Exploring The Mechanical Integrity and Bonding Characteristics of Geopolymer Concrete: An Investigative Study

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Abstract— ***In contemporary civil engineering, Geopolymer concrete (GPC) has emerged as an ecologically sound alternative to conventional Portland cement-based concrete, owing to its enhanced mechanical properties and diminished carbon footprint. This study focuses on formulating GPC by partially replacing fly ash with Ground Granulated Blast Furnace Slag (GGBS) and utilizing an alkaline activator solution comprising sodium hydroxide and sodium silicate. Both mortar cubes and concrete specimens underwent testing, with variations in alkaline solution molarities and fly ash/GGBS proportions. Ambient temperature curing was employed, and the mixture design was optimized for optimal workability and strength. Comprehensive assessments of compressive, tensile, and flexural strengths were conducted to systematically evaluate the performance of GPC specimens. The microstructure of GPC was analyzed using X-ray diffraction (XRD) to investigate the composition and morphology of the geopolymer (GPR) binder and its influence on concrete performance. A pull-out experiment was executed to assess the bond strength of GPC under diverse loading conditions. This research significantly contributes to the expanding knowledge base on GPC, furthering its application in sustainable building practices.***

Index Terms— ***Flyash, GGBS, Molarity, Proportions, Workability, Strength, Pullout Test***

I. INTRODUCTION

The imperative of ensuring sustainability for the well-being of the Earth and human progress is evident in various industries. This paper focuses on the concrete industry, a widespread contributor to global construction, and its substantial role in carbon dioxide (CO2) emissions, primarily stemming from the production of Portland cement, a key constituent. The environmental ramifications and resource constraints associated with this process will play a pivotal role in shaping the trajectory of sustainable development within the cement and concrete industry in the 21st century. This study seeks to contribute to the discourse on sustainable practices in the industry and underscore the significance of addressing environmental concerns for future growth. Depletion of high-quality limestone, essential for cement, poses a threat to Portland cement production. The potential elimination of concrete industry jobs in areas lacking quality limestone underscores the urgency for sustainable alternatives. Some regions face reduced cement production due to resource scarcity and environmental concerns. To address this, future concrete structures must adopt sustainable alternatives, emphasizing the use of recycled materials. Sustainable concrete should possess high thermal mass, durability, energy efficiency, and minimal waste generation. Sustainable construction minimizes environmental impact, employing "green" materials primarily made of recyclable or recycled elements, featuring low energy costs, exceptional durability, and minimal maintenance. High-performance cements and concrete, incorporating green components, reduce energy consumption and resource utilization. Concrete must continually evolve to meet growing user needs while considering immediate and long-term environmental effects in sustainable design.

II. GEOPOLYMER CONCRETE

Geopolymer concrete, termed by Davidovits in 1978, offers a sustainable option to conventional Portland cement-based concrete. GPR binders, featuring an amorphous microstructure similar to zeolites, employ fly ash and GGBS as primary binding agents. This eco-friendly approach not only mitigates environmental impacts linked to traditional cement but also leverages the distinctive properties of GPR binders. By utilizing fly ash and GGBS, GPC emerges as a promising and sustainable alternative in construction materials, contributing to ongoing discussions on eco-conscious building practices. Activation is accomplished via an alkaline solution comprising sodium hydroxide and sodium silicate.offering advantages such as reduced carbon emissions, enhanced durability, and lower energy consumption in manufacturing. This study aims to comprehensively examine the composition, characteristics, and investigates the mechanical properties of GPC utilizing fly ash and GGBS. Inorganic polymers, classified as geopolymers, consist of Aluminum (Al) and Silicon (Si) ions arranged in a chain-like configuration. Despite their amorphous morphology, the chemical makeup resembles naturally occurring zeolitic minerals. Geopolymerization initiates with a swift chemical reaction on Si-Al minerals within a highly alkaline setting, yielding a three-dimensional polymeric structure formed by Si-O-Al-O bonds, expressed by the molecular formula: $M_n [-(SiO_2) z–AlO_2] n. wH_2O$. In this formula, M signifies the alkaline element or cation (e.g., potassium, sodium, or calcium), - denotes a linkage, n indicates the degree of polycondensation or polymerization, z ranges from 1 to higher values up to 32, and w represents the number of moles of water. The synthesis of geopolymer material, as per equations proposed by van Jaarsveld, van Deventer et al. (1997) and Davidovits (1999), implies that geopolymer material can be derived from any silicon (Si) and aluminum (Al)-rich substance. The precise kinetics and mechanisms governing the reaction, setting, and hardening of GPR materials remain elusive. Nonetheless, proposed mechanisms generally encompass the following steps: a) Dissolution of Si and Al atoms from the source material by hydroxide ions ,b) Movement, orientation, or condensation of precursor ions into monomers. Introduction of monomers into polymeric structures during polycondensation or polymerization reactions, c) Isolating and examining each process independently can be challenging due to their overlapping and simultaneous occurrences.Davidovits (1999) classifies GPR into three fundamental forms:

1. Poly (sialate): with a repeating unit [- Si - O - Al - O -].
2. Poly (sialate-siloxo): with a repeating unit [- Si - O - Al - O - Si - O -].
3. Poly (sialate-disiloxo): with a repeating unit [- Si - O - Al - O - Si - O - Si - O -]. These structural variations offer insights into the composition and potential applications of GPR materials.

III. EXPERIMENTAL PROTOCOL

3.1 Materials Employed

While GPC is frequently acknowledged as an eco-conscious option, it may still incorporate a minute quantity of conventional Portland cement (OPC). This research abstains from using cement in the concrete production process; nevertheless, tests involving OPC are incorporated for comparative analysis. The OPC selected is OPC 53 grade Dalmia cement, functioning as a binder to enhance the setting and early strength development of the GPR mix. Emphasizing sustainability in GPC, a primary focus is on diminishing the OPC content. Fly ash, a byproduct of coal combustion and vital for geopolymerization due to its alumina and silica content, is a crucial component in GPC. Class C fly ash from the Neyveli thermal power plant is employed in this study. Ground Granulated Blast Furnace Slag (GGBS), an industrial byproduct rich in calcium and silicon from the iron and steel sector, can be incorporated into GPC to reduce alkalinity, elevate strength, and augment durability. The GGBS used is sourced from Chennai United Metal Industries. Sodium Hydroxide (NaOH), recognized as caustic soda, functions as a robust alkaline solution initiating the geopolymerization process and serving as an activator. It catalyzes the chemical interaction between the silicate component and aluminosilicate elements like fly ash. The ratio of sodium silicate to NaOH concentration plays a pivotal role in determining the characteristics of GPC. Sodium silicate, a liquid chemical, contributes the essential silica component for the reaction. Both sodium hydroxide and sodium silicate are procured from an industrial services distributor in Chennai. GPC necessitates fine aggregates to enhance cohesiveness and density, typically composed of crushed stone dust or sand. M-Sand is selected as the fine aggregate for this study, meeting criteria for inertness and the absence of contaminants that could impede the geopolymerization process. Coarse aggregates, providing structural stability and strength, consist of 20 mm natural aggregate for experimentation. Compatibility with the GPR binder is considered when selecting coarse aggregates to prevent negative reactions.

3.2 Preparation of alkaline liquid

The alkaline solution was formulated a day in advance of casting the geopolymer samples. This process involved determining the mass of NaOH needed, adding it to a calculated amount of water to achieve the required molarity. The solution was prepared in a 100 kg capacity bucket placed in an ice bath to facilitate rapid cooling, as the reaction of NaOH releases a significant amount of heat. Following this, a specified volume of Na2SiO3 solution was combined with the NaOH liquid, adhering to a ratio of 2.5 times Na2SiO3 to NaOH, as indicated by prior studies as the optimal proportion for attaining the intended results.

Figure (1): Mixing of alkali activator solution

3.3 Test on materials

Accurate proportioning of elements in the concrete mix relies on specific gravity, a crucial quantity for determining the relative densities of various materials like aggregates, water, and GPR binder. Proper mix design is vital to achieve desired GPC attributes like strength and workability. Assessing the particle fineness of constituent materials is essential in GPC production, optimizing overall performance, workability, reactivity, and particle packing for the creation of a sustainable and durable building material. To ensure consistent, high-quality concrete and maximize material utilization while meeting necessary performance standards, a comprehensive understanding of the water absorption characteristics of aggregates is imperative. Tests were conducted following IS 2386 (part -3)-1963 guidelines. Bulk density is a critical factor in assessing the structural performance of concrete. Concrete with higher bulk density tends to be stronger and more resilient, impacting workability. An ideal bulk density makes the mix easier to lay and compact, reducing the required labor and equipment.

Table 1. Test results on material properties

MATERIAL	SPECIFIC GRAVITY	FINENESS	WATER ABSORPTION (%)	BULKDENSITY (kg/m^3)
FLYASH	2.32	3.5	-	-
GGBS	2.82	3	-	-
CEMENT	3.14	3.2	-	-
FINE AGGREGATE (M SAND)	2.74	2.26 (Zone 3)	2.5	1632
COARSE AGGREGATE (20 mm)	2.7	7.4	0.7	1586

3.4 Tests on Geopolymer Mortar (GPM)

Achieving the necessary qualities in GPC mix design requires a thorough process of testing and adjustments. The optimization of GPC mixes involves extensive testing and modifications, particularly in the selection and dosage of alkaline activators, such as sodium hydroxide (NaOH). Testing various types and concentrations of alkaline activators is crucial to determine the optimal combination for geopolymerization. The setting times and strength evolution in GPC are notably affected by the concentration of NaOH, a pivotal factor in the geopolymerization process. Finding the best NaOH concentration through testing is essential to attain the desired strengths while ensuring practicality and cost-effectiveness. This study examines eight molar and six molar NaOH solutions. The proportion of fly ash to GGBS is a critical factor determining the final properties and environmental benefits of GPC.

Proportions between fly ash and GGBS at 70:30, 60:40, and 50:50 are investigated. To minimize errors and meet project specifications and performance standards, mortar cubes with different ingredient combinations and molarities are prepared. Due to the caustic nature of ingredients used in the alkaline activator solution, vigilance is necessary during its preparation. In the course of this research, the maintained proportion of NaOH to Na2SiO3 is set at 1:2.5. Achieving a uniform and highly alkaline activator solution involves a meticulous process of gently adding NaOH pellets to water, stirring, and gradually combining with sodium silicate solution. These careful steps ensure the quality of GPC, adherence to design guidelines, and environmental advantages.

Table 2. Quantity of materials for different molarities of alkali activator solution

INGREDIENTS	8 MOLARITY	6 MOLARITY
Sodium hydroxide	312 g	200 g
Sodium silicate	780 ml	500 ml
Water	688 ml	800 ml

Experimental assessments were performed to determine the initial setting time (IST) and final setting time (FST) of geopolymer binder pastes.. Following the mix design guidelines, measure Fly ash, GGBS, and M sand in a 1:3 ratio for binder material to fine aggregate. Prepare a 75mmx75mmx75mm mold for casting mortar cubes, requiring 600g M-sand and 200g binder material. For the alkaline activator solution, blend sodium silicate and sodium hydroxide in appropriate ratios, ensuring adherence to safety protocols. Methodically integrate aluminosilicate materials with the activator solution to generate the initial GPR paste. Once the right consistency is achieved, carefully pour the GPR mortar into the mold. Compaction is performed with a tamping rod, and curing is done at ambient temperature. Designations like GPM 78, GPM 68, and GPM 58 represent GPR mortar cubes with flyash and GGBS in proportions of 70:30, 60:40, and 50:50, respectively, all activated by 8M sodium hydroxide solution. Similarly, GPM 76, GPM 66, and GPM 56 indicate GPR mortar cubes with 70:30, 60:40, and 50:50 ratios of fly ash and GGBS, individually activated using a 6M sodium hydroxide solution. The compressive strength (CS) at 7 days (CS7) and 28 days (CS28) was measured utilizing a compressive strength testing machine.

Table 3. Test results on 8M and 6M mixes

MIX	Consistency	8 Molarity		6 Molarity	
		IST (in minutes)	FST (in minutes)	IST(in minutes)	FST(in minutes)
GPM76	30 %	20	110	20	100
GPM66	30 %	15	100	20	110
GPM56	28 %	15	90	20	100

Table 4. Test results on 8M and 6M GPR mortar cubes

MIX	8 Molarity		6 Molarity	
	CS7 (MPa)	CS28 (MPa)	CS7 (MPa)	CS28 (MPa)
GPM76	14.25	26.13	13.23	25.32
GPM66	16.23	28.54	17.89	29.22
GPM56	18.24	30.35	18.24	27.97

3.5 Designing the composition of GPC blends.

GPC, recognized as a pioneering and environmentally friendly substitute for conventional Portland cement concrete, captures the attention of researchers keen on comprehending its attributes, resilience, and ecological advantages. The choice of M30 grade GPC proves to be a practical option for research, particularly in scenarios requiring large quantities. Its cost-effectiveness compared to higher-grade concretes makes it an appealing choice for experimental studies in concrete technology and sustainability, balancing strength, affordability, and research potential. Presently, there exists no established codal methodology for the mix design of GPC. Achieving the refinement of mix design involves an exhaustive examination of available literature. In this current investigation, emphasis is placed on formulating the mix design specifically for M30 grade GPC.Concrete specimens are cast for varying proportions, specifically 70:30 (GPC78), 60:40 (GPC68), and 50:50 (GPC58) ratios of fly ash and GGBS, maintaining a sodium hydroxide concentration of 8 molarity.

Table 5. Optimized mix proportions of GPC

MIX	Sodium silicate (kg /m³)	Sodium hydroxide (kg /m³)	Extra water (kg /m³)	Fly ash (kg /m³)	GGBS (kg /m³)	Fine aggregate (kg /m³)	Coarse aggregate (kg /m³)
GPC78	216	86	5	385	165	531	917
GPC68	216	86	8	330	220	531	917
GPC58	216	86	11	275	275	531	917

3.6 Manufacturing of GPC specimens

Ensuring the structural integrity and functionality of GPC necessitates the examination of its mechanical characteristics in both its fresh state, which includes workability, and its hardened state, encompassing flexural strength (FS), split tensile strength (SS), and compressive strength (CS). The assessment of bond strength commonly employs a pull-out test, particularly in the evaluation of the bond between reinforcing bars (rebar) and concrete within GPC structures. This study extensively explored each of these properties. The formulation of an optimal mix design played a critical role in creating GPC specimens. To accelerate the geopolymerization process, plastic coverings were applied to the specimens during the ambient curing phase. The focus of this investigation revolved GPC specimens under ambient conditions

Figure. (3): a) GPC specimen casting b) Curing of specimens under plastic covers

3.7 Workability Tests

To evaluate the pourability and compaction characteristics of GPC, assessments were conducted using workability tests, including the slump test and compaction factor test.

Table 6. Workability tests on GPC specimen

Mix	Slump value	Compaction factor	Workability
GPC78	30	0.86	Low
GPC68	55	0.9	Medium
GPC58	100	0.95	High

3.8 Compressive strength test

Manufactured cubic specimens, sized at 150mm x 150mm x 150mm, underwent standard curing procedures. Subsequently, these specimens were positioned within a compression testing apparatus, and the gradually applied maximum load was recorded until specimen failure. Compressive strength (CS) was determined by dividing the load by the specimen's area.

3.9 Split Tensile Strength Test

This examination evaluates the resistance of GPC withstand tensile forces, a crucial factor in evaluating the durability and crack resistance of the material. Cylindrical specimens, prepared and cured under standard conditions, are utilized for this test. The specimen undergoes a compressive load applied by two parallel platens until it fractures longitudinally, revealing the force required to split the specimen. The resistance of the concrete to tension forces is quantified by its split tensile strength (SS), expressed in MPa.

3.10 Flexural Strength Test

This test evaluates the bending or flexural stress-bearing capacity of GPC, particularly relevant for applications like slabs and beams. Specimens shaped like beams or prisms are prepared and cured, and the specimen is loaded at its midpoint while being supported. The maximum load is recorded as the specimen is subjected to a load until it fails to bend. The concrete's resistance to bending forces is determined by its flexural strength (FS), expressed in MPa.

Figure (4): a) CS Test b) SS Test c) FS Test

Table 7. Results of tests for compressive, split tensile, and flexural strength in GPC

MIX	Tests conducted	7th Day (MPa)	28th day (MPa)
GPC 78	CS	21.83	26.23
	SS	1.02	2.92
	FS	1.5	3.98
GPC 68	CS	22.23	28.32
	SS	1.23	3.13
	FS	1.98	4.22
GPC 58	CS	24.533	30.15
	SS	1.428	3.33
	FS	2.13	5.15

3.11 Non Destructive Tests

To evaluate the properties of GPC without causing harm, non-destructive testing (NDT) methodologies were applied. The Rebound hammer was utilized to assess surface hardness, serving as an indicator of compressive strength. Following the guidelines of IS 13311 (Part 1): 1992, the Ultrasonic Pulse Velocity (UPV) test for concrete was employed as a non-destructive approach to evaluate the quality and integrity of concrete structures. This technique entails measuring the velocity of sound waves traversing the concrete, offering insights into the material's quality.

Table 8. Results of Rebound hammer test (RHT)

MIX	7th Day (MPa)	28th day (MPa)
GPC 78	16	24
GPC 68	18	26
GPC 58	20	28

Figure (5): a) RHT b) UPV

Table 9. Findings from the ultrasonic pulse velocity assessment.

Mix	7 th Day (km /s)	28 thDay (km /s)	Inference
GPC 78	3	3.3	Medium
GPC 68	3.5	3.9	Good
GPC 58	3.8	4.1	Good

3.12 PULLOUT TEST

Pull-out assessments were conducted to evaluate the bonding strength between concrete and reinforcing bars (rebar) in GPC structures, gauging the force required for the bond to rupture under progressively increasing axial loads on a bonded area. Adhering to the specifications outlined in IS 2770:1967 (reaffirmed 2002), pull-out test specimens were cast in cube forms. The study employed deformed steel bars, with 100 mm cubes accommodating 12 mm diameter bars. Each specimen integrated vertically embedded steel bars along its central axis. The bars extended upward from the cube's top face by 750 mm and downward from the bottom face by approximately 10 mm, ensuring sufficient length to pass through bearing blocks of the testing machine and achieve the necessary fixity. A helix, fashioned from 6 mm-diameter steel bars in compliance with Grade I of IS: 432-1:1982, and featuring a 25 mm pitch according to IS 2770:1967, reinforced the cubes. The outer diameter of the helix matched the size of the cube A specimen was mounted for testing in a universal testing machine (UTM) with a 100-ton capacity, with the bar axially pushed from the cube. A circular steel plate, featuring a hole for the bar, supported the bearing surface of the concrete cube. Test specimens underwent axial loading, applying tension to the extended lengths of the bars protruding from the cube's top face of the specimen was mounted for testing in applying tension to the extended lengths of the bars protruding from the cube's top face. Measurements of the bar's pullout concerning the concrete were acquired at both the loaded and free ends, utilizing dial gauges with a least count of 0.002 mm, following the specifications of IS 2770:1967.

1. The point at which the reinforcing bars exhibited yielding,
2. Failure of the surrounding concrete, or
3. The occurrence of a minimum slippage of 2.5 mm at the loaded end.

Initially, the bond stress is at its minimum on the outer concrete surface and reaches its maximum at the interface of the concrete and steel bar in the initial two stages. As fractures form and slip increases, the bond stress becomes uniformly distributed, leading to the computation of average bond stress (τ) using the following formula:

$$\tau = P / (\pi \times d \times l)$$

where, l represents the embedded length of the steel bar (mm), d indicates the diameter of the steel bar (mm), and P signifies the force in the bar (kN).

Table 10. Pull-out test results

Test Duration	Maximum bond stress at failure (MPa)	Bond stress at 0.25 mm slip (MPa)
7days	1.76	1.06
28 days	2.32	1.95

Figure (6) a) Reinforcement for concrete casting b) Specimen casted for pullout test

Figure (7) a) Pullout test setup b) Failure by steel bar pulling out of concrete

3.13 X-ray Diffraction Test for Understanding Microstructural Properties

GPR concrete, known for its durability and environmental benefits, can be further enhanced by understanding its microstructure. This understanding facilitates the optimization of the combination, leading to improvements in strength, durability, and overall performance. X-ray Diffraction (XRD) is a primary tool for analyzing the mineralogical composition of concrete. It identifies crystalline phases like calcium silicate hydrates (C- S- H), calcium hydroxide (C - H), and other products of hydration. XRD is instrumental in assessing hydration levels and detecting undesirable phases such as unreacted clinker or deleterious minerals (e.g., gypsum, ettringite). It is also valuable for studying structural changes in concrete over time, including during curing or exposure to diverse environmental conditions.

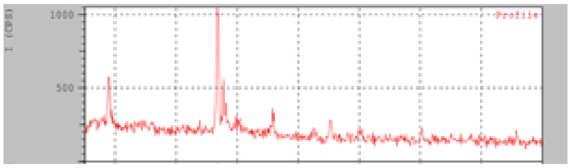

Figure (8): XRD pattern for GPC 58 (X Axis: 2theta, Y Axis: Intensity counts)

Table 11. XRD Result analysis of GPC58

Strongest peak number	Intensity counts	2 Theta	Compound
23	339	26.77	Mullite

7	134	8.96	Calcium Silicate Hydrate Gel
24	82	27.7	Quartz

IV. RESULTS AND DISCUSSION

In this section, the outcomes derived from diverse experiments were scrutinized to formulate specific conclusions based on the research findings. In evaluating the geopolymer paste, notable differences in setting times were observed when compared to traditional cement paste.

Figure (9) Comparison of various experimental results

1. Geopolymer paste, particularly those incorporating 8 Molar and 6 Molar sodium hydroxide solutions, exhibited remarkable initial set within 20 minutes and final set within 110 minutes.
2. The influence of Ground Granulated Blast Furnace Slag (GGBS) content on setting time and compressive strength revealed a decrease in setting time with an escalating percentage of GGBS.
3. The blend denoted as GPM 58, with a balanced 50:50 proportion of fly ash and GGBS, showcased superior compressive strength, surpassing other mix proportions. Noteworthy percentage increases in compressive strength from 7 days to 28 days were documented across various mixtures.
4. For instance, GPM 76 demonstrated a 47.74% increase, GPM 66 exhibited a 45.58% rise, and GPM 56 showcased a 38.77% increment. The compressive strength of GPC58 specifically showed an 18.63% enhancement at 28 days compared to 7 days, accompanied by substantial increases in split tensile and flexural strength.
5. A comparative analysis of compressive strength testing methods highlighted a 30.21% increase with the nondestructive method (Rebound hammer test) at 28 days, while the destructive method exhibited an 18.63% increase.
6. The bond stress characteristics in GPC 58 indicated robust strength, with maximum bond stress surpassing conventional M30 grade concrete (which is 1.5 MPa), reaching 2.32 MPa at 28 days.
7. These findings underscore the promising performance and enhanced bond strength of geopolymer concrete, particularly in formulations like GPC 58.

CONCLUSION

1. The heightened molarity of sodium hydroxide significantly enhances the mechanical properties of GPC, including compressive strength, split tensile strength, and flexural strength. This improvement is attributed to the intensified activation of aluminosilicate materials, fostering a robust geopolymerization process. The increased alkalinity of sodium hydroxide facilitates a stronger chemical reaction, enhancing bonding and mechanical properties within the GPC matrix and promoting the dissolution of Si and Al atoms from source materials, contributing to the creation of a durable GPR structure.
2. The optimal mix design with an 8 Molar NaOH solution and a 50:50 proportion of fly ash and GGBS demonstrates superior mechanical properties compared to other binder material proportions, striking a balance between workability and strength.
3. Geopolymer mortar exhibits faster setting times than ordinary Portland cement (OPC) mortar due to the swift geopolymerization process, omitting the slower hydration process of OPC. This unique

geopolymerization process, independent of traditional cement hydration, expedites setting times, providing insights into GPC's efficiency.

4. The increase in compressive strength percentages at 7 days (18.63%) and 28 days (30.21%) in GPC, tested destructively and nondestructively, is linked to the progressing geopolymerization process shaping material characteristics. Nondestructive methods, such as the Rebound hammer test, capture higher strength values by considering chemical reactions and structural advancement within the geopolymer matrix, providing a comprehensive evaluation of GPC strength evolution.
5. The elevated bond stress observed in GPC during pullout tests compared to OPC can be attributed to the unique bonding mechanisms of the geopolymerization process. The absence of traditional cement hydration in GPC results in a robust GPR structure with enhanced chemical bonds, leading to improved adhesion and interlocking with embedded steel reinforcement.

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