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Geopolymer Concrete: An Alternative to Conventional Concrete for Sustainable Construction

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ABSTRACT

Geopolymer concrete is a sustainable alternative to conventional concrete, offering significant environmental protection and carbon reduction benefits. This study presents a comparative analysis between Ordinary Portland Cement (OPC)-based conventional concrete (CC) and geopolymer concrete (GPC) utilizing ultrafine fly ash (UFFA) and ultrafine ground-granulated blast furnace slag (UFGGBS) as binders, with identical binder-to-aggregate ratios. GPC was developed using sodium hydroxide and sodium silicate as alkaline activators, while CC relied on OPC as its binding agent. The mechanical properties and durability of GPC were evaluated under controlled conditions. The results demonstrated that GPC is comparable to CC in terms of strength and durability. Moreover, GPC reduces CO_2 emissions by incorporating industrial by-products such as fly ash and slag as binders, replacing energy-intensive Portland cement and significantly lowering greenhouse gas emissions. This underscores the potential of GPC as a sustainable, eco-friendly material for modern construction, supporting environmental conservation and sustainability.

Keywords: Geopolymer; Ultrafine fly ash; Ultrafine GGBS; Sustainability; Conservation.

1. INTRODUCTION

Portland cement concrete is a highly engineered composite material consisting of Portland cement, water, sand, and crushed stone aggregate, which combine to form a durable, stone-like structure (Shah, 2017). Widely regarded as a cornerstone of modern construction, this material is valued for its adaptability and its role in enabling innovative architectural designs (Glavind, 2009). However, the increasing demand for cement production, driven by rapid infrastructure development worldwide, has heightened concerns related to climate change, sustainable practices, material durability, and efficient resource management (Mehta, 2004). The cement industry is a significant contributor to global CO_2 emissions, releasing approximately 0.83 kg of CO_2 per kilogram of cement produced. By 2020, it accounted for 12% of total global CO_2 emissions (Banu *et al*. 2017). The production of Portland cement alone generates over 4.1 billion tons of carbon dioxide annually, representing 5-7% of total anthropogenic greenhouse gas emissions linked to climate change (Aliabdo *et al*. 2016). These environmental concerns underscore the urgent need to adopt alternative, sustainable materials to minimize the ecological impact of Portland cement concrete (PCC) and reduce reliance on traditional resource extraction. Geopolymer concrete (GPC) has gained attention as a viable, eco-friendly alternative to CC, offering a potential solution to the environmental challenges posed by conventional cement production (Oyebisi *et al*. 2022). Geopolymer concrete (GPC) employs industrial by-products such as fly ash, ground-granulated blast furnace slag (GGBS), and silica fume, significantly reducing reliance on the energy-intensive production of Portland cement (Tanildizi and Gökalp, 2023). These materials undergo polymerization through the reaction with alkaline activators like sodium hydroxide and sodium silicate, resulting in a durable and environmentally sustainable binder. GPC offers several benefits, including lower carbon emissions, superior durability, energy efficiency, and mechanical properties comparable to or exceeding those of conventional concrete. The term "geopolymer" was introduced by Davidovits in 1979 to describe a group of mineral-based binders with an amorphous microstructure and a chemical composition similar to that of zeolites (Pacheco-Torgal 2015). Geopolymers are classified as inorganic polymers, characterized by chain structures formed on an aluminosilicate backbone of aluminum and silicon ions. While their chemical composition resembles natural zeolitic materials, geopolymers possess an amorphous microstructure rather than a crystalline one (Palomo *et al*. 1999; Xu and Van, 2000). Geopolymerisation is a polycondensation process that occurs between alumino-silicate precursors and alkali metal silicates in highly alkaline environments, leading to the formation of polymers characterized by Si-O-Al-O bonds (Bisarya, 2015). Unlike Ordinary Portland Cement (OPC), which gains strength primarily through the development of Calcium Silicate Hydrate (C-S-H) gel, geopolymers derive their structural strength from the polycondensation mechanism (Chowdhury *et al*. 2021). Studies have demonstrated that geopolymers can achieve an 80% reduction in CO_2 emissions compared to OPC, emphasizing their potential as an environmentally sustainable alternative (Pacheco-Torgal 2015). Although the setting and hardening mechanisms of geopolymer concrete (GPC) remain an active area of research, the formation of geopolymers can be represented by specific chemical equations, outlined by (Heah *et al*. 2015). The combined use of ultrafine fly ash and ground-granulated blast furnace slag (GGBS) as a partial replacement for cement in Portland pozzolana cement (PPC) demonstrates feasibility and has been reported to enhance the compressive strength and split tensile strength of concrete (Kumar *et al*. 2024). The replacement of cement in PPC with the blending of ultrafine GGBS and fly ash has also shown comparable results, reinforcing the use of pozzolanic materials across all types of concrete (Harshit *et al*. 2024). This study focuses on a detailed comparative analysis of conventional concrete and geopolymer concrete, with a focus on the use of ultrafine fly ash and ultrafine ground-granulated blast furnace slag (UFGGBS) as alternative binders. To ensure consistency and reliability in the comparison, the binder-to-aggregate ratio is kept constant across all concrete mixes. This methodology facilitates the assessment of both mechanical properties and durability, demonstrating the potential of GPC as a sustainable and eco-friendly alternative to traditional PCC.

2. MATERIALS

2.1. Cement

This study utilized Ordinary Portland Cement 43 Grade conforming to IS: 269-2015. The cement's properties were assessed as the following IS: 4031-1988, and the results are presented in Table 1.

Table 1. Chemical properties of OPC 43 grade

Constituent	Percentage
Loss on Ignition (L.O.I.)	3.43
Insoluble residue	3.24
SO_3	2.54
MgO	1.01
Chloride	0.030
CaO	63.70
SiO_2	22.00
Al_2O_3	4.25
Fe_2O_3	3.40

2.2. Fine Aggregate (FA)

Locally sourced natural sand that passed through a 4.75 mm IS sieve was employed as the fine aggregate in this study. Sieve analysis was carried out following the relevant Indian Standard code IS: 383-1970 to ascertain the fineness modulus and zone classification of the river sand. To evaluate the properties of the sand, a series of tests were conducted following the guidelines specified in the Indian standard code IS: 2386 (Part I). The characteristics of the fine aggregates are summarized in Table 2.

Table 2. Characteristics of fine aggregate

Characteristic	Value
Fineness Modulus	2.86
Specific Gravity	2.55
Grading Zone	Zone 2
Water Absorption	1.6%

2.3. Coarse Aggregates (CA)

Coarse aggregates of two distinct sizes, passing through 20 mm and 12.5 mm IS sieves, were sourced locally for experimental investigation. Sieve analysis was performed on these aggregates to calculate their fineness modulus according to IS: 383-1970. Specific gravity was determined using the Pycnometer Test, based on the guidelines of IS: 2386 (Part I). The properties of these aggregates are presented in Table 3. For the duration of the experimental study, the proportion of 20 mm and 10 mm coarse aggregates was maintained at 60% and 40%, respectively.

Table 3. Characteristics of coarse aggregate

Property	Coarse Aggregate	
	20 mm	10 mm
Fineness Modulus	7.8	8.21
Specific Gravity	2.78	2.63
Water Absorption	0.42%	0.56%

2.4 Superplasticizer

In this experimental study, a high-range water-reducing admixture, formulated with advanced superplasticizers based on sulfonated naphthalene formaldehyde which enhances the dispersion of cement particles was used, complying with IS: 9103–1999 and ASTM C494 (Type G) standards.

2.5 UFFA

UFFA is a processed variant of traditional fly ash, achieved through grinding or air classification, resulting in much finer particles compared to conventional fly ash (Obla *et al*. 2020). The reduced particle size leads to a larger surface area, which enhances its capacity for better bonding within cementitious systems (Jaiswal *et al*. 2023). UFFA is effective in filling the micro-pores within the concrete, contributing to increased compactness and improved compressive strength (Shaikh and Supit 2015). From the chemical perspective, UFFA exhibits a high degree of pozzolanic reactivity, enabling it to readily interact with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) through a pozzolanic reaction ash (Obla *et al*. 2020). This reaction significantly contributes to the mechanical strength, durability, and resistance of concrete against chemical degradation, such as chloride penetration and sulfate-induced reactions, thereby proving its effectiveness in harsh environmental conditions (Jaiswal *et al*. 2023).

Table 4. Chemical properties of UFFA

Silicon dioxide (SiO_2) + Aluminium oxide (Al_2O_3) + Iron oxide (Fe_2O_3) in percent by mass	93.6
Reactive silica in percentage by mass	24.3
Magnesium oxide (MgO) in percentage by mass	2.55
Total sulfur as sulfur trioxide (SO_3) is in percent by mass	0.21
Available alkalis as equivalent sodium oxide (Na_2O)	0.64
Total chlorides in percentage by mass	0.022
Loss on ignition in percentage by mass (max.)	0.70
Moisture content (%)	0.60

2.6 UFGGBS

UFGGBS, characterized by a particle size of less than 45 microns, is an effective mineral admixture that enhances the properties of concrete. UFGGBS improves workability, durability, and microstructure, leading to reduced permeability and greater resistance to chloride ion penetration (Kumar *et al*. 2018). Composed primarily of silica, alumina, calcium oxide, and magnesium oxide, it exhibits pozzolanic and some hydraulic properties, which facilitate the formation of cementitious compounds when exposed to water. Its light grey or off-white appearance is an indicator of its composition and functionality. Through the reaction with hydroxide ions, UFGGBS promotes the formation of additional calcium silicate hydrate (C-S-H), which directly contributes to improved concrete strength, durability, and resistance to chemical degradation, including chloride penetration and sulfate attacks (Jaiswal *et al*. 2023). These properties make UFGGBS particularly suitable for use in concrete exposed to aggressive environmental conditions, enhancing both its structural and service life performances.

Table 5. Chemical Composition of UFGGBS

Manganese oxide (MnO) % by mass	0.45
Magnesium oxide (MgO) % by mass	8.91
Sulfide sulfur (S) % by mass	0.63
Sulphate (SO_3) % by mass	0.22
Insoluble residue % by mass	2.28
Chloride content (Cl) % by mass	0.07
Loss on Ignition % by mass	0.72
CaO + MgO + 1/2 Al_2O_3 SiO_2 + (2/3) Al_2O_3	1.05
CaO + MgO + Al_2O_3 SiO_2	1.74
Glass content %	93.50
Moisture content % by mass	0.56
CaO % by mass	33.03
SiO_2 % by mass	33.80

2.7 Alkaline Liquid

The alkaline solution used in this study was a combination of Sodium hydroxide (NaOH) and Sodium silicate (Na_2SiO_3) solutions.

2.7.1 Sodium Hydroxide Flakes

Sodium hydroxide (NaOH), commonly known as caustic soda, is extensively utilized across various industries, including paper, textile, soap, and detergent manufacturing. It is available in multiple forms, such as flakes, granules, pellets, or as a 50% saturated solution. The chemical composition of the NaOH flakes is presented in Table 6.

Table 6. Chemical composition of Sodium hydroxide flakes

Chemical Composition	Percentage
NaOH (Purity)	98.8
Chloride	1
Carbonate (CO_3)	0.01
Silicates (SiO_2)	0.01
Nitrate (NO_3)	0.005
Size	3-6 mm
Color	White

The flakes were stored in an airtight container to prevent moisture exposure from the surrounding environment. A sodium hydroxide (NaOH) solution was prepared by dissolving the flakes in a pre-measured amount of water. The dissolution of NaOH is an exothermic reaction; hence, careful handling was essential during the preparation to ensure safety and avoid any accidents. The molarity of the sodium hydroxide solution utilized in this experiment was 10.

2.7.2 Sodium Silicate Solution

Sodium silicate (Na_2SiO_3), commonly referred to as water glass or liquid glass, is a transparent, viscous liquid (gel) with adhesive and fire-resistant characteristics. It finds applications across various industries, including detergents, manufacturing, pottery, paper, wood treatment, and fabric printing. The compound is typically maintained in a thick gel form and stored in covered containers to prevent drying and solidification. The specific chemical composition of the Na_2SiO_3 solution, as supplied by the distributor, is detailed in Table 7.

Table 7. Chemical Composition of Sodium silicate

Chemical Composition	Percentage
Na_2O	14.70
SiO_2	29.40
Water	55.90
Specific gravity	1.27

In this experimental study, the ratio of sodium silicate to sodium hydroxide was maintained at 2. The solutions of sodium silicate and sodium hydroxide were combined 15 minutes before the preparation of the concrete mixture.

Table 8. Ingredients and the mix proportion of 1 m^3 CC

Ingredient	Quantity (kg)	w/b ratio	Mix proportion
Cement	400	0.45	1:1.42:3.14
Fine aggregate	568		
Coarse aggregate	1256		
Water	180		
Superplasticizer (1.5% kg/m^3)	6		

3. MIX PREPARATION

The concrete mix was prepared following the guidelines outlined in IS 10262 – 2009 for conventional concrete. M40 grade concrete was designed with a mix ratio of 1:1.42:3.14, a water-to-binder ratio of 0.45, and a cement content of 400 kg/m^3. The detailed quantities and the mix proportions derived from the design are presented in Table 8. The coarse aggregates consisted of a combination of 20 mm and 10 mm aggregates in a ratio of 60% and 40%, respectively. The same proportions were maintained in the geopolymer concrete formulation.

Ingredients and the mix proportion of 1 m^3 geopolymer concrete are shown in Table 9 where the molarity of sodium hydroxide is 10 and sodium silicate to sodium hydroxide proportion is 2.

Table 9. Ingredients and the Mix Proportion of 1 m^3 of GPC

Ingredient	Quantity (kg)	w/b ratio	Mix proportion
UFFA	160	0.45	1:1.42:3.14
UFGGBS	240		
Fine aggregate	568		
Coarse aggregate	1256		
Sodium silicate	120		
NaOH solution	60		
Superplasticizer (1.5% kg/m^3)	6		

4. MIXING OF CONCRETE

Geopolymer concrete can be produced using methods like those employed in the production of Portland cement concrete. The process began by conditioning the aggregates to a saturated-surface-dry state before mixing, with all mixing and compacting procedures conforming to IS: 516 (1959). The initial step involved dry mixing of UFGGBS and aggregates using a mixer for approximately three minutes. An alkaline liquid combination prepared already, combined with a superplasticizer, was then added to the dry mixture. The entire mixture was further blended for an additional four minutes to ensure a thorough and uniform distribution of the alkaline activator. Then, the fresh geopolymer concrete was cast and compacted using standard techniques like those used for Portland cement concrete. Geopolymer concrete specimens were allowed to be cured under open-air conditions, while conventional concrete specimens were subjected to water curing,

5.1 Workability

Workability is used to describe the ease or difficulty with which the concrete is handled, transported, and placed between the forms with minimum loss of homogeneity (Shetty, 2019).

The reduction in slump values in geopolymer concrete was primarily due to differences in binder composition. Geopolymer concrete replaces Ordinary Portland Cement with UFFA and UFGGBS, which possess distinct chemical and physical properties. These materials have finer particles and unique reactivity, affecting the rheological behavior of the mix. The angular nature of these particles and their hydration reactions typically result in lower workability. Additionally, the reaction of UFFA and UFGGBS forms a denser matrix, further reducing the fluidity of the geopolymer mixture during mixing.

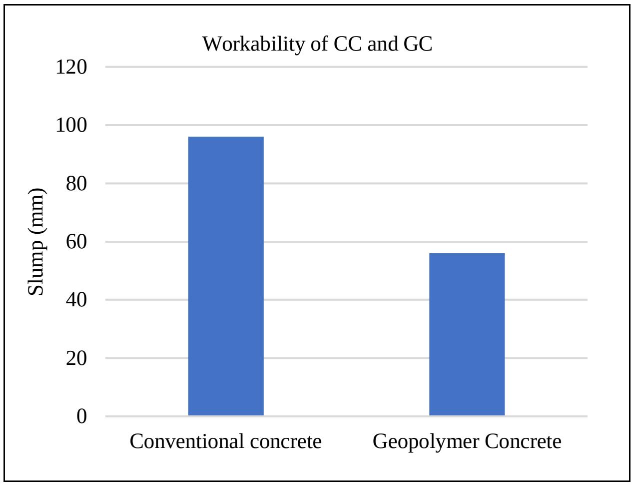

Fig. 1: Slump values of CC and GC

5.2 Compressive Strength

The tests were conducted on cube specimens of size 100 mm. The testing was done as per IS: 516-1959. The results obtained are shown on Fig. 2.

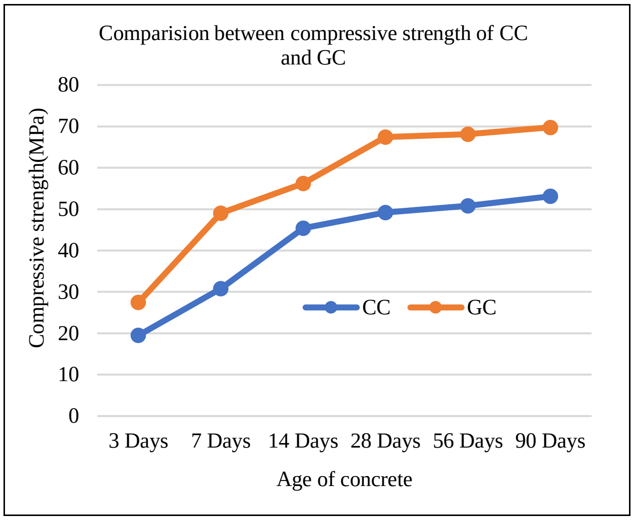

Fig. 2: Compressive strength of CC and GC at different ages

GC exhibited superior early strength compared to CC, achieving 27.46 N/mm^2 at 3 days, 41% higher than CC's 19.50 N/mm^2. This was due to rapid repolymerization, where UFFA and UFGGBS activated effectively under ambient curing conditions. At 28 days, GC attained 67.40 N/mm^2, surpassing CC's 49.20 N/mm^2 by 37%. The enhanced reactivity of ultrafine binders in GC resulted in dense calcium silicate hydrate (C-S-H) and aluminosilicate gel formation, ensuring considerable structural strength. By 90 days, GC maintained a compressive strength of 69.78 N/mm^2, outperforming CC's 53.10 N/mm^2 by 32%. Geopolymer concrete demonstrated strong performance under open-air curing, proving its potential as a sustainable alternative in water-scarce conditions. Unlike conventional concrete, which depends on OPC hydration, geopolymer concrete utilizes the synergistic activation of ultrafine fly ash and ultrafine GGBS. This alkali activation enables both rapid and sustained strength development, positioning geopolymer concrete as an environment-friendly construction option.

5.2 Flexural Strength

Beams measuring 100 mm × 100 mm × 500 mm were cast for the flexural strength test. All specimens were tested at 14 and 28 days of curing using the three-point bending method with a universal testing machine, as per IS: 516-1959.

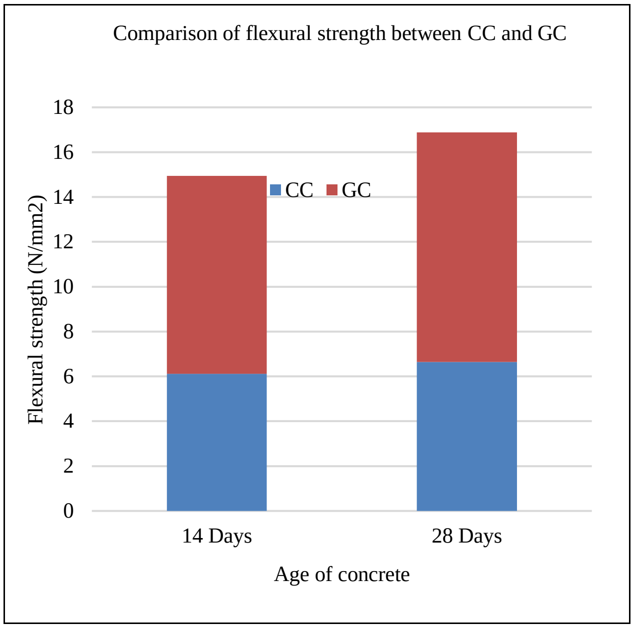

Fig. 3: Flexural strength of CC and GC

The results showed a significant improvement in the flexural strength of GC compared to CC at both 14 and 28 days. This can be attributed to the higher reactivity of ultrafine fly ash and ultrafine ground-granulated blast furnace slag used in GC. These materials provide better bonding and improved microstructure due to the formation of dense calcium-aluminosilicate hydrate (C-A-S-H) and sodium-aluminosilicate hydrate (N-A-S-H) gels. At 14 days, GC exhibited a flexural strength of 8.82 N/mm^2, approximately 44% higher than the 6.12 N/mm^2 of CC. This demonstrated the accelerated pozzolanic reaction in GC compared to the hydration process in CC. By 28 days, GC reached a flexural strength of 10.24 N/mm^2, which is 54% higher than CC (6.64 N/mm^2). The enhanced performance highlighted the durability and load-bearing capacity of geopolymer concrete even under different curing conditions.

5.4 Split Tensile Strength

Split tensile strength was evaluated using cylindrical specimens with a diameter of 100 mm and a height of 200 mm, cast for the study. The specimens were subjected to testing after 14 and 28 days of curing, following the guidelines outlined in IS: 5816 (1999).

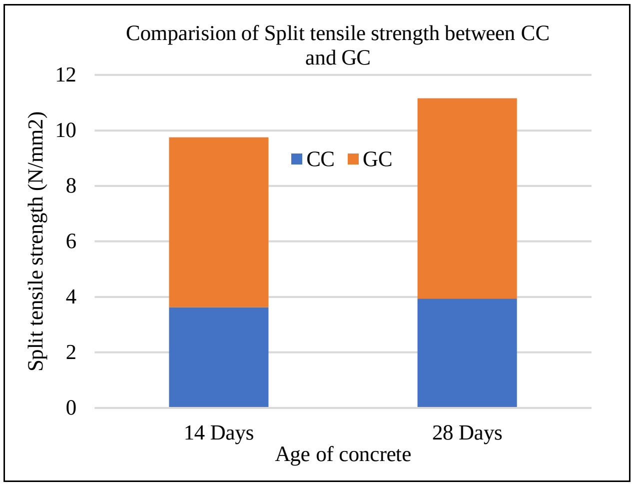

Fig. 4: Split tensile strength of CC and GC

Geopolymer concrete achieved a split tensile strength of 6.12 N/mm^2, 68.6% higher than conventional concrete at 3.63 N/mm^2. This was due to the denser aluminosilicate matrix formed by ultrafine fly ash and GGBS with alkaline activators. At 28 days, GC reached 7.22 N/mm^2, an 83.7% increase over CC's 3.93 N/mm^2, attributed to ongoing polymerization reactions, whereas CC's strength gain was dependent on slower cement hydration. The superior tensile strength of GC arose from enhanced particle packing and reduced voids due to ultrafine fly ash and GGBS, compared to CC's less-refined microstructure from OPC. GC demonstrated rapid strength development, making it a sustainable, high-performance alternative for tensile stress-prone structural applications.

5.5 Water Absorption

ASTM C 642 guidelines were followed for the water absorption test. Concrete cubes (100 mm) were oven-dried, cooled to room temperature, and submerged in water for 24 hours. The test results are depicted in Fig. 5. The 24-hour water absorption test revealed notable differences in the permeability characteristics of CC and GC. The water absorption for CC was 4.92%, indicating a higher presence of capillary pores and, consequently, greater permeability. This can be attributed to the hydration process of OPC-based concrete, where calcium hydroxide formation created additional pore spaces. In contrast, GC showed a lower water absorption rate of 2.95%. This reduced rate was due to the dense microstructure formed during the polymerization of UFFA and UFGGBS, which limited the pore connectivity. Additionally, the formation of aluminosilicate gels enhanced GC's resistance to water penetration, contributing to its reduced permeability. The lower water absorption in GC compared to CC demonstrated its improved durability, as reduced permeability limited the ingress of water and harmful agents. This enhanced its resistance to chemical attacks, and chloride penetration, positioning GC as a viable and superior alternative to CC for use in environments with aggressive conditions.

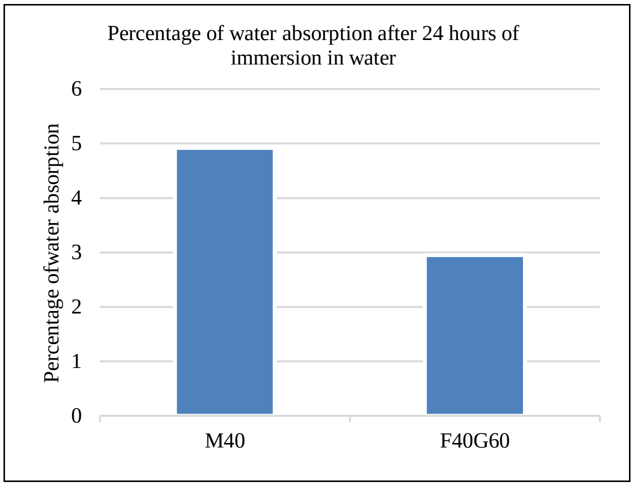

Fig. 5: Water absorption of CC and GC

5.6 Sorptivity

The cylindrical specimens of size 100 mm (dia.) x 50 mm were preconditioned to a certain moisture condition by drying the sample for 7 days in a 50 °C oven. The sides of the concrete sample were sealed, with an electrician's tape while the suction face and its opposite face were left unsealed.

The results indicated that geopolymer concrete exhibited significantly lower sorptivity values compared to conventional concrete, across all measured time intervals. GC exhibited a reduced capillary water absorption rate, which can be attributed to the denser microstructure formed by the polymerization process. The sorptivity of both GC and CC decreased with time, showing that initial absorption was higher but slowed as the concrete became saturated with water. However, GC showed a steeper reduction, indicating improved resistance to further water penetration. The lower sorptivity of GC implied better durability performance under moisture-related challenges such as chloride ingress, water exposure, and freeze-thaw cycles. This makes GC a promising alternative for construction projects requiring enhanced durability.

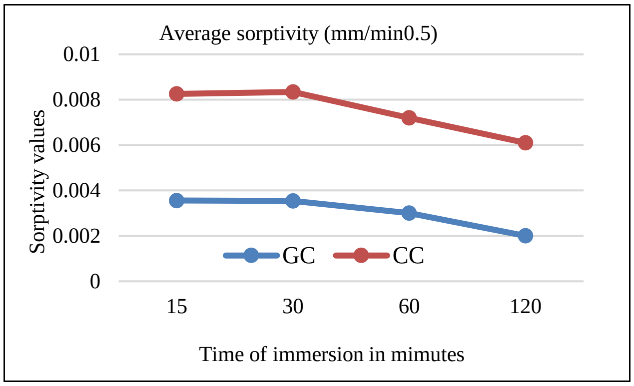

Fig. 6: Sorptivity of CC and GC

6. CONCLUSION

The comparative analysis of conventional Portland cement concrete and geopolymer concrete revealed that GPC, using ultrafine fly ash and ultrafine ground-granulated blast furnace slag as binders, demonstrated superior mechanical and durability performance. The key findings of the study were:

- **Mechanical properties**: GPC showed comparable compressive strength to conventional concrete, confirming its suitability for structural applications.
- **Durability:** GPC offered enhanced resistance to water absorption, chloride penetration, and other environmental challenges due to its lower porosity and improved microstructure.
- **Environmental impact**: GPC reduced CO_2 emissions by up to 80% compared to traditional OPC, making it an eco-friendly alternative for construction.
- **Sorptivity:** GPC exhibited lower moisture ingress rates, improving its performance under humid or chemically aggressive conditions.

These findings underscore geopolymer concrete as a sustainable, durable, and low-carbon alternative to traditional concrete without compromising the mechanical properties, offering a strategic solution for future infrastructure needs.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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