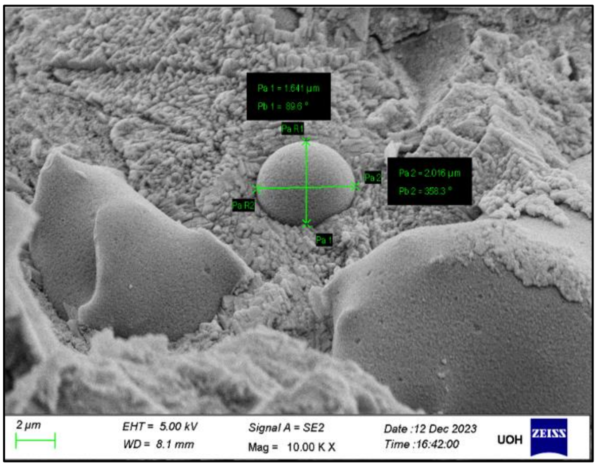

Fig. 12 FESEM image of flyash particle of GPC-4M mix

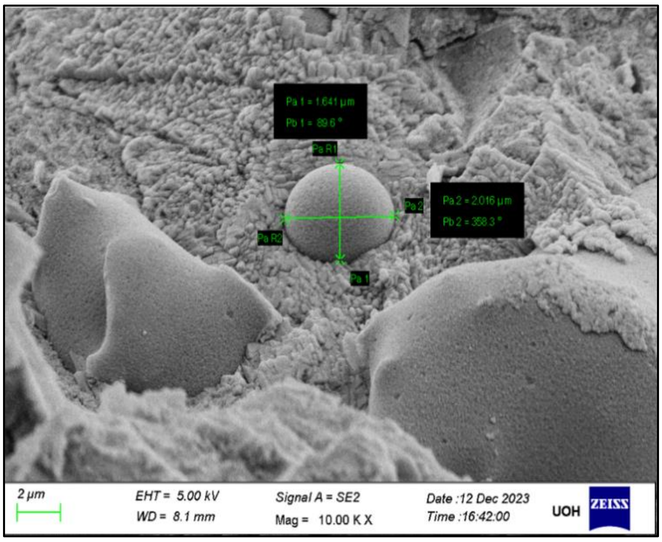

Fig. 13 FESEM image of fly ash particle of GPC-10M mix

3.2.1 Field Emission Scanning Electron Microscopy (FESEM)

Elemental analysis of various components inside the concrete may be performed using energy-dispersive X-ray spectroscopy (EDX) in conjunction with FESEM. This helps to determine the presence and distribution of distinct elements, which is essential for understanding concrete composition and probable sources of degradation. Configure the EDS system to gather data. Ensure that the detector is calibrated and aligned appropriately. After that, diagram the components on the concrete surface and designate specific regions or characteristics for in-depth elemental investigation. Obtain X-ray spectra from different concrete surface regions of interest. Analyze the spectra to determine their elemental composition.

Higher NaOH molarity suppressed calcium dissolution, resulting in lesser hydration products in GPC 10M from Table 4. The steady rise in GPC sample strength with increased activator concentrations is mostly due to the greater disintegration of aluminosilicate resources. The presence of magnesium in GPC offers chemical stability or so-called interatomic connections in the matrix through the creation of various linkages such as Si-O-Mg, Si-O-Al, Ca-O-Si, and Si-O-Si. From the above EDX compositions shown in Fig 15-16, it can observe that with an increase in molarity, there will be more reactions between particles and more gel formation, such as N-A-S-H and C-A-S-H gel which directly indicates the decrease in weight percent of Na in higher molarities from table 6. In lower molarities, because of fewer reactions, there will be more unreacted particles and more water content, and the gel formed will be less viscous, indicating an increase in the weight percent of Na in lower molarities from Table 4.

Table 4. Elements presents in various mixes

Element	Weight%		
	PCC	GPC-2M	GPC-10M
O K	41.25	55.04	46.14
Ca K	33.37	17.97	26.92
Si K	12.29	13.43	6.51
Al K	3.89	6.26	8.12
Na K	0.98	4.29	1.95
Mg K	0.00	1.52	0.64

Higher concentrations of oxygen, silicon, and aluminum have been found in GPC 10M samples from Table 6, confirming the production of aluminum silicate gels. In contrast, the PCC's EDX spectra from Table 4 show relatively high amounts of calcium and silica. These high calcium concentrations, along with the presence of oxygen, silicon, and aluminum, resulted in the development of extra calcium silicate (C-S-H) and calcium aluminosilicate (C-A-S-H). The development of these additional outcomes led to more compact & denser microstructures in PCC samples.

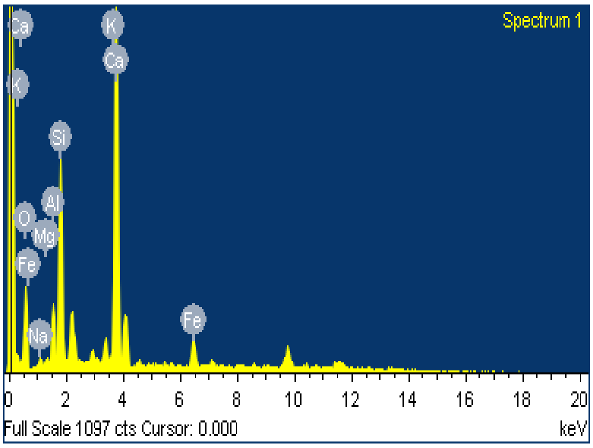

Fig. 14. EDX of PCC mix

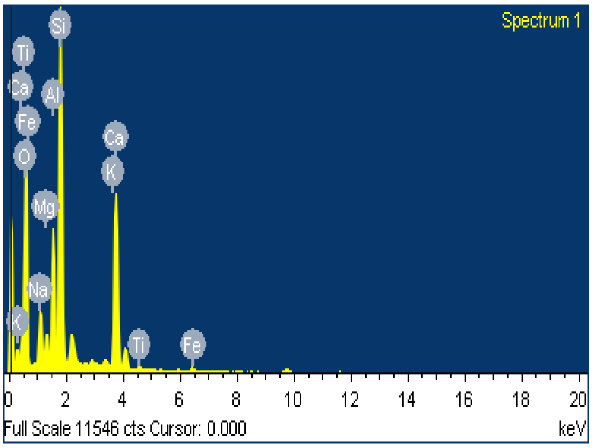

Fig. 15. EDX of GPC-2M mix

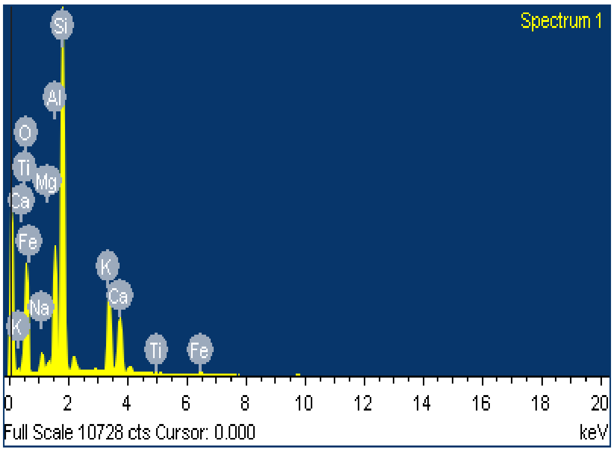

Fig. 16. EDX of GPC-10M mix

4. Conclusions

From the investigation of the effect of NaOH molarity on the various properties of geopolymer concrete (GPC) made with ternary binders, the study concludes that,

- Geopolymer concrete with Nano-silica increased the dissolution rate of Si and Si–Al phases, which strongly affects the polymerization rate. The presence of Nano-silica in the geopolymer mixture is the key factor in enhancing the polymerization process for its amorphous property and the high specific surface area.

- PCC mix loses greater compressive strength when compared to other mixes. The PCC mix loses 26.81%, and GPC-10M loses 12.26% of its compressive strength after 28 days of immersion in 5% H2SO4 solution.
- The GPC-2M has a higher absorption value of 0.38 mm when compared to the GPC-10M mix, i.e., 0.14 mm, which has absorbed less water in comparison to the other mixes.
- Geopolymer concrete samples at higher molarities are composed of aluminosilicate materials and contain less calcium content and fewer pores when compared with PCC, has undergone a geo-polymerization process forming a three-dimensional network composed of Si-O-Al bonds, which are more resistant to the corrosive effects of sulfuric acid.
- In PCC, it primarily consists of calcium silicate compounds, when exposed to sulfuric acid, these compounds can undergo chemical reactions leading to the formation of gypsum (calcium sulfate) and other soluble compounds. This results in the degradation of the PCC matrix and the weakening of the concrete.
- From FESEM, it can understand that the high cross-sectional area of fly ash components is evidenced at low solution molarity because more unreacted particles, more pores, and less N-A-S-H gel formation led to a less dense matrix.
- Increasing NaOH molarity in the N-A-S-H phase reduced the cross-sectional area of fly ash components and led to the strength development of GPCS.
- EDX spectra confirmed the enhanced dissolution of silicate with an increase in alkali concentration, which indicates the formation of more N-A-S-H gel, and enhanced dissolution of calcium at the Conventional PCC mix, which indicates the formation of more C-S-H gel.
- From the above EDX compositions, at higher alkaline concentrations, due to more polymerization, the weight percent of Na is less, and at lower alkaline concentrations, the weight percent of Na is more.
- In real-world construction, GPC could help build longer-lasting structures with lower maintenance which can provide a sustainable solution by using industrial waste materials.

5. Future Study

This study will be extended to investigate the effect of ternary blend GPC on other durability properties at long-term durations. The authors are also focusing on investigating other microstructural studies, such as FTIR, to understand the effect of nano silica incorporation in the ternary blend.

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