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Original Article

Optimized Alkaline-Activated Geopolymer Concrete with Recycled Aggregates: Mechanical and Microstructural Insights with Application

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Abstract *- Geopolymer concrete is increasingly being seen as a green alternative to OPC, with a significant reduction in greenhouse gas emissions and the use of industrial waste materials. This research explores the mechanical strength properties, durability, and microstructure of GPC using Class-F fly ash as a binder, M sand as fine aggregate, and recycled aggregate as coarse aggregate. An alkali-activated mix-design was formulated with sodium silicate and NaOH solution as activating agents to create an alkaline condition, where NaOH molarities were fixed at 10, 12 and 14 molar (M) and the stable liquid-to-binder ratio at 0.4, with alkaline liquid ratios being 2.5, 5, and 7.5. The specimens of GPC were dry-cured for 24 hours at 60°C at an elevated temperature in a hot air oven to promote polymerization and strength development. Experimental results showed that the mixture of 12M NaOH, an alkaline liquid ratio of 7.5, and an alkaline liquid-to-binder ratio of 0.4 showed the finest mechanical performance, with 52.74 MPa compressive strength, 4.68MPa flexural and 4.54MPa split tensile strength, with lower water absorption & disintegration under acid test. The GPC proved to be better concrete than OPC concrete when the test results were compared. Precast elements like paver block cast were for the optimized mix and tested. The microscopic view showed the compact and dense microstructure formed with reduced porosity by neatly developed geo-polymeric gels, which led to increased strength properties and durability.*

Keywords *- Geopolymer concrete, Recycled aggregate, Alkaline activators, Microstructural analysis, SEM.*

1. Introduction

The rising universal demand for sustainable and eco-friendly building materials has prompted extensive research into viable alternatives to OPC, which is associated with high environmental costs. The industry of Cement alone generates roughly 8% of global emissions of CO_2 [1, 2]. Simultaneously, the construction sector generates nearly 3.6 billion tons of Construction Demolition (C&D) waste annually, a major portion of which is in landfills, contributing to severe environmental issues such as air pollution, land degradation, and water contamination [3]. The lack of adequate recycling infrastructure in many countries results in less than 50% of C&D waste being reused, in contrast to developed nations where recycling capacities exceed 100 million tons annually [4, 5].

To address these growing environmental challenges, GPC has become a promising alternative to traditional OPC concrete. The GPC is synthesized using by-products of industries rich in alumina and silica, such as fly ash, rice husk ash, and GGBFS [6, 7]. Thus significantly decreasing the cement dependency. Initially, incorporating these industrial residues into concrete formulations faced setbacks due to the lack of binding ability. However, the introduction of alkaline activators, namely NaOH and Na_2SiO_3 revolutionized the action by initiating the geopolymerization reaction—a chemical transformation that converts aluminosilicate materials into a strong, durable polymeric matrix [8, 9]. This reaction involves dissolution, transportation, and polycondensation of tetrahedral species of silicate (SiO_4) and aluminate (AlO_4) in the medium of an alkaline, forming a three-dimensional amorphous to semicrystalline aluminosilicate network [10-12]. The resulting matrix enhances mechanical strength and offers excellent resistance to thermal degradation, chemical attack, and deterioration caused by environmental effects. Thus, GPC is an attractive concreting material for structures subjected to aggressive environments. Studies on durability have indicated that GPC exhibits lessened shrinkage, decreased permeability, and superior resistance to sulphate acid attacks compared to OPC concrete. These advantages will make GPC suitable for infrastructures that require long-term performance, such as pavement slabs, marine structures, sewer systems and precast components [13].

Moreover, incorporating Recycled Aggregates (RA) and manufactured sand (M-sand) in GPC addresses another pressing concern-excessive mining of natural resources. By utilizing recycled concrete aggregates and alternative fine aggregates, the concrete industry can significantly reduce its carbon footprint, promote a circular economy, and bring down the environmental issue regarding waste disposal [14], [15, 16]. The combined use of recycled aggregates and Fly ash in GPC provides the benefit of dual sustainability by mitigating CO_2 emissions and addressing the effective disposal of C&D waste while enhancing concrete longevity.

Despite its potential, practical implementation of GPC still faces challenges, particularly in workability, curing requirements, and optimization of mix proportions. Studies have shown that Alkaline Liquid-To-Binder Ratio (AL/B), NaOH molarity and Alkaline Liquid (AL) ratio greatly influence the mechanical and microstructural performance of GPC. Increasing NaOH concentration enhances the dissolution of raw materials and promotes polymerization, but it can also induce higher porosity, potentially compromising long-term durability [17]. Excessive alkali concentrations can swiftly accelerate polymerization reaction kinetics; conversely, it may also result in the incompletion of geopolymer gel formation or leave the particles unreacted, weakening the resistance to aggressive agents over time. Similarly, a proper AL/B ratio is crucial to maintain workability without excess water, which could hinder the geopolymer gel formation [18]. Compared to OPC, GPC also requires heat curing (50–80°C) to accelerate geopolymerization and improve early-age strength, posing practical limitations for in-situ applications [19, 20].

Several researchers have explored various combinations of mix parameters curing conditions to elevate the performance of GPC, as summarized in Table 1. However, many of these studies have focused on individual variables or conventional aggregates, with limited attention to the complete integration of recycled materials in precast applications [21, 22]. In addition, while the strength characteristics of GPC have been documented, studies integrating both durability and mechanical performance, particularly with recycled materials, are very limited. This indicates the need for a proper comprehensive approach that explores the strength, durability and microstructural evolution of optimized alkaline-activated GPC mix.

Table 1. List of studies on GPC mix combinations

Molarity	AL/B Ratio	Alkaline Liquid Ratio	Curing Methods	Source
12M & 14M	0.3, 0.35, 0.40	2.5 to 3.5	7, 28 and 90 days of ambient curing.	[19]
10, 12 & 14 M	0.35	-	20 to 80°C for 3, 7 and 14 days.	[20]
12, 14 & 16M	0.6, 0.65. 0.7	1, 1.5, 2, 2.5	40°C to 120 °C oven curing for 24, 48, and 72 hours 25°C ambient curing for 1, 3, 7, and 28 days.	[23]
2M	0.40, 0.45, 0.50, 0.55	1.5	Ambient curing for 7 days.	[24, 25]
10, 12 & 14M	0.35	1.5, 2, 2.5, 3	Ambient curing for 28 days.	[25]

1.1. Research Gap

While extensive studies have tested the effects of molarity, AL/B ratios and curing parameters on mechanical and microstructural arrangements of GPC, only limited research has described the use of 100% recycled coarse aggregates and M-sand combination with concentrations of optimized alkaline liquid activators. The durability performance of such eco-concretes, especially under realistic environmental and curing conditions, remained insufficiently explored. The existing literature has rarely explored precast applications such as paver blocks, mainly in the context of long-term stability and field-simulative testing. The study focuses on bridging those gaps in research by optimizing the GPC mixes using fly ash as the complete binder and complete recycled aggregates as concrete aggregates, evaluating the mechanical strength and durability characteristics of these materials. Furthermore, this study's novelty lies in its real-world applications, such as casting and evaluating the highway precast elements (paver blocks) using an optimized GPC mix and providing a feasible, sustainable alternative for infrastructure development.

1.2. Research Gap

- To properly optimize the mix design of geopolymer concrete using 100% recycled aggregates and different ratios of alkaline activator for amplified performance.
- To determine the durability and mechanical characteristics of the prepared GPC.
- To inspect the microstructure of hardened GPC with the help of SEM and EDX analysis, concentrating on geopolymer gel formation, porosity reduction and densification.
- Preparing and testing the precast elements (paver blocks) using an optimized GPC mix to assess its field application feasibility.

2. Experimental Methods

Figure 1 showcases the flow of the methodology followed.

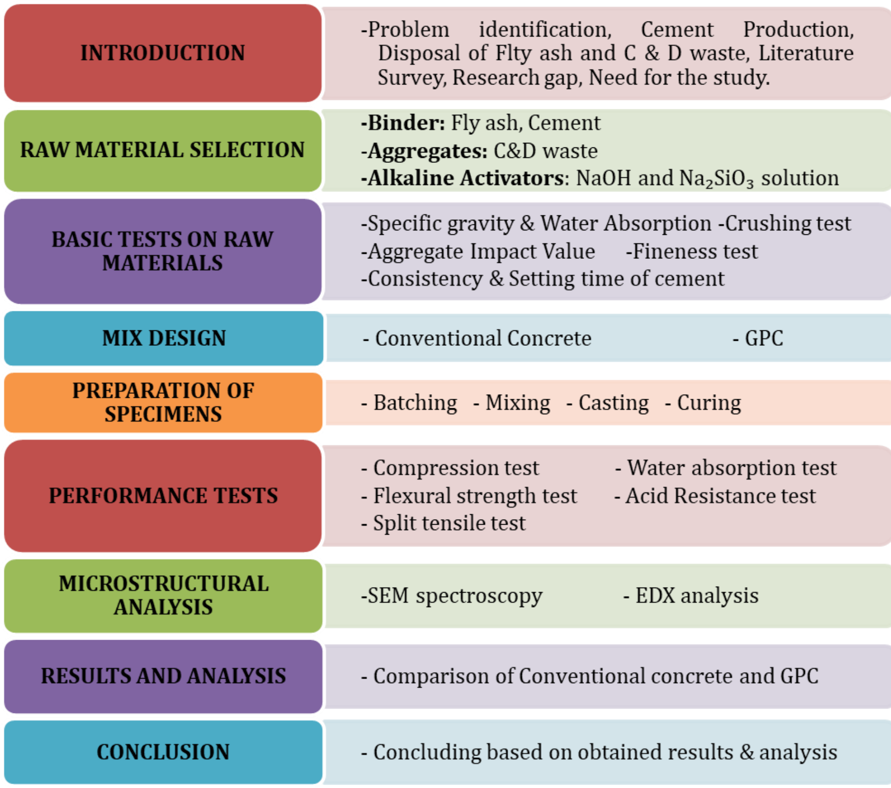


Fig. 1 Flow of work done

2.1. Materials Used

The materials selected in this research to produce Geopolymer Concrete (GPC) are:

- Binder: Cement was used for conventional concrete, and fly ash (Class-F) from thermal plants was adopted as the primary binder in GPC because of its higher alumina and silica content.
- Fine Aggregate: Manufactured sand was utilized to achieve good gradation and particle size distribution.
- Coarse Aggregate: Processed Recycled Aggregates (RA) from the C&D waste segregation plant were utilized as coarse aggregate.
- Alkaline Activators: NaOH and a solution of Na_2SiO_3 were employed as activators for the geopolymerization reaction.
- Water: Very little water was consumed solely for workability maintenance and preparation of the alkaline solution.

2.2. Tests on Materials

Before their application in GPC, their characteristics were first tested to determine the following:

2.2.1. Cement

Ultratech OPC 43 grade was employed for preparing the traditional concrete mix, which will be considered for comparison as a benchmark. The Cement used in this study meets the required IS standards. Consistency was ensured in the laboratory experimental analysis. The results are tabulated in Table 2.

Table 2. The test results of Cement

List of Tests	Obtained Results	Permissible Results	Codes Referred
Specific Gravity	3.14	3.10 to 3.16	IS 4031
Initial Setting time in min	46	> 30	
Final setting time in min	315	< 600	
Fineness (%)	5	<10	
Consistency (%)	30	25 to 35	

2.2.2. Fly Ash

Basic tests like specific gravity fineness tests were conducted in the laboratory, and chemical composition analysis was performed in a scientific test agency to confirm the traces of silica, alumina and other oxides.

The chemical composition test report given by the scientific testing agency is represented in Figure 2, and laboratory-tested results are tabulated in Table 3.

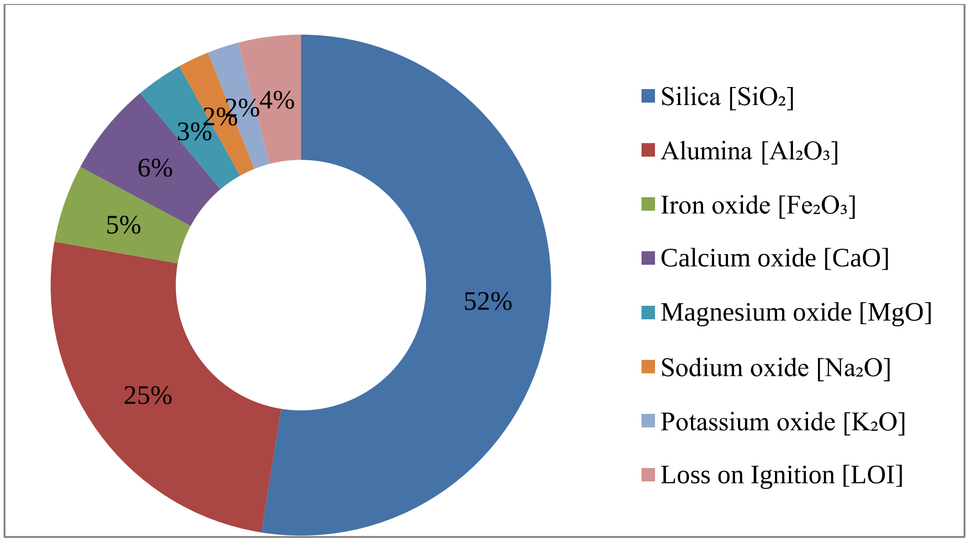


Fig. 2 Chemical composition of flyash (Class-F)

Table 3. Physical test results of Fly ash (Class F)

Tests	Result	Limits	Code
Fineness (%)	4	Less than 10	IS 3812 Part 1 & 2 [27]
Specific Gravity	2.2	2.0 to 2.3	

2.2.3. Fine and Coarse Aggregate

Repeated tests such as sieve analysis, water absorption, specific gravity and impact tests were performed on recycled aggregates to identify their acceptability. Table 4 presents the test results of RA.

Table 4. Physical and mechanical test results of recycled aggregates

Test	Result	Limits	Code
Fine Aggregates			
Specific Gravity	2.70	2.5-2.9	IS 2386 Part 3 [27]
Fineness Modulus	2.51	2.2-2.9	IS 383 [28]
Water Absorption [%]	1.30	< 2.0%	IS 2386 Part 3 [27]
Coarse Aggregates			
Specific gravity	2.69	2.5-2.9	IS 2386 Part 3 [27]
Aggregate Impact [%]	24%	< 30%	IS 2386 Part 4 [29]
Crushing Value [%]	25%	< 30%	IS 2386 Part 4 [29]
Water Absorption [%]	0.8	< 2.0%	IS 2386 Part 3 [27]

2.2.4. Alkaline Solution Preparation

The required concentration solution of NaOH for the mix of GPC was produced by liquefying industrial-grade NaOH flakes in distilled water for 24 hours prior to the addition of Na_2SiO_3. The dosage of NaOH flakes to be added per litre of water to make a solution for required molarities is shown in Table 5.

Table 5. Calculations of molarity values

Molarity (M)	Weight of NaOH (gm/lt.)
10	400
12	440
14	480

2.3. Mix Design

The mix proportionate of concrete mass plays a prime role in its performance. Hence, the mix proportion must be carefully selected to develop durable concrete. The mix designs for conventional cement concrete, and GPC were calculated according to the IS code guidelines before further laboratory investigations.

2.3.1. Conventional Concrete Mix Design

The mix design of M_{30}, M_{35}, and M_{40} grades conventional cement concrete, which was designed as per IS 10262:2019. The materials proportionate obtained are tabulated in Table 6.

Table 6. Mix proportion of conventional cement concrete mix

Sl. No	Conventional Concrete	Cement	Fine aggt.	Coarse Aggt.	W/C ratio
1	M-30	1	1.63	2.64	0.45
2	M-35	1	1.60	2.90	0.43
3	M-40	1	2.07	2.26	0.36

2.3.2. Geopolymer Concrete Mix Design

Geopolymer Concrete (GPC) mixtures were prepared using materials like fly ash, recycled aggregates and alkaline activators with NaOH concentrations of 10 M, 12 M, 14 M.

Then, the alkaline liquid ratios of 2.5, 5.0 and 7.5 are made with alkaline liquid/binder ratio combinations of 0.4. The needed mix design was performed by following conventional methods, such that 75% combined aggregates and the remaining 25% binder with alkaline liquids of the total mass of the GPC mixture were considered [30]. The mix proportions followed in this study are summarized in Table 7.

2.4. Preparation of Specimens

The procedure endorsed in the preparation of geopolymer concrete specimens is as follows:

- Blending of Materials: Dry blending of fly ash, recycled aggregates, and M-sand was carried out for even distribution. The pre-prepared (24hrs before cast) solution of NaOH was blended with Na_2SiO_3, and the obtained solution was transferred to the dry mix and gradually mixed properly.
- Specimen Casting: The fresh GPC mix was cast into standard moulds (cubes to compression, beams to flexural and cylinders to split tensile strength tests). The mix was vibrated for 15 seconds to expel the entrapped air.
- Curing Process: Specimens were left to harden for 24 hours at room temperature and oven-cured for 24 hours at 60°C for early strength gain by geo-polymerization reaction. After curing, the specimens were demoldened. Standard guidelines of the IS code were followed for the casting and curing of conventional concrete specimens.

2.5. Testing of Specimens

To test the PC's performance, the following tests were conducted:

- Compression Test: Performed on cubes according to IS:516 of 1959, using CTM of 2000kN frame capacity.
- Test for Flexural Strength: A test for specimens was conducted to measure the resistance of GPC against bending force.
- Split Tensile Test: Conducted on cylindrical specimens to check tensile strength properties of GPC.
- Water Absorption Test: Performed to find the permeability of hardened GPC.
- Acid Resistance Test: Performed to determine the resistance to disintegration in an acid environment.
- Microstructure Analysis: Advanced methods like SEM and EDX analysis were performed on the specimens of the optimized mix to study the morphological factors, formation of geopolymeric gel, and structure-like crystal.

Figure 3 depicts the methodology adopted in this study for test specimen preparation and tests conducted.

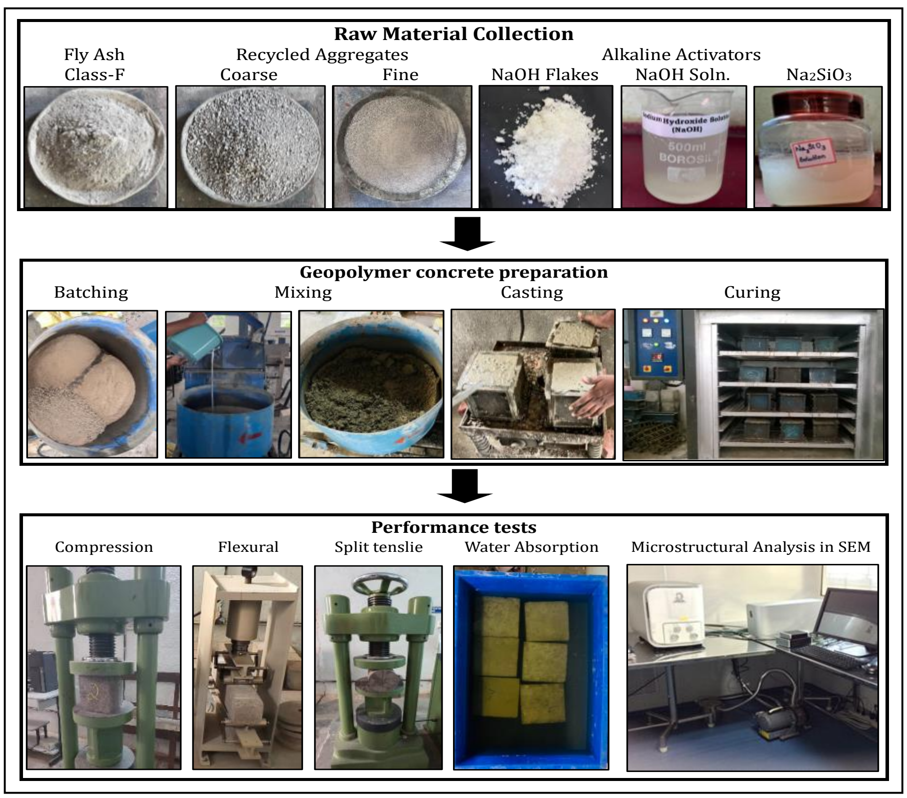


Fig. 3 Methodology adopted in this study for test specimen making and testing

Table 7. Mix proportions of GPC mix

ID	M	AL/B	Weight of combined aggregates (kg)		Weight of binder and alkaline liquid (kg)	Na_2SiO_3/ NaOH ratio	Fly ash (Kg/m^3)	AAS (Kg/m^3)	
			Recycled fine aggregates	Recycled coarse aggregates	Flyash +NaOH+Na_2SiO_3			NaOH	Na_2SiO_3
1	10	0.4	720	1080	600	2.5	462	39.43	98.57
2			720	1080	600	5	462	23	115
3			720	1080	600	7.5	462	16	122
4	12		720	1080	600	2.5	429	49	122
5			720	1080	600	5	429	28.5	142.5
6			720	1080	600	7.5	429	20	151
7	14		720	1080	600	2.5	400	57	147
8			720	1080	600	5	400	33.33	167
9			720	1080	600	7.5	400	23.5	176.5

Note: ID-Mix Design, M-Molarity, AL/B - Alkaline liquid/binder ratio and AAS-Alkaline activators solution.

3. Results and Discussion

3.1. Properties of Cement Concrete

The conventional cement concrete specimens are prepared to find out mechanical properties. These specimens were water-cured for 28 days before the test. The test results are tabulated in the Table 8.

3.2. Properties of GPC

The laboratory tests were employed on hardened GPC specimens after 48 hours of casting and curing to evaluate the mechanical durable characteristics.

The laboratory experiment findings are listed in Table 9 and graphically represented in Figures 4, 5, 6, and 7.

Table 8. Mechanical & durable properties of conventional concrete

Conventional Concrete	M-30	M-35	M-40
Compressive Strength (MPa)	38.5	44.2	48.7
Flexural Strength (MPa)	4.5	5.1	5.4
Split Tensile Strength (MPa)	3.2	3.6	3.9
Water Absorption (%)	2.5	2.3	2.0
Acid Resistance (% loss)	6.8	6.1	5.5

Table 9. Mechanical & durable properties of conventional concrete

ID	1	2	3	4	5	6	7	8	9
Compressive Strength (MPa)	31.67	34.51	35.30	46.24	49.15	52.74	30.25	35.21	36.04
Flexural Strength (MPa)	2.56	2.62	2.69	3.70	3.92	4.68	2.34	2.42	2.48
Split Tensile Strength (MPa)	2.37	2.58	2.64	4.16	4.42	4.54	2.19	2.66	2.32
Water Absorption (%)	6.15	5.80	5.25	4.60	4.34	4.02	5.65	5.40	5.10
Acid Resistance (% loss)	7.25	6.80	6.45	5.35	4.95	4.62	6.95	6.50	6.20

3.2.1. Effect of Varying Alkaline Liquid Ratio and Molarity on Compression Strength

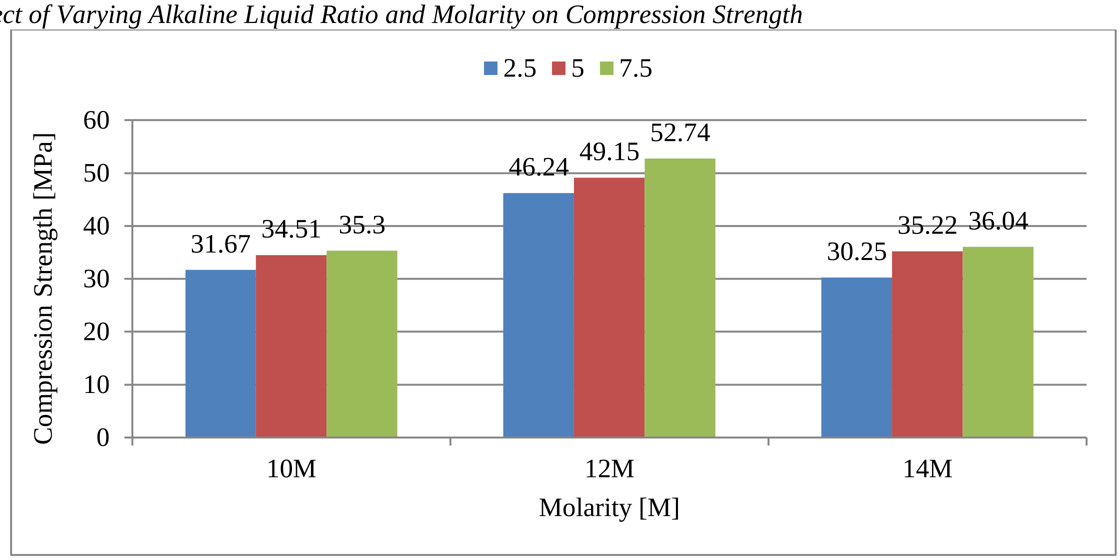


Fig. 4 Molarity v/s Compression Strength

The compression strength results are shown in Figure 4, which shows that the mixed proportions of GPC affect the strength to a greater extent. The highest strength of 52.74 MPa was found in Mix 6 with 12M NaOH, Al/B of 0.4 and an AL ratio of 7.5. The findings highlighted that the increased alkaline activation maximized the reaction of geo-polymerization. This effect is responsible for the dense and well-organized GPC matrix. The strength is less in the 10M mix due to polymerization incompletion and unreacted fly ash particles. Lower strength values of Mixes 1, 2 and 3 indicate an incomplete activation of fly ash particles, leading to poor bonding between the binder-aggregates and weakened matrix formation.

3.2.2. Effect of Varying Alkaline Liquid Ratio and Molarity on Flexural Strength

The flexural strength values also follow the trend shown in Figure 5 and Mix 6, which has a maximum value of 4.68 MPa. The enhanced geopolymer matrix provided higher cohesion and bending stress resistance. A higher alkaline liquid ratio assisted in the higher dissolution of alumina and silica, resulting in better gel formation and better interfacial bonds among aggregates. Mixes 7, 8 and 9 had lower flexural strength values, which shows poor bonding due to a weaker geo-polymerization process.

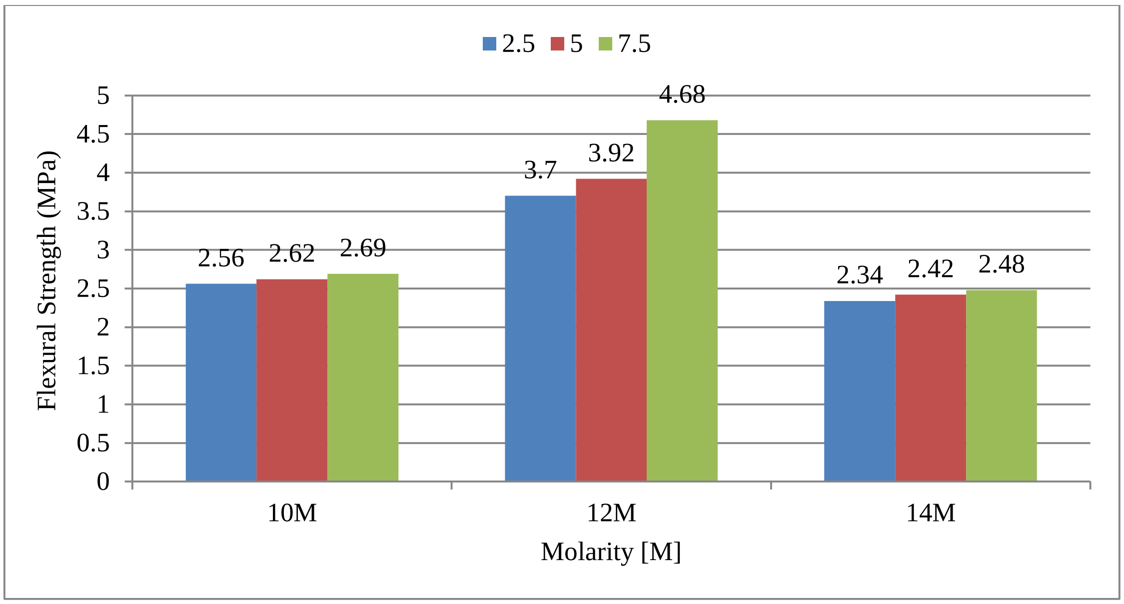


Fig. 5 Molarity v/s Flexural Strength (MPa)

3.2.3. Effect of Varying Alkaline Liquid Ratio and Molarity on Split Tensile Strength

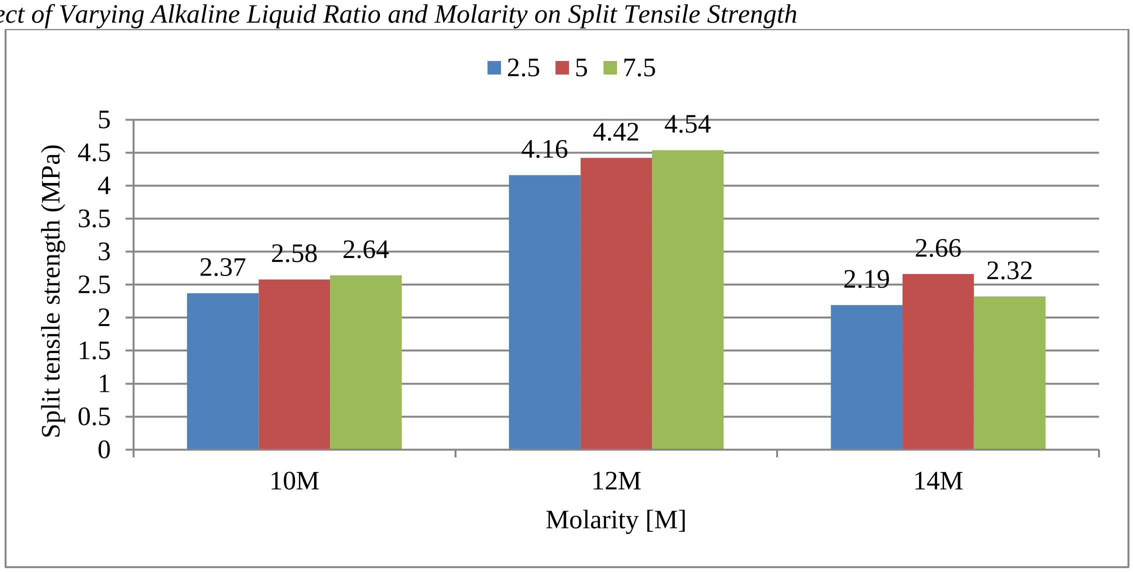


Fig. 6 Molarity v/s Split tensile strength (MPa)

From Figure 6, splitting tensile strength for mix 6 was the best, with a maximum value of 4.54 MPa. Increased tensile strength could be attributed to the increased development of aluminosilicate gels that enhanced cohesion between the matrix and helped in load-carrying capacity. A decreased split tensile strength in other mixes, particularly at lower NaOH molarity, indicates a weaker microstructure with poor tensile resistance formed due to incomplete activation. The effect of the alkaline liquid ratio was also pronounced as increased ratios enhanced polymerization and resulted in increased tensile strength. Effect of varying alkaline liquid ratio and molarity on split tensile strength.

3.2.4. Effect of Varying Alkaline Liquid Ratio and Molarity on Water Absorption

The outcome of the water absorption test also determines the effect of mixed proportions on the durability of GPC. From Figure 7, Mix 6 recorded the lowest value of water absorption of 4.02%, which is a sign of good compaction of the microstructure with low porosity. The lower permeability of this mix is attributed to the ideal binder content and dissolving of aluminosilicate compounds, leading to a dense and impermeable matrix formation.

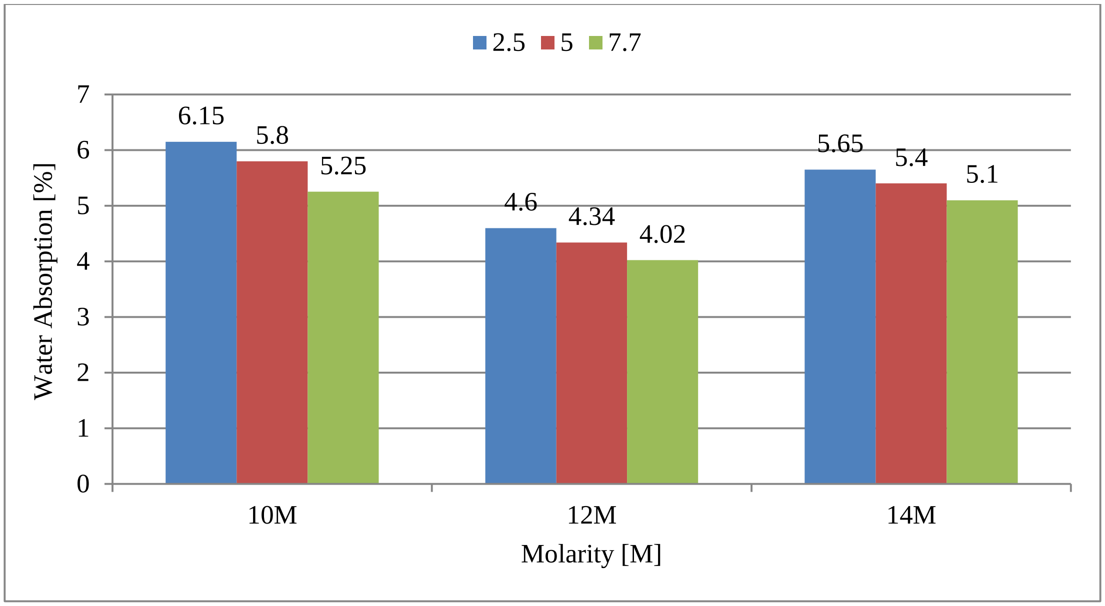


Fig. 7 Molarity v/s Water absorption (%)

3.2.5. Effect of Varying Alkaline-Liquid Ratio and Molarity on Acid Resistance

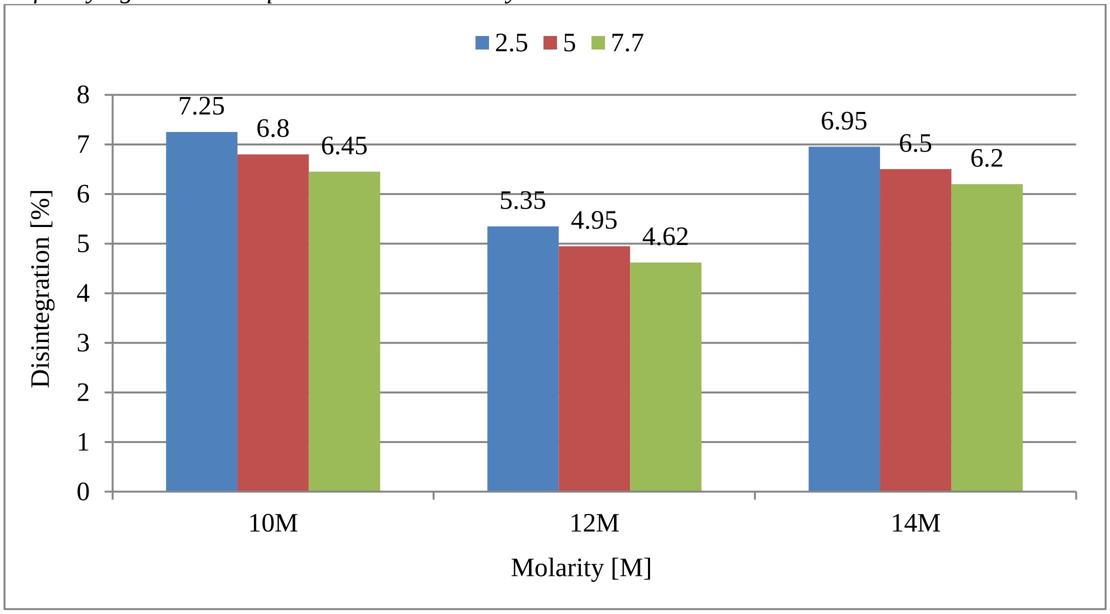


Fig. 8 Molarity v/s Disintegration (%)

The acid resistance of GPC was evaluated by measuring the weight loss percentage after exposure to an acidic environment. As observed in Table 9 and Figure 8, the GPC mixes of higher molarity exhibited lesser weight loss, indicating improved acid resistance. In specific, mixes with 12 M and 14 M molarity (IDs 4-6) showed weight losses ranging from 5.35% to 4.62%**,** significantly lower than those with 10 M molarity (IDs 1–3), which ranged from 7.25% to 6.45%. This trend can be attributed to an enhanced geopolymerization process at higher molarities, resulting in a denser microstructure with reduced permeability. A lower alkaline liquid-to-binder ratio in these mixes also reduced porosity, further improving acid resistance. These findings demonstrate that increased molarity of alkaline activator and optimizing the liquid ratio effectively enhance the durability of GPC in aggressive environments.

3.3. Comparison of Conventional Concrete and GPC Mix

A comparative analysis of Conventional concrete and GPC from Tables 8 and 9 reveals that conventional cement concrete exhibits higher mechanical strength and better durability performance than geopolymer concrete at lower molarities. However, geopolymer mixes with higher molarity (12 M and 14 M) show comparable and better results, particularly in compressive and tensile strength, and improved acid resistance than conventional concrete. Notably, GPC mixes 4 to 6 demonstrate compressive strengths exceeding 46 MPa and lower acid-induced weight loss, indicating enhanced resistance in aggressive environments. While water absorption is slightly higher in GPC, the performance gap narrows with increased molarity, highlighting the potential of GPC as a sustainable alternative to OPC systems.

3.4. Casting of Precast Element-Paver Block

The precast elements were cast using a GPC mix after optimizing it for better performance. The precast element, the paver block, was cast in the laboratory. The tests were done to check their strength and water absorption levels. The paver blocks of I-shaped and Zig-zag patterns were selected for casting in this study. The guidelines for aspect ratio, thickness and casting procedure were followed as mentioned in IS:15658 of 2006 [30]. The compression strength and water absorption tests were done on the hardened paver block. The casting, curing, and testing process followed is shown in Figure 9. The results are mentioned in the Table 10.

Casting, Curing and Testing of Fly ash GPC Paver blocks

Fig 9. Preparation of paver block

Table 10. Test results of paver block

Specimen	Tests	Results	Reference
I-Shaped	Compression test	51.28 MPa	IS 516:1959 [27]
	Water absorption	4.10 %	IS 1199:1959 [28]
Zig-zag	Compression test	54.10 MPa	IS 516:1959 [27]
	Water absorption	3.85 %	IS 1199:1959 [28]

The compression strength values of I-shaped and zig-zag paver blocks are 51.28MPa and 54.10MPa, respectively, similar to the average compressive strength of cube 52.74MPa. The water absorption percentage of I-shaped and zig-zag paver blocks are 4.10 % and 3.85 %, respectively. There was no notable increase or decrease in strength and water absorption results of the GPC paver block. Hence, the GPC can be suggested for manufacturing precast elements like paver blocks.

3.5. SEM

SEM testing was done on the optimum mix of 12M NaOH content, AL/B of 0.4 and alkaline solution ratio of 7.5, which performed the best mechanically among all the mixes under consideration. Figure 10 demonstrates the high-magnification SEM images taken at different magnifications (×100, ×240, ×500, ×550, ×800 and ×1100) to investigate the internal structure, distribution of fly ash particles, formation of polymerized matrix and the existence of voids or microcracks. The SEM micrographs show a dense, well-developed geopolymer matrix with a high proportion of fully reacted fly ash particles, which is the reason for the enhanced mechanical properties of the mix. Higher alkali activator content ensured efficient silica [SiO_2] alumina [Al_2O_3] dissolution from fly ash to form homogeneous aluminosilicate gel that well bonded the matrix. The dense and compact structure confirms the high level of geopolymerization, which is directly related to the enhanced compressive, flexural, and tensile strength measured in the mechanical tests. The polymerized matrix is continuous with fewer gaps, which signifies efficient binding and low porosity in the GPC mass [34, 35].

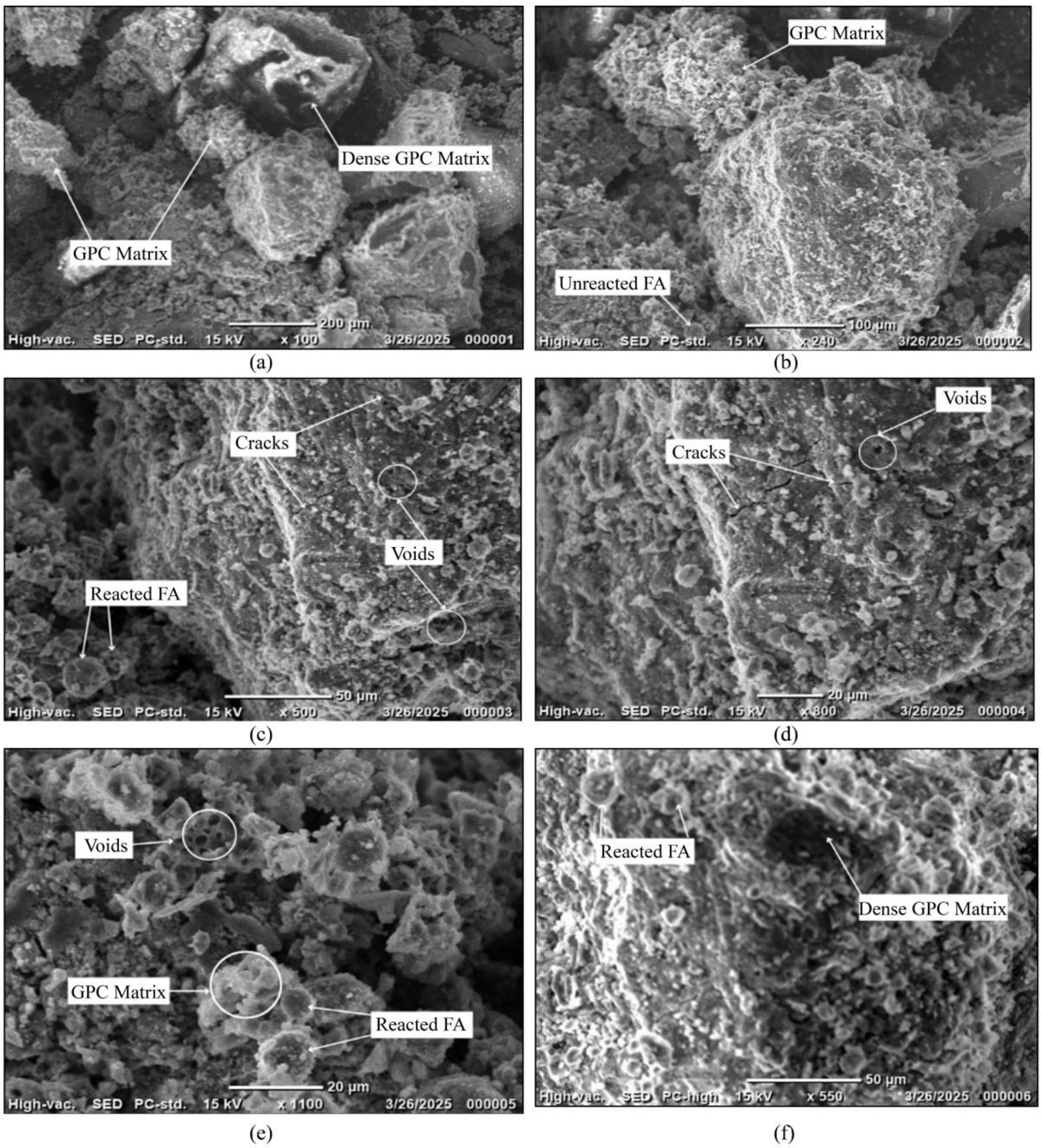


Fig. 10 Micrographs from SEM with magnifications (a) x100, (b) x240, (c) x500, (d) x800, (e) x1100, and (f) x550.

Discrete islands of unreacted fly ash particles are observed in trace quantities, showing that most fly ash underwent a chemical reaction and formed a stable geopolymer network. Rare unreacted fly ash spherical particles are observed trapped within the matrix, but these do not compromise the structure's integrity to any great degree.

The particles will likely be unreacted because of limited exposure to the alkaline activators during the mixing process. However, the quantity is significantly lower than in previous studies with lower molarity of NaOH and less than optimal alkaline liquid ratios. Unreacted particles are covered with well-crystallized geopolymer gel, which shows partial dissolution and participation in the polymerization reaction.

In addition, voids and microcracks also appear at higher magnifications but are relatively few and do not appear to propagate much within the matrix. Low void content in the optimized mix indicates better compaction and effective gel formation, improving water absorption and durability. Low microcracking indicates the internal stress distribution of the GPC matrix to be better controlled, most likely due to the optimal alkaline solution ratio yielding enough polymerization and low shrinkage effects.

Cracks, if present, are most likely caused due to thermal shrinkage when oven curing is performed at 60°C for 24 hours. Their contribution to the overall performance, however, is negligible, as the network of polymerized gel does not allow extensive propagation of cracks.

SEM analysis shows that the extremely dense microstructure is consistent with the high strength values obtained in the experimental tests. The existence of continuous, dense, and homogeneously distributed geopolymer gel proves that this mix provides higher compressive, flexural, and split tensile strength with low permeability.

The higher reaction of fly ash optimized alkaline ratios resulted in a higher formulation of C-S-H & N-A-S-H gels, responsible for the higher bonding and overall strength of the GPC mass.

3.6. EDX Analysis

The optimized mix specimen was subjected to EDX spectroscopy analysis with the help of analysis station JED-2300. The role of fly ash GPC chemical composition on microstructural and strength properties was determined by this analysis method. With no surprise, the analysis results confirmed the traces of Silicon [Si], oxygen [O], alumina [Al], and other various oxides, which are believed to be held responsible for triggering the geo-polymerization reaction leading to the mechanical strength development.

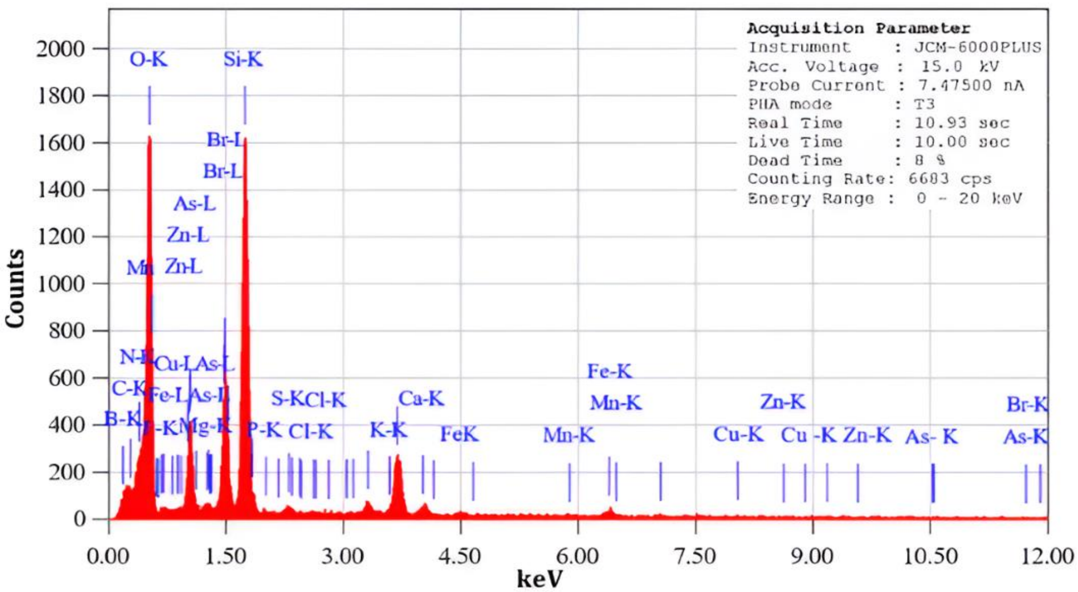
The elements like Silicon [Si] and aluminium [Al] at high peaks were observed in the spectrum of EDX, as shown in Figure 11. This proves the fly ash reaction with alkaline activators at higher levels. These are the main elements essential in forming the binding phase in GPC, named sodium aluminosilicate hydrate (N – A – S – H) gel. Also, it was found that greater Si/Al ratios have well-formed matrices in GPC with active polymerization reaction, resulting in higher strength values. The increase in C – S – H gel formation observed due to the traces of reactive silica in fly ash, in turn, makes the concrete strong and more durable. The oxygen (O) content of the GPC matrix is very high, as it reinforces the chemical bonding among silica, alumina, and alkali activators. The oxygen content is directly associated with the polymerization of aluminosilicate compounds, forming a dense and free-volume structure. Uniformly distributed dispersed oxides are accountable for lowering the porosity, diminishing the absorbed water and enhancing the long-term durability.

Bromine (Br) traces in trace amounts could be attributed to impurities in raw materials or external environmental influences. Its influence on mechanical performance is, however, insignificant compared to the overriding Effect of Si, Al, and O. The combined oxide content of 24.0% is indicative of a high level of chemical reaction, as also evidenced by microstructural observation from SEM analysis of a closely packed geopolymer matrix with few unreacted fly ash particles. Utilization of the JED-2300 analysis station allowed accurate detection and quantification of elemental composition, ascertaining high accuracy in assessing the chemical structure of the GPC matrix.

The EDX result indicates successful geo-polymerization in the selected mix at 12M NaOH, 0.4 alkaline liquid-to-binder ratio and 7.5 alkaline solution ratio. The dominance of Si and Al peaks and high total oxide content support the development of a strong, durable, and well-bonded geopolymer concrete matrix.

3.7. Overall Summary

The comparative study between conventional cement concrete and GPC highlights significant durability and mechanical performance differences. Conventional mixes (M30–M40) consistently exhibit higher early-age strength and lower water absorption due to the well-established hydration mechanism of OPC. However, the GPC with higher molarities (12 M and 14 M) achieves comparable and superior compressive, flexural and split tensile strengths. Moreover, GPC demonstrates better acid resistance at increased molarity levels due to the denser and more chemically stable geopolymer matrix. These results underscore the viability of GPC as a sustainable, durable alternative to OPC systems.



Standard Quantitative Analysis (Oxide)
Fitting Coefficient: 0.0851
Total Oxide: 24.0

Element	(keV)	Mass%	Sigma	Mol%	Compound	Mass %	Cation	K
B K*	0.183	15.96	0.94	47.87	B_2O_3	51.39	10.44	5.3922
C K		ND		ND		ND		
N K*	0.392	0.45	0.24	2.08	N	0.45	0.00	1.6434
O		54.32				ND		
F K*	0.677	0.51	0.09	1.76	F	0.51	0.00	1.3566
Na K*	1.041	3.68	0.15	5.19	Na_2O	4.96	1.13	9.4306
Mg K*	1.253	0.25	0.05	0.67	MgO	0.42	0.07	0.5831
Al K*	1.486	1.83	0.34	2.20	Al_2O_3	3.45	0.48	5.7762
Si K	1.739	11.53	0.33	26.62	SiO_2	24.66	2.90	35.3130
P K*	2.013	0.04	0.05	0.04	P_2O_5	0.09	0.01	0.1332
S K*	2.307	0.21	0.06	0.42	SO_3	0.51	0.05	0.7395
Cl K*	2.621	0.04	0.02	0.08	Cl	0.04	0.00	0.1616
K K*	3.312	0.60	0.06	0.50	K_2O	0.73	0.11	2.4013
Ca K*	3.690	4.25	0.16	6.88	CaO	5.95	0.75	17.7239
Mn K*	5.894	0.09	0.07	0.11	MnO	0.12	0.01	0.3206
Fe K*	6.398	1.34	0.15	1.56	FeO	1.73	0.17	4.6122
Cu K*	8.040	0.06	0.14	0.06	CuO	0.07	0.01	0.1857
Zn K*	8.630	0.28	0.20	0.28	ZnO	0.35	0.03	0.9031
As L*		ND		ND		ND		
Br L*	1.480	4.54	0.40	3.68	Br	4.54	0.00	13.3238
Pb M*		ND		ND		ND		
Total		**100.00**		**100.00**		**100.00**	**16.16**	

Fig. 11 EDX graph with peak points

The study successfully captured the high-performance aspects of fly ash GPC with optimized alkaline activator ratios. The experimental study identified that the chosen mix parameters (12M NaOH, 0.4 AL/B ratio, and 7.5 alkaline solution ratio) were responsible for a well-structured geopolymer network, improving strength and durability. The mechanical tests identified exemplary improvements in compressive, flexural, and tensile strengths, with the optimized mix yielding the highest values among all the tested samples. The water absorption results also captured a low-porosity matrix, improving moisture penetration resistance and long-term durability.

Microstructure examination by SEM validated the successful polymerization of the fly ash into a very dense geo-polymer matrix with few voids, reduced cracks and a strong interparticle bonding network. The EDX examination also validated the chemical composition and rich silicon and aluminium content for forming a robust N – A – S – H gel structure. Evidence of balanced oxide composition ensured successful chemical reactions, validating the creation of a stable and durable concrete matrix. The study also emphasized the sustainability potential of geopolymer concrete by using wastes from industries like fly ash, manufactured sand, and recycled aggregate. Not only does it decrease the environmental impact, but it also provides a sustainable option compared to conventional concrete. These findings suggest the structural use potential of geopolymer concrete with optimized mix designs for high strength, durability, and low carbon footprint. To verify its practical application, long-term durability implications, exposure to harsh environments, and widespread application in real construction projects can be further explored in subsequent studies. The GPC also has some limitations when used directly in the field. The mix cannot be prepared instantly as a cement concrete mix because the alkaline activators must be prepared 24 hours before mixing and preparing the GPC. Skilled workers are needed to handle the concrete since the workability of GPC is low. Curing is the central part of the strength development of the GPC mix, which needs elevated temperature for curing for 24 hours. Thus, the GPC is more suitable for precast element applications such as paver blocks, kerbstones, roof tiles, drainage cover slabs, etc.

4. Conclusion

These conclusions are drawn based on the laboratory investigation's findings on conventional and geo-polymerized concrete with recycled aggregates and varying alkaline activators.

- The 12M NaOH, 0.4 alkaline liquid to binder ratio, 7.5 alkaline solution ratio geopolymer concrete mix exhibited improved mechanical properties, which achieved 52.74 MPa compressive strength, 4.68MPa flexural strength and 4.54MPa split tensile strength than conventional concrete (M_{40}) which was found that 48.7MPa compression strength and 3.9MPa split tensile strength.
- 4.02% water absorption reflects a well-compacted and dense matrix with low porosity and increased durability of the perfect mix. Still, the water absorption is more than that of the conventional mix, which is 2%.
- The acid resistance test reveals that a GPC of 12M with a 7.5 alkaline liquid ratio and alkaline liquid/binder ratio of 0.4 is more durable than conventional concrete. GPC exhibits 4.62%, and conventional concrete exhibits 5.5% disintegration.
- SEM examination revealed a dense and homogeneous geopolymer matrix with well-reacted particles of fly ash, negligible amounts of unreacted fly ash particles, and fewer microcracks, suggesting successful polymerization and interparticle bonding.
- EDX analysis confirmed high Si and Al content, which is crucial for N-A-S-H gel formation, thus providing excellent mechanical strength and durability.
- Utilizing recycled aggregates in GPC significantly maximized sustainability by reducing reliance on natural resources with better performance.
- Differences in strength and water absorption between various mixes were explained by NaOH molarity, liquid alkaline ratio, and binder ratio, emphasizing the significance of mix optimization for optimal performance.
- According to the IS 15658-2006 code, the specified compressive strengths of paver blocks for the traffic categories like zero, light, and medium traffic are 30 MPa, 35 MPa, and 40 MPa, respectively. Hence, the compression strengths of all the GPC mixtures of 10M and 12M are greater than 30MPa, which makes them suitable for zero-traffic paver blocks. Also, all the 12M mixtures are suitable for light medium traffic category paver blocks.
- The study proved that the GPC is suitable for manufacturing precast elements like paver blocks.

4.1. Scope for Further Work

Long-term durability testing, like performance under harsh weather, chloride penetration, and freeze-thaw, should be prioritised for future fly ash-based Geopolymer Concrete (GPC) investigations. Further studies incorporating different curing conditions, e.g., ambient curing, to provide more practicality is recommended. Utilizing other industrial by-products as binders or additives will contribute more to sustainability. Large-scale structural performance testing and Life Cycle Assessment (LCA) are also needed to ensure its use in actual applications. Sophisticated microstructural investigation, including nano-scale characterization, can provide further insight into geo-polymerization mechanisms to optimize mix designs even more.

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