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OPTIMIZATION AND PERFORMANCE EVALUATION OF SUGARCANE BAGASSE ASH BLENDED GEOPOLYMER CONCRETE: MECHANICAL STRENGTH, THERMAL/FIRE RESISTANCE, AND ACID–SULFATE DURABILITY

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ABSTRACT

Rapid industrialization and urbanization have significantly increased the demand for Portland cement, contributing nearly 8% of global CO_2 emissions. To address environmental concerns, geopolymer concrete (GPC) has emerged as a sustainable alternative binder produced from industrial by-products such as low-calcium fly ash activated with alkaline solutions. This study investigates the performance of fly ash-based geopolymer concrete partially blended with Sugarcane Bagasse Ash (SCBA) as a supplementary aluminosilicate material. SCBA was incorporated at replacement levels of 5%, 10%, and 15% by mass, along with a control mix. The experimental results indicate that SCBA significantly influences the geopolymerization process and mechanical performance. The mix containing 10% SCBA achieved optimum compressive strength due to enhanced geopolymer gel formation and denser microstructure. In addition, SCBA-blended GPC exhibited improved resistance to acid and sulfate attack and demonstrated superior performance under elevated temperature exposure. The findings confirm that SCBA-incorporated geopolymer concrete is a durable, eco-friendly, and high-performance construction material suitable for aggressive environmental and fire-resistant applications, thereby supporting sustainable infrastructure development..

Keywords: Geopolymer concrete; Sugarcane Bagasse Ash; Fly ash; Compressive strength; Durability; Thermal resistance; Acid resistance; Sulfate attack; Sustainability.

I. Introduction

The rapid expansion of infrastructure and urban development has significantly increased the global demand for cement-based construction materials. Ordinary Portland Cement (OPC), which is the primary binder used in conventional concrete, is associated with substantial environmental impacts due to energy-intensive manufacturing processes and limestone calcination. It is estimated that cement production contributes approximately 7–8% of global carbon dioxide (CO_2) emissions, thereby intensifying concerns regarding climate change and environmental sustainability (Andrew, 2018; Scrivener et al., 2018). Consequently, considerable research efforts have been directed toward the development of sustainable alternative binders that can reduce the carbon footprint of the construction industry.

Among the proposed alternatives, geopolymer concrete (GPC) has emerged as a promising low-carbon material capable of partially or completely replacing OPC in structural applications. Geopolymers are synthesized through the alkali activation of aluminosilicate-rich precursor materials such as fly ash, slag, and metakaolin, resulting in the formation of a three-dimensional aluminosilicate polymeric network with excellent mechanical and durability characteristics (Davidovits, 1994; Provis & van Deventer, 2014). In particular, low-calcium Class F fly ash has been widely utilized as a primary precursor in geopolymer systems due to its high silica and alumina content, global availability, and ability to form stable geopolymer gel structures with enhanced resistance to chemical and environmental degradation (Hardjito & Rangan, 2005; Nath & Sarker, 2014).

Despite these advantages, fly ash-based geopolymer concrete often exhibits relatively slow strength development under ambient curing conditions, which can restrict its widespread adoption in field construction applications (Rangan, 2008). To overcome this limitation, several studies have explored the incorporation of supplementary reactive materials capable of accelerating geopolymerization reactions and improving the microstructural densification of the binder matrix.

Sugarcane Bagasse Ash (SCBA), an agro-industrial by-product generated during the combustion of sugarcane bagasse in sugar mills, has gained increasing attention as a potential supplementary precursor in geopolymer systems. When subjected to controlled combustion and appropriate grinding processes, SCBA contains a high proportion of reactive amorphous silica, making it suitable for use in cementitious and geopolymeric materials (Ganesan et al., 2007). In sugar-producing countries such as India and Brazil, large quantities of SCBA are generated annually, and its improper disposal poses significant environmental challenges (Sales & Lima, 2010). Therefore, its utilization in concrete production represents an effective strategy for both waste management and sustainable material development.

The incorporation of SCBA in fly ash-based geopolymer systems may provide additional reactive silica, improve particle packing density, and enhance the overall microstructure of the geopolymer matrix. Previous studies have reported that the inclusion of agro-industrial ashes can improve mechanical performance and durability characteristics when used at optimal replacement levels (Bakharev, 2005; Rukzon & Chindaprasirt, 2014). However, the performance of SCBA-modified geopolymer concrete remains highly dependent on ash characteristics, replacement levels, and curing conditions. Furthermore, comprehensive investigations addressing the combined effects of mechanical performance, thermal stability, and resistance to aggressive chemical environments remain relatively limited in the current literature.

Therefore, the present study aims to investigate the influence of sugarcane bagasse ash as a partial replacement of fly ash in geopolymer concrete under ambient curing conditions. Four replacement levels of SCBA (0%, 5%, 10%, and 15%) were considered to evaluate their effects on compressive strength and split tensile strength. In addition, the thermal performance of the developed geopolymer concrete was assessed at elevated temperatures, while durability characteristics were examined through exposure to 3% H_2SO_4 and 5% $MgSO_4$ solutions. The primary objective of this research is to identify the optimum SCBA replacement level that provides a balanced improvement in mechanical strength, thermal resistance, and chemical durability, thereby contributing to the development of sustainable and waste-utilizing construction materials..

II. Literature

2.1 Geopolymer Concrete and Sustainable Construction

The increasing environmental concerns associated with ordinary Portland cement (OPC) production have encouraged the development of alternative and sustainable cementitious materials. OPC manufacturing contributes significantly to global carbon dioxide emissions and energy consumption, prompting researchers to explore environmentally friendly binder systems. Among the various alternatives, geopolymer concrete (GPC) has emerged as a promising sustainable construction material due to its ability to utilize industrial and agricultural waste materials rich in aluminosilicates (Davidovits, 1991; Duxson et al., 2007).

Geopolymers are inorganic polymeric materials formed through the alkali activation of aluminosilicate precursors such as fly ash, slag, and metakaolin. During geopolymerization, silica and alumina dissolve in an alkaline medium and subsequently reorganize into a three-dimensional polymeric network structure (Xu & Van Deventer, 2003). This reaction results in the formation of a strong binder system capable of replacing conventional cement-based materials in many structural applications. Previous studies have shown that geopolymer concrete can achieve mechanical strength comparable to or even exceeding that of OPC-based concrete while also exhibiting enhanced durability and chemical resistance (Hardjito et al., 2004; Provis & Van Deventer, 2014).

Furthermore, geopolymer technology offers significant environmental advantages by reducing greenhouse gas emissions, utilizing industrial by-products, and minimizing the demand for natural resources. Due to these benefits, geopolymer materials are increasingly recognized as a key component in sustainable construction and circular economy strategies (Van Deventer et al., 2012; Amran et al., 2022).

2.2 Sugarcane Bagasse Ash as a Sustainable Aluminosilicate Source

In recent years, increasing attention has been given to the utilization of agricultural wastes as supplementary precursors in geopolymer systems. Among these wastes, sugarcane bagasse ash (SCBA) has attracted considerable interest due to its high silica content and widespread availability in sugar-producing countries. Sugarcane bagasse is the fibrous residue remaining after juice extraction from sugarcane, and its combustion in sugar factories generates large quantities of ash that often pose disposal challenges (Singhal & Shukla, 2016).

Several studies have reported that SCBA contains a significant amount of amorphous silica, making it suitable for use as a pozzolanic or geopolymeric material when properly processed through controlled burning and grinding (Cordeiro et al., 2009; Chusilp et al., 2009). The fine particles of SCBA can contribute to pore refinement and matrix densification in cementitious systems through both chemical and micro-filling effects (Ganesan et al., 2007). As a result, the incorporation of SCBA can improve mechanical properties while simultaneously enhancing sustainability by converting agricultural waste into value-added construction materials.

However, the properties of SCBA are highly dependent on combustion temperature, collection methods, and processing techniques. Variations in these parameters may lead to differences in chemical composition, carbon content, and particle morphology, which in turn influence the reactivity and performance of SCBA-based binders (Raza & Siddique, 2019). Therefore, careful characterization and processing of SCBA are essential to ensure consistent performance in geopolymer systems.

2.3 Mechanical Properties of SCBA-Blended Geopolymer Concrete

Numerous studies have investigated the mechanical performance of geopolymer concrete incorporating fly ash as the primary precursor. Hardjito et al. (2004) demonstrated that fly ash-based geopolymer concrete can achieve compressive strengths comparable to conventional concrete when appropriate activator concentrations and curing conditions are used. Subsequent research further confirmed that the strength development of geopolymer concrete is strongly influenced by alkaline activator concentration, activator-to-binder ratio, and curing temperature (Fernández-Jiménez & Palomo, 2005; Nath & Sarker, 2015).

More recently, researchers have explored the potential of incorporating SCBA as a partial replacement for fly ash in geopolymer systems. Experimental investigations have indicated that moderate SCBA replacement levels can enhance compressive strength due to improved particle packing and additional reactive silica content (Ali & Kamaruddin, 2016). Similarly, Singh and Ishwarya (2018) reported that the incorporation of SCBA in geopolymer mixtures resulted in improved compressive and tensile strength up to an optimal replacement level.

Recent studies also highlight the role of microstructural densification in improving mechanical performance. The presence of finely divided SCBA particles can promote the formation of a denser geopolymer matrix and improve the interfacial transition zone between the binder and aggregates (Kumar et al., 2022). However, excessive replacement of fly ash with SCBA may reduce workability and mechanical strength due to increased water demand and the presence of unburnt carbon particles. Therefore, an optimal balance between fly ash and SCBA content is essential to achieve desirable mechanical properties in geopolymer concrete mixtures.

2.4 Durability Performance of Geopolymer Concrete

Durability is one of the most critical aspects determining the long-term performance of concrete structures. Compared with conventional Portland cement concrete, geopolymer concrete has demonstrated superior resistance to aggressive environmental conditions such as acid attack, sulfate exposure, and chloride penetration.

Bakharev (2005) reported that geopolymer binders exhibit excellent resistance to acidic environments due to their dense microstructure and lower calcium content. Similarly, Chindaprasirt et al. (2007) observed that fly ash-based geopolymer mortar shows significantly improved resistance to sulfate and acid attack compared to OPC-based systems. The enhanced durability performance is primarily attributed to the formation of stable aluminosilicate gel structures that are less susceptible to chemical degradation.

The incorporation of SCBA may further improve durability performance by refining pore structure and reducing permeability. Raza and Siddique (2019) reported that SCBA-modified concrete exhibits improved resistance to sulfate attack and reduced water absorption. Recent studies have also indicated that geopolymer concrete incorporating agricultural waste materials demonstrates improved resistance to chemical attack and enhanced long-term durability (Ahmad et al., 2021; Mohammed et al., 2023).

Despite these promising results, comprehensive studies investigating the durability of SCBA-based geopolymer concrete under combined aggressive environments remain limited. In particular, long-term resistance to acid and sulfate exposure requires further experimental evaluation.

2.5 Thermal and Fire Resistance of Geopolymer Concrete

Concrete structures may be exposed to elevated temperatures during fire incidents or high-temperature industrial applications. Therefore, the thermal stability of construction materials is an important consideration in structural design.

Geopolymer materials generally exhibit superior thermal resistance compared to OPC-based concrete due to their ceramic-like microstructure and absence of calcium hydroxide decomposition products (Nath & Sarker, 2014). Studies have shown that geopolymer concrete can retain a significant portion of its compressive strength even after exposure to temperatures exceeding 600°C (Soutsos et al., 2005).

The incorporation of agricultural ashes such as SCBA may further influence thermal behavior by modifying the microstructure and pore distribution of geopolymer matrices. Palaksha and Prasad (2017) reported that geopolymer concretes incorporating agro-waste materials exhibit improved resistance to thermal degradation and reduced cracking under elevated temperatures. However, the thermal performance of SCBA-based geopolymer systems remains insufficiently explored in the existing literature.

2.6 Research Gaps

Although significant progress has been made in the development of geopolymer concrete, several research gaps remain regarding the utilization of sugarcane bagasse ash in geopolymer systems. First, the variability in SCBA properties resulting from different combustion and processing conditions presents challenges for consistent material performance. Second, there is currently no standardized mix design approach for SCBA-based geopolymer concrete, and existing studies employ varying activator concentrations, curing conditions, and precursor proportions.

Moreover, while some investigations have examined the mechanical properties of SCBA-modified geopolymer concrete, comprehensive studies addressing durability aspects such as acid resistance, sulfate resistance, and long-term performance are relatively limited. Similarly, the thermal and fire resistance behavior of geopolymer concrete incorporating SCBA has received comparatively little attention.

Therefore, a systematic experimental investigation evaluating the combined mechanical, durability, and thermal performance of fly ash–SCBA geopolymer concrete is necessary. Such research can provide valuable insights into the optimal utilization of agricultural waste materials in sustainable construction applications.

III. Materials And Methods

3.1 Experimental Program

The experimental investigation was designed to develop ambient-cured fly ash–based geopolymer concrete incorporating Sugarcane Bagasse Ash (SCBA) as a partial replacement material. The primary objective was to evaluate the influence of SCBA incorporation on mechanical performance and durability characteristics under aggressive environmental conditions. Different replacement levels of SCBA were considered while maintaining constant alkaline activation parameters to enable systematic evaluation of its effect on geopolymer concrete properties.Durability performance was assessed through exposure to acidic and sulfate environments as well as elevated temperature conditions. Relevant Indian Standard provisions were adopted wherever applicable, while geopolymer-specific procedures were derived from established literature due to the absence of standardized codes for geopolymer concrete mix design (Hardjito & Rangan, 2005; Provis & van Deventer, 2014).

3.2 Materials

3.2.1 Sugarcane Bagasse Ash (SCBA)

Sugarcane Bagasse Ash (SCBA) was obtained from a local sugar industry name as " Bhoramdeo sahakari shakkar utpadak karkhana maryadit, kawardha" and processed prior to its use in geopolymer concrete. The collected ash was first oven-dried at 105 ± 5 °C for 24 h to remove moisture. Subsequently, controlled calcination was performed at 650 °C for 3 h to increase the proportion of amorphous silica and improve its pozzolanic reactivity. The calcined material was then ground and sieved through a 75 µm sieve to obtain a fine powder.

Figure 3.1: Sugarcane Bagasse Ash (SCBA)

The processed SCBA exhibited a grey to dark grey color with a porous texture. Its chemical composition was adopted from previously reported studies involving SCBA processed under comparable thermal conditions. Such an approach is commonly adopted in geopolymer research where advanced characterization facilities are unavailable. The high silica content of SCBA contributes to additional geopolymeric reactions, leading to microstructural densification and improved matrix integrity (Ganesan et al., 2007; Cordeiro et al., 2009).

3.2.2 Fly Ash

Low-calcium Class F fly ash was used as the primary aluminosilicate precursor. The fly ash was procured from Korba Super Thermal Power Station. As the material was collected for academic research purposes, a detailed chemical test certificate was not available. Therefore, the chemical composition of fly ash was adopted from standard published literature for Class F fly ash conforming to ASTM C618 and IS 3812 (Part 1). The use of literature-based composition is justified as fly ash is a standardized industrial by-product and its properties are well established. The fly ash particles were spherical and glassy, contributing to improved workability and reduced water demand during mixing.

Figure 3.2:- Fly Ash (Class F)

3.2.3 Alkaline Activator

The alkaline activator solution consisted of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. A 10 M NaOH solution was prepared by dissolving NaOH pellets in distilled water according to standard molarity calculations.

Figure 3.3 :- Sodium Silicate (Na_2SiO_3) & Sodium Hydraoxide (NaOH)

The NaOH solution was combined with sodium silicate in a mass ratio of 1:2.5 (NaOH : Na_2SiO_3). This proportion was selected based on previously reported optimum performance for low-calcium fly ash-based geopolymer systems under ambient curing conditions (Hardjito & Rangan, 2005; Nath & Sarker, 2014).

The alkaline solution was prepared 24 h before mixing to allow temperature stabilization and ensure uniformity during mixing.

3.2.4 Aggregates

Natural river sand conforming to Zone II grading according to IS 383:2016 was used as fine aggregate. Crushed coarse aggregates of 20 mm and 10 mm nominal sizes were blended in a 60:40 ratio to achieve proper particle gradation and mechanical interlocking.

Figure 3.4 :-: Fine Aggregate And Coarse Aggregate

Before mixing, aggregates were washed and oven-dried to remove surface impurities and ensure accurate moisture control during batching.

3.2.5 Mixing Water

Potable water conforming to IS 456:2000 was used only where additional moisture was required beyond the alkaline solution content.

3.2.6 Chemicals for Durability Testing

To simulate aggressive environmental conditions, chemical exposure tests were conducted using controlled solutions:

- 3% sulfuric acid (H_2SO_4) solution for acid resistance evaluation
- 5% magnesium sulfate ($MgSO_4$) solution for sulfate attack assessment

These concentrations are widely used in durability studies to represent aggressive industrial and sulfate-rich soil environments (Bakharev, 2005).

Mass loss and residual compressive strength were determined after specified exposure durations.

3.2.7 Non-Use of Chemical Admixtures

No chemical admixtures such as superplasticizers or retarders were incorporated. This approach ensured that the influence of SCBA on fresh and hardened properties could be evaluated independently without interference from external additives. Although SCBA may reduce workability due to its porous and angular morphology, acceptable consistency for casting was achieved by optimizing activator dosage and controlled mixing procedures. The exclusion of admixtures also aligns with the sustainability objective of minimizing reliance on manufactured chemical additives.

3.3 Mix Proportioning

Since no dedicated Indian Standard code is currently available for geopolymer concrete mix design, the mixture proportions adopted in this study were based on established literature and preliminary trial mixes targeting a compressive strength of 30–35 MPa.

SCBA was used as a partial replacement of fly ash at 0%, 5%, 10%, and 15**%** by mass of binder. These replacement levels fall within the commonly reported range in SCBA-based geopolymer research.

A total binder content of 400 kg/m³ was adopted, which lies within the recommended range (350–450 kg/m³) for fly ash-based geopolymer concrete (Hardjito & Rangan, 2005).

The alkaline activator-to-binder ratio was fixed at 0.40, corresponding to 160 kg/m³ of alkaline solution. The Na_2SiO_3/NaOH mass ratio was maintained at 2.5, and a 10 M NaOH solution was used to facilitate geopolymerization under ambient curing.

Fine and coarse aggregate contents were selected as 650 kg/m³ and 1200 kg/m³, respectively, with a fine-to-coarse aggregate ratio of 40:60.

Table 3.1:-Nominal Mix Proportions (per m³)

Component	Quantity (kg/m³)
Binder (Fly ash + SCBA)	400
Fine aggregate	650
Coarse aggregate	1200
Alkaline solution	160

Only the binder composition was varied across mixes, while aggregate content and activator dosage were kept constant to ensure systematic evaluation of SCBA influence.

Table 3.2:-Binder Composition for Different Mixes

Mix ID	SCBA (%)	Fly Ash (kg/m³)	SCBA (kg/m³)
GPC-0	0%	400	0
GPC-5	5%	380	20
GPC-10	10%	360	40
GPC-15	15%	340	60

3.4 Mixing, Casting and Curing of Geopolymer Concrete

A uniform and controlled procedure was adopted for mixing, casting, and curing of all geopolymer concrete (GPC) batches to ensure reproducibility and minimize experimental variability. The same protocol was followed for all mix proportions to enable reliable comparative assessment of SCBA incorporation.

3.4.1 Mixing Procedure

Dry materials (fly ash, SCBA, and aggregates) were first mixed for 5 min in a laboratory tilting-drum mixer. The alkaline activator solution was then gradually introduced while mixing continued for 4–6 min until a homogeneous mixture was obtained.

Workability of fresh geopolymer concrete was evaluated using the slump test according to IS 1199.

3.4.2 Casting of Specimens

Specimens were cast in:

- 150 mm cube moulds for compressive strength and durability tests
- 150 mm × 300 mm cylindrical moulds for split tensile strength tests

Concrete was placed in three layers, each compacted with 35 strokes of a 16 mm tamping rod, in accordance with IS 516.

3.4.3 Curing of Specimens

Unlike OPC concrete, geopolymer concrete does not rely on hydration but on alkali-activated polymerization reactions. Therefore, ambient curing was adopted in this study to evaluate practical field applicability.

After casting, specimens were kept at 27 ± 2 °C for 24 h, demoulded, and then stored under ambient laboratory conditions without water curing.

3.5 Specimen Planning and Experimental Program

Mechanical and durability properties were evaluated using relevant **Indian Standard testing procedures.**

Compressive Strength

- Standard: IS 516:1959
- Ages: 7, 28, 56, 90 days
- Specimens: 3 cubes per age per mix

Total specimens = 3 × 4 ages × 4 mixes = **48 cubes**

Split Tensile Strength

- Standard: IS 5816:1999
- Age: 28 days
- Specimens: 3 cylinders per mix

Total specimens = 3 × 4 mixes = **12 cylinders**

Water Absorption

- Standard: IS 3085:1965
- Age: 28 days
- Specimens: 3 cubes per mix

Total specimens = 3 × 4 mixes = **12 cubes**

Acid Attack

- Exposure Periods: 28 and 56 days
- Specimens: 3 cubes per exposure per mix

Total specimens = 3 × 2 × 4 = **24 cubes**

Sulfate Attack

- Exposure Periods: 28 and 56 days
- Specimens: 3 cubes per exposure per mix

Total specimens = 3 × 2 × 4 = **24 cubes**

Thermal / Fire Resistance

- Temperature Levels: 200°C and 400°C
- Specimens: 3 cubes per temperature per mix

Total specimens = 3 × 2 × 4 = **24 cubes**

3.6 Summary of Specimens

Table: 3.3:-Summary of Specimens

Test	**Specimen Type**	**Test Condition**	**Total Specimens**
Water Absorption	Cube	28 days	12
Compressive Strength	Cube	7, 28, 56, 90 days	48
Split Tensile Strength	Cylinder	28 days	12
Acid Attack	Cube	28, 56 days	24
Sulfate Attack	Cube	28, 56 days	24
Thermal Resistance	Cube	200°C, 400°C	24

Total Specimens Cast = 144

3.7 Testing Methods

A comprehensive experimental program was conducted to evaluate fresh, mechanical, durability, and thermal performance of SCBA-blended geopolymer concrete. All tests were performed using calibrated equipment and relevant Indian Standard provisions.

3.7.1 Workability Test

Workability was determined using the slump cone method in accordance with IS 1199:2018. Concrete was placed in three layers, each compacted with 25 strokes of a standard tamping rod. The slump value was measured immediately after lifting the cone vertically.

Since IS 1199 does not classify slump ranges, reference values from IS 456:2000 were used for interpretation. The obtained slump values ensured adequate consistency for proper casting and compaction.

3.7.2 Compressive Strength

Compressive strength was measured on 150 mm cube specimens at 7, 28, 56, and 90 days in accordance with IS 516:2018. Load was applied at a constant rate of 2.5 kN/s until failure.

Figure 3.5 :- Compressive Strength Test

The average of three specimens was reported for each mix and age. Failure was predominantly brittle, characterized by vertical cracking typical of dense geopolymer matrices.

3.7.3 Splitting Tensile Strength

Splitting tensile strength was determined on 150 mm × 300 mm cylindrical specimens at 28 days as per IS 5816:1999. Specimens were loaded diametrically until failure, inducing tensile stresses perpendicular to the applied load.
The average of three specimens was reported for each mix to ensure statistical reliability.

Figure 3.6 :-Splitting Tensile Strength

3.7.4 Water Absorption

Water absorption was determined on 150 mm cube specimens at 28 days. Specimens were oven-dried at 105 ± 5°C for 24 hours to obtain dry mass (W_1), then immersed in water for 24 hours to obtain saturated mass (W_2).

Water absorption (%) was calculated as:

Water Absorption = $[(W_2 - W_1) / W_1] \times 100$

Lower absorption indicates a denser geopolymer matrix with refined pore structure. The 5% limit suggested for good quality concrete in IS 456:2000 was used as a reference benchmark.

3.7.5 Acid Resistance

Acid resistance was evaluated using 3% H_2SO_4 solution. After 28 days of ambient curing, cube specimens were immersed for 28 and 56 days. The solution was renewed at 7-day intervals to maintain aggressiveness.

Performance indicators included:

- Percentage mass loss
- Residual compressive strength
- Strength retention (%)

Lower mass loss and higher strength retention indicated superior acid resistance.

3.7.6 Sulfate Resistance

Sulfate resistance was assessed using 5% $MgSO_4$ solution with exposure durations of 28 and 56 days. The solution was renewed periodically to maintain concentration.

Evaluation parameters included:

- Mass change
- Residual compressive strength
- Strength retention (%)

Comparative assessment across mixes enabled evaluation of SCBA influence on sulfate durability.

3.7.7 High-Temperature (Thermal) Resistance

Thermal resistance was evaluated by exposing 28-day cured cube specimens to 200°C and 400°C in a programmable muffle furnace. A controlled heating rate of 5°C/min and a 2-hour soaking period were adopted.

After gradual cooling under still air, specimens were tested for:

- Visual damage
- Residual compressive strength
- Strength retention (%)

This test assessed the stability of the geopolymer matrix under fire-like conditions.

3.5.8 Evaluation Criteria

Performance evaluation was based on:

- Percentage change in compressive strength relative to control mix
- Percentage mass loss after chemical exposure
- Residual strength retention (%)
- Comparative graphical analysis

The 0% SCBA mix served as the control reference. All reported values represent the mean of three specimens to reduce variability.

3.6 Data Analysis Strategy

Experimental results were averaged and analyzed comparatively using the control mix as baseline. Percentage variation was calculated to quantify improvement or deterioration due to SCBA incorporation.

Graphical representation was used to identify:

- Strength development trends
- Durability degradation patterns
- Thermal stability behavior
- Optimum SCBA replacement level

This systematic analytical framework enabled balanced evaluation of mechanical strength, durability, and thermal resistance for sustainable SCBA-based geopolymer concrete.

IV. Results And Discussion

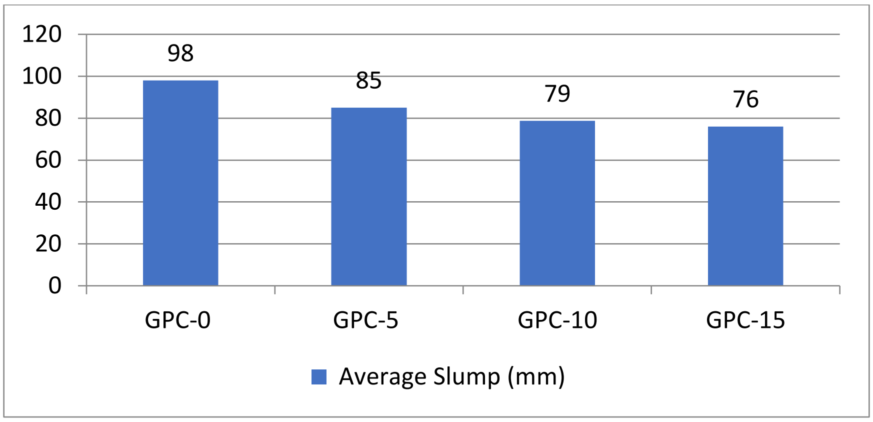
4.1 Workability

The workability of SCBA-incorporated geopolymer concrete was evaluated using the slump cone test in accordance with IS 1199:1959. The measured slump values are presented in Table 4.1.

Table 4.1. Slump values of SCBA-blended geopolymer concrete

Mix	SCBA (%)	Average Slump (mm)
GPC-0	0	98
GPC-5	5	85
GPC-10	10	79
GPC-15	15	76

Graph 4.1 :- SCBA % vs Average Slump



The control mix exhibited a slump of 98 mm, indicating high workability. Incorporation of SCBA resulted in a gradual reduction in slump, decreasing to 85 mm, 79 mm, and 76 mm at 5%, 10%, and 15% replacement levels, respectively.

The reduction in workability with increasing SCBA content is attributed to the high specific surface area and porous nature of SCBA particles, which increase water demand and reduce free water availability in the mix. Despite the decreasing trend, all mixes remained within the medium-to-high workability range as per IS 1199, indicating adequate cohesion and ease of placement without the need for chemical admixtures.

The results suggest that SCBA replacement up to 10% maintains satisfactory fresh properties suitable for practical applications.

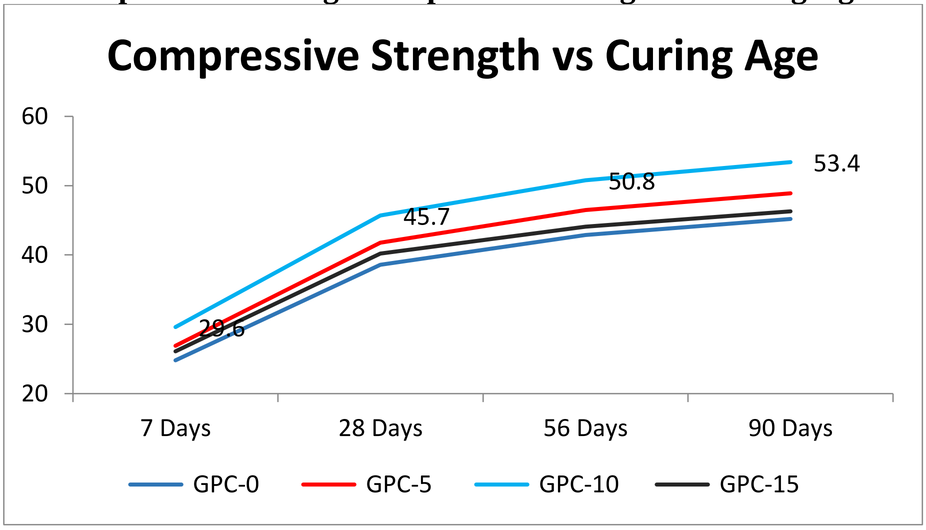
4.2 Compressive Strength Development

The compressive strength results at 7, 28, 56, and 90 days are summarized in Table 4.2 and Graph-4.2.

Table 4.2. Average compressive strength (MPa)

Age (Days)	GPC-0	GPC-5	GPC-10	GPC-15
7	24.8	26.9	29.6	26.1
28	38.6	41.8	45.7	40.2
56	42.9	46.5	50.8	44.1
90	45.2	48.9	53.4	46.3

Graph 4.2 :- Average Compressive Strength vs Curing Age



All mixes exhibited progressive strength gain with curing age, confirming the time-dependent geopolymerization process under ambient conditions. Continuous dissolution of aluminosilicate species and subsequent formation of geopolymeric gel contributed to long-term strength development.

At 7 days, incorporation of SCBA up to 10% significantly enhanced early-age strength, with GPC-10 achieving 29.6 MPa compared to 24.8 MPa for the control mix. Similar trends were observed at later ages, where GPC-10 attained 45.7 MPa, 50.8 MPa, and 53.4 MPa at 28, 56, and 90 days, respectively.

The improvement in compressive strength at 5–10% SCBA can be attributed to:

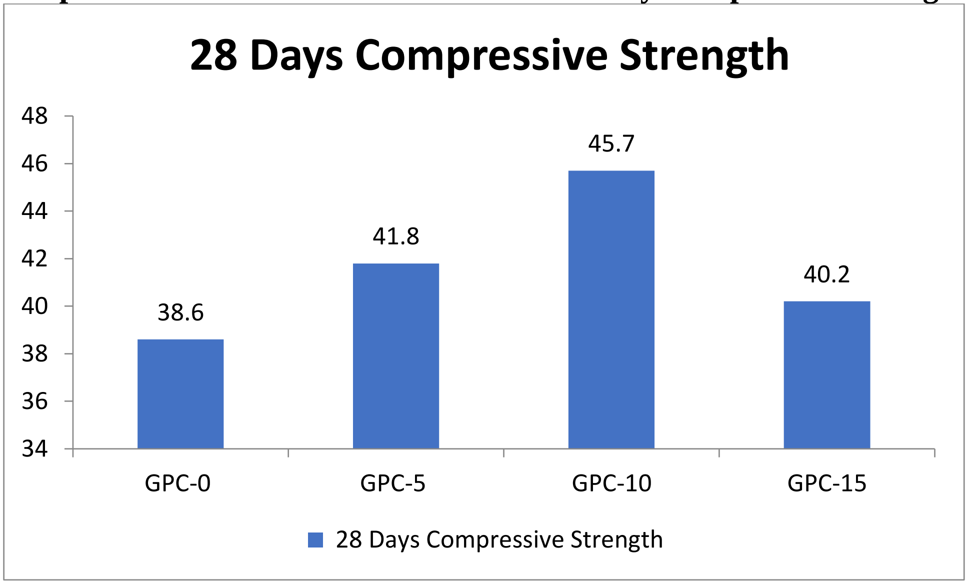
- Pozzolanic reactivity of reactive silica in SCBA
- Filler effect leading to improved particle packing
- Enhanced geopolymer gel formation
- Increased matrix densification

However, at 15% replacement, a slight reduction in strength was observed compared to the 10% mix, although values remained higher than the control. This decline may be due to excess unreacted or partially reactive SCBA particles, which disrupt the continuity of the geopolymer matrix and reduce effective bonding.

4.2.1 Effect of SCBA Content on 28-Day Strength

The variation in 28-day compressive strength with SCBA replacement clearly demonstrates the existence of an optimum replacement level. Strength increased from 38.6 MPa (control) to 45.7 MPa at 10% SCBA, representing a significant enhancement. Beyond this level, strength decreased to 40.2 MPa at 15% replacement.

Graph 4.3 :- Effect of SCBA Content on 28-Day Compressive Strength

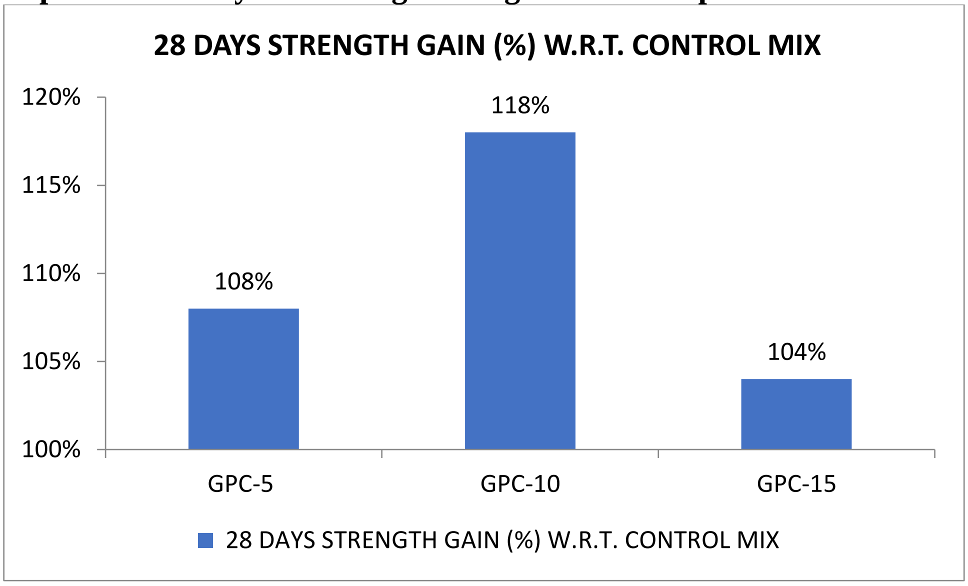


This behavior indicates that moderate SCBA incorporation enhances microstructural compactness and reaction efficiency, whereas excessive replacement reduces effective geopolymerization due to dilution and incomplete reaction.

4.2.2 Percentage Strength Gain

The percentage strength gain at 28 days relative to the control mix confirms the beneficial role of SCBA within an optimum range. Mixes containing 5% and 10% SCBA exhibited positive strength increments, with maximum gain recorded at 10% replacement.

Graph 4.4 :- 28 days Percentage Strength Gain Compared to Control mix



The reduction in percentage gain at 15% SCBA further validates that excessive incorporation adversely affects matrix development.

4.2.3 Overall Performance Assessment

The combined results indicate that SCBA significantly influences both fresh and hardened properties of geopolymer concrete. While increasing SCBA content reduces workability due to higher water demand, compressive strength improves up to an optimum level of 10% replacement.

The strength–age relationship confirms sustained geopolymerization under ambient curing conditions. The enhancement in mechanical performance is primarily associated with improved particle packing and additional reactive silica contribution from SCBA.

An optimum SCBA replacement level of 10% is identified for maximizing compressive strength without significantly compromising workability. Beyond this level, dilution effects and incomplete reaction reduce performance efficiency.

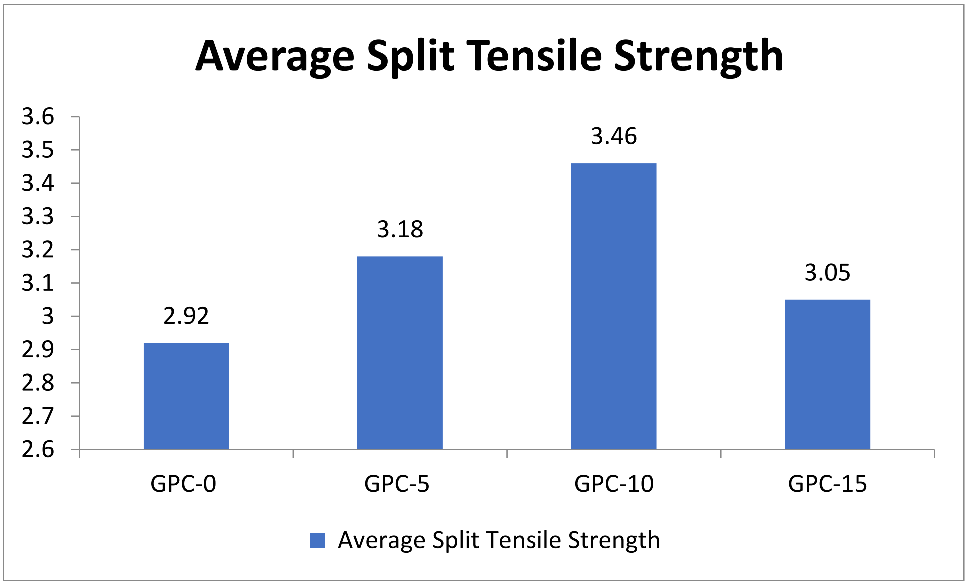
4.3 Split Tensile Strength

The 28-day split tensile strength results are presented in Table 4.3**,** and the corresponding variation trend is illustrated in Graph. 4.5.

Table 4.3 :- Split Tensile Strength Results of SCBA-Blended Geopolymer Concrete (28 Days)

Mix-ID	SCBA Replacement (%)	Specimen 1	Specimen 2	Specimen 3	Average Split Tensile Strength
GPC-0	0%	2.92	2.88	2.95	2.92
GPC-5	5%	3.18	3.21	3.15	3.18
GPC-10	10%	3.46	3.5	3.42	3.46
GPC-15	15%	3.05	3.08	3.02	3.05

Graph 4.5 :-Average split tensile strength of SCBA-blended geopolymer concrete at 28 days



As observed from Table 4.3 and Graph. 4.5, the split tensile strength increases with SCBA incorporation up to 10% replacement, followed by a marginal decline at 15%. The control mix exhibits the lowest tensile strength, whereas the mix containing 10% SCBA achieves the maximum value.

The ascending trend shown in Graph. 4.5 confirms that moderate SCBA incorporation enhances matrix compactness and improves stress transfer capacity within the geopolymer system. The improvement may be attributed to the filler effect and additional reactive silica content contributing to improved geopolymer gel formation.

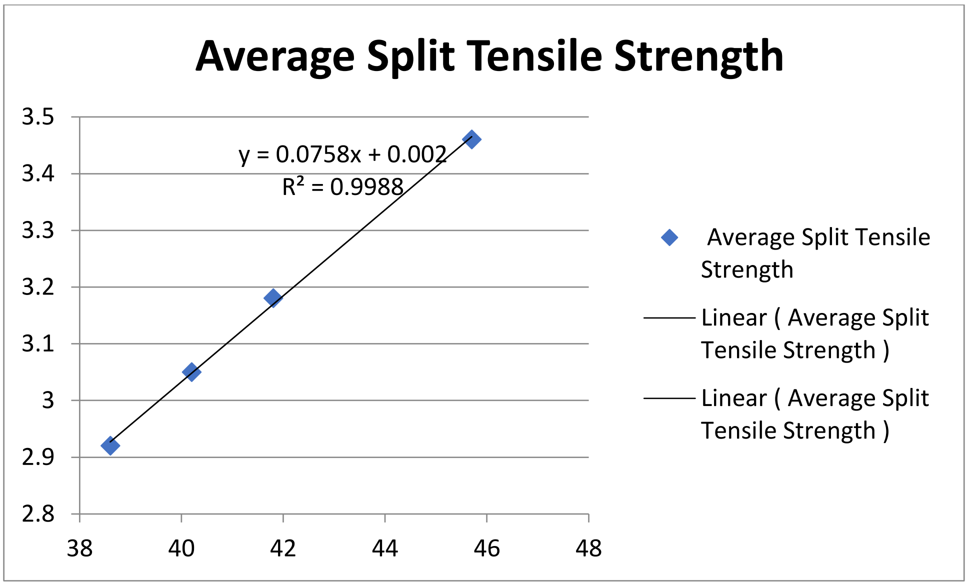
However, beyond the optimum replacement level, as indicated by the downward slope in Graph. 4.5, excessive SCBA results in slight reduction in tensile strength, possibly due to incomplete geopolymerization and increased unreacted particles within the matrix.

Thus, the combined interpretation of Table 4.3 and Graph. 4.5 clearly establishes 10% SCBA as the optimum replacement level for maximizing tensile performance.

4.3.1 Correlation Between Compressive and Split Tensile Strength

The relationship between compressive strength and split tensile strength is illustrated in Graph. 4.6**,** while the corresponding compressive strength values are given in Table 4.2 and Table 4.3**.**

Graph 4.6 :- Split Tensile Strength vs Compressive Strength



As evident from Graph. 4.6, both properties follow a similar increasing trend up to the optimum SCBA content. The graphical representation demonstrates a near-linear correlation between compressive and tensile strengths.

The slope of the curve in Graph. 4.6 indicates that tensile strength remains within the expected proportional range relative to compressive strength, confirming consistent microstructural development across mixes.

4.4 Water Absorption

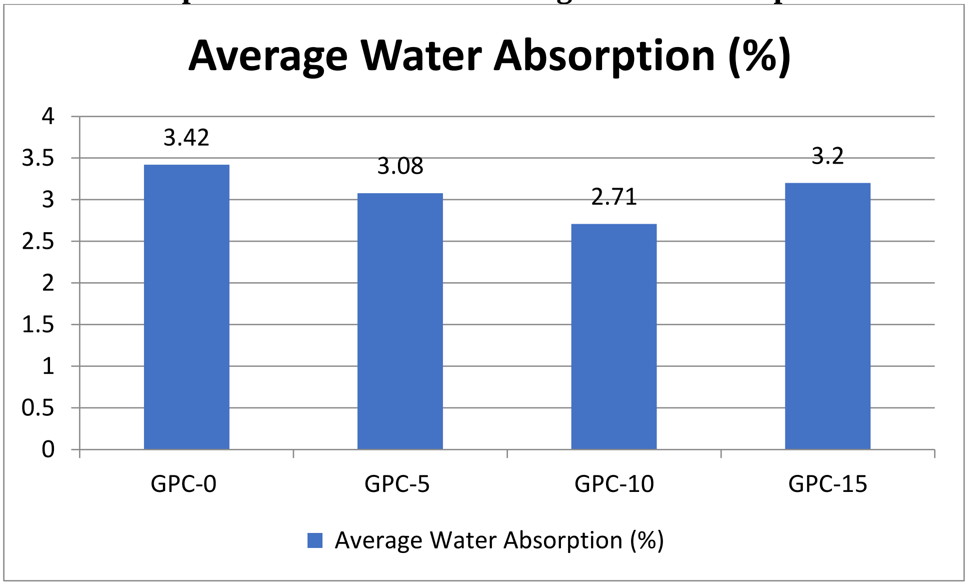
The water absorption results are presented in Table 4.4, and their variation with SCBA replacement is depicted in Graph. 4.7.

Table 4.4 :- Test Results of Water Absorption Test

Mix ID	SCBA Replacement (%)	Specimen 1 (%)	Specimen 2 (%)	Specimen 3 (%)	Average Water Absorption (%)
GPC-0	0	3.42	3.38	3.45	3.42
GPC-5	5	3.08	3.12	3.05	3.08
GPC-10	10	2.71	2.68	2.74	2.71

GPC-15	15	3.19	3.23	3.17	3.20

Graph 4.7 :- SCBA % vs Average Water Absorption



As shown in Table 4.4 and Graph. 4.7, water absorption decreases progressively with increasing SCBA content up to 10%, reaching a minimum value at the optimum replacement level. The descending trend in Graph. 4.7 indicates improved pore refinement and reduced capillary connectivity.

At 15% SCBA, a slight increase in absorption is observed, as reflected in the final bar/point of Graph. 4.7. This suggests that excessive SCBA may lead to incomplete reaction and increased porosity.

The combined graphical and tabular analysis confirms enhanced durability performance at 10% SCBA replacement.

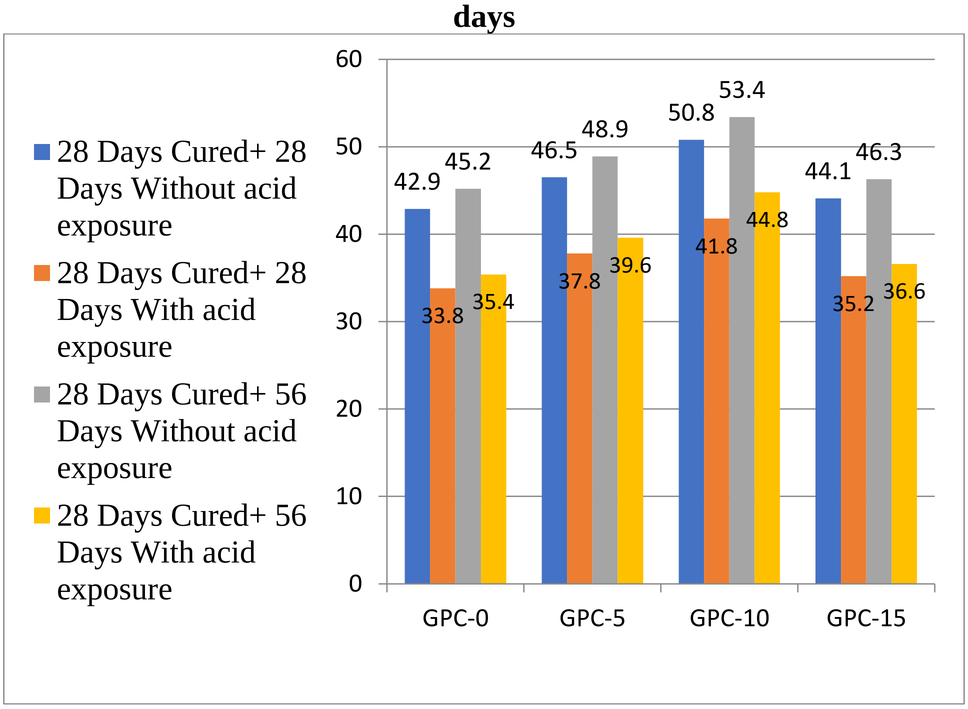
4.5 Acid Resistance

The residual compressive strength after acid exposure is summarized in Table 4.5, and the strength retention trend is illustrated in Graph. 4.8.

Table 4.5 :- Residual Compressive Strength under 3% H_2SO_4 Exposure (MPa)

Mix ID	28 Days Cured+ 28 Days Without acid exposure	28 Days Cured+ 28 Days With acid exposure	28 Days Cured+ 56 Days Without acid exposure	28 Days Cured+ 56 Days With acid exposure
GPC-0	42.9	33.8	45.2	35.4
GPC-5	46.5	37.8	48.9	39.6
GPC-10	50.8	41.8	53.4	44.8
GPC-15	44.1	35.2	46.3	36.6

Graph 4.8 :- Residual Compressive Strength under 3% H_2SO_4 Exposure (MPa) at 28 an 56 days



As evident from Table 4.5 and Graph. 4.8, all mixes exhibit strength reduction after acid exposure; however, SCBA-modified mixes show improved residual strength compared to the control. The graphical trend clearly indicates that the 10% SCBA mix retains the highest strength after exposure.

The percentage reduction in compressive strength after exposure to 3% H_2SO_4 solution is presented in Table 4.6 and Graph 4.9. The results indicate that all geopolymer mixes experienced strength deterioration under acidic conditions; however, the extent of reduction varied depending upon SCBA replacement level and exposure duration.

After 28 days curing followed by 28 days of acid exposure, the control mix (GPC-0) exhibited a strength reduction of 21.21%, whereas GPC-5, GPC-10, and GPC-15 showed reductions of 18.71%, 17.72%, and 20.18%, respectively. Among all mixes, GPC-10 demonstrated the lowest percentage reduction, indicating better resistance against acid attack.

Similarly, after 28 days curing followed by 56 days of acid exposure, a slight increase in strength reduction was observed for most mixes. The control mix (GPC-0) showed a reduction of 21.68%, while GPC-5, GPC-10, and GPC-15 recorded reductions of 19.02%, 16.10%, and 20.95%, respectively. Again, GPC-10 exhibited the minimum strength loss, confirming its improved durability performance under prolonged acidic exposure.

The trend illustrated in Graph 4.9 clearly supports the numerical values reported in Table 4.6. The graph shows that moderate incorporation of SCBA (10%) enhances resistance to sulfuric acid, whereas higher replacement (15%) results in comparatively higher deterioration. This behavior may be attributed to improved matrix densification at optimum SCBA content and increased porosity at higher replacement levels.

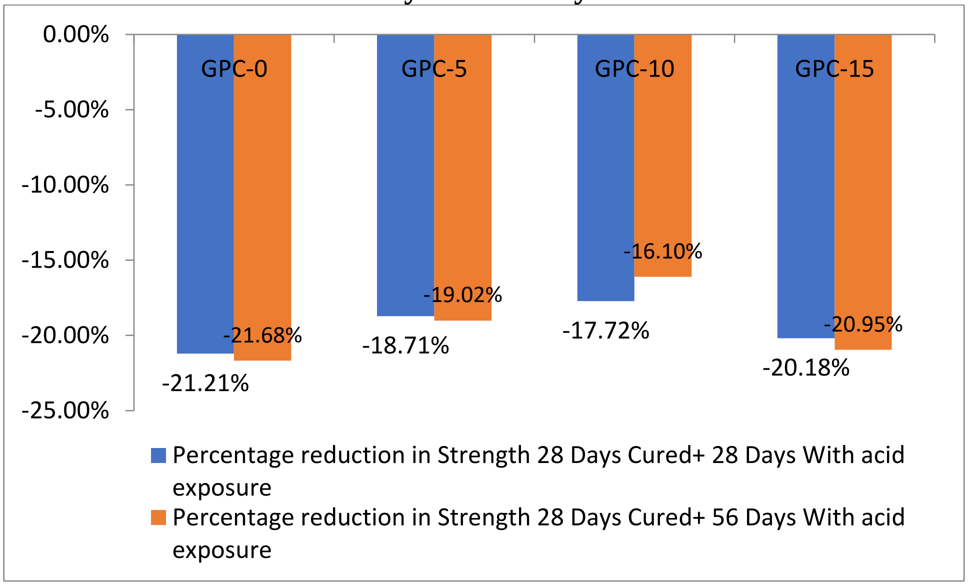
Thus, both Table 4.6 and Graph 4.9 collectively demonstrate that 10% SCBA replacement provides optimum resistance against 3% H_2SO_4 exposure, while excessive replacement slightly reduces acid resistance performance.

Table 4.6 :- Percentage reduction in Strength after 3% H_2SO_4 Exposure

Mix ID	Percentage reduction in Strength

	28 Days Cured+ 28 Days With acid exposure	28 Days Cured+ 56 Days With acid exposure
GPC-0	21.21%	21.68%
GPC-5	18.71%	19.02%
GPC-10	17.72%	16.10%
GPC-15	20.18%	20.95%

Graph 4.9 :- Percentage reduction in Compressive Strength after 3% H_2SO_4 Exposure of 28 days and 56 days



4.5.1 Weight Loss Under Acid Exposure

The mass loss results are provided in Table 4.7, with graphical representation shown in Graph. 4.10. where as percentage mass loss results are privded in Table 4.8 and Graph 4.11

Table 4.7 :- Weight Loss after 3% H_2SO_4 Exposure (Kg) for 28 days and 56 days

Mix ID	Weight after 28 Days curing (kg)	Weight after 28 Days curing+ 28 days Exposure (kg)	Weight after 28 Days curing+ 56 days Exposure (kg)
GPC-0	8.2	8.03	7.9
GPC-5	8.16	8.07	7.97
GPC-10	8.13	8.1	8.03
GPC-15	8.1	8.01	7.88

Graph 4.10 :- Weight Loss after 3% H_2SO_4 Exposure (Kg) for 28 days and 56 days

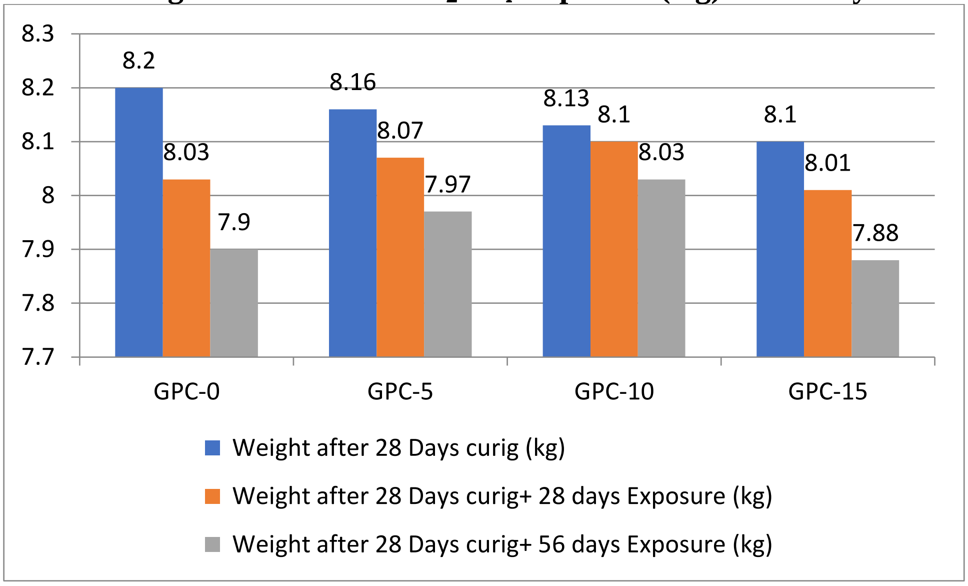
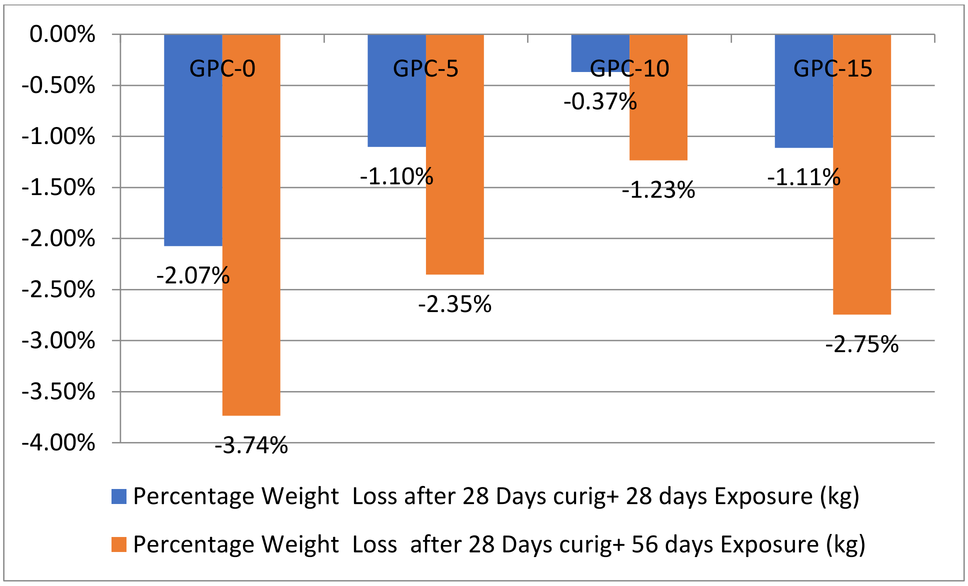


Table 4.8 :- Percentage Weight loss after 3% H_2SO_4 Exposure for 28 days and 56 days

Mix ID	Percentage Weight Loss	
	after 28 Days curig+ 28 days Exposure (kg)	after 28 Days curig+ 56 days Exposure (kg)
GPC-0	2.07%	3.74%
GPC-5	1.10%	2.35%
GPC-10	0.37%	1.23%
GPC-15	1.11%	2.75%

Graph 4.11 :-Percentage Weight loss after 3% H_2SO_4 Exposure for 28 days and 56 days



As observed from Table 4.8 and Graph. 4.11, the control mix experiences the highest mass loss, whereas the optimum SCBA mix exhibits the lowest deterioration. The graphical trend confirms improved resistance due to reduced permeability and enhanced matrix densification.

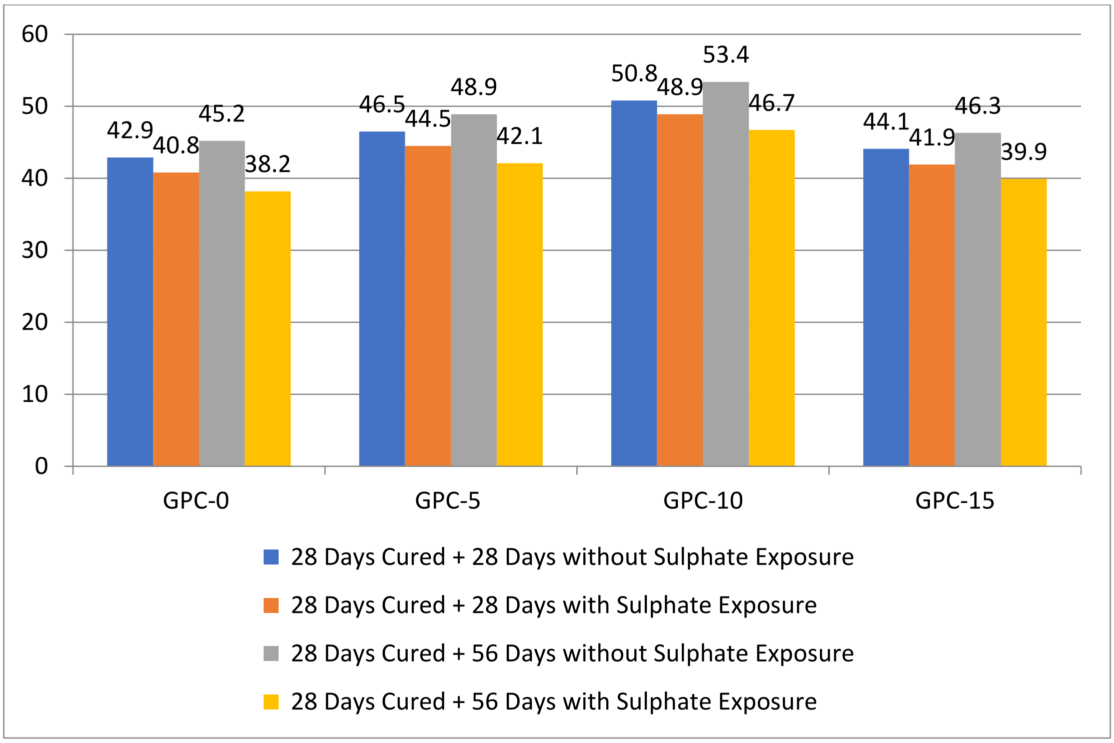
4.6 Sulphate Resistance

The residual strength values under sulphate exposure are presented in Table 4.9, and the variation trend is shown in Graph. 4.12.

Table 4.9 :-Residual Strength with sulphate exposure(MPa) at 28 and 56 Days

Mix ID	28 Days Cured + 28 Days without Sulphate Exposure	28 Days Cured + 28 Days with Sulphate Exposure	28 Days Cured + 56 Days without Sulphate Exposure	28 Days Cured + 56 Days with Sulphate Exposure
GPC-0	42.9	40.8	45.2	38.2
GPC-5	46.5	44.5	48.9	42.1
GPC-10	50.8	48.9	53.4	46.7
GPC-15	44.1	41.9	46.3	39.9

Graph 4.12 :- Residual Strength with sulphate exposure(MPa) at 28 and 56 Days

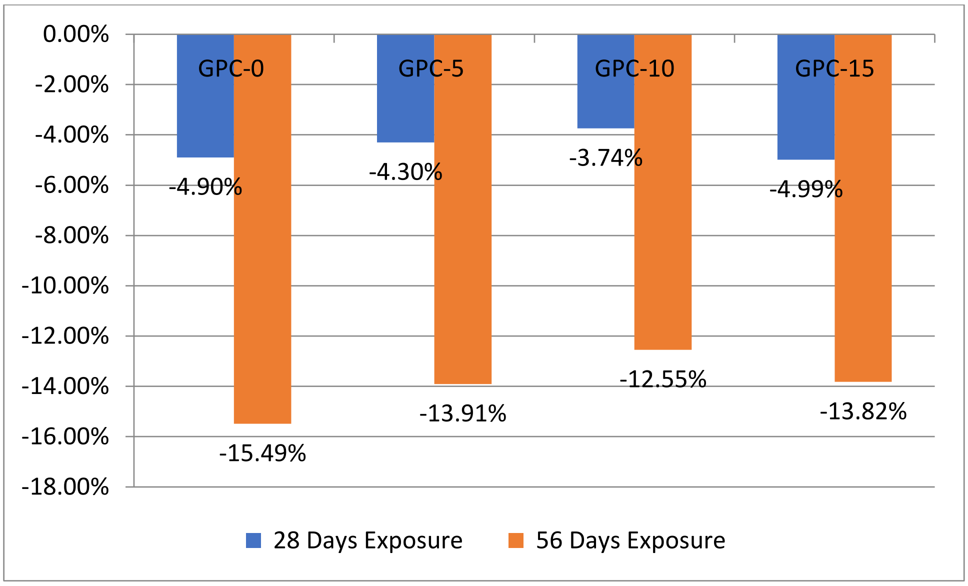


From Table 4.9 and Graph. 4.12, it is clear that strength reduction under sulphate exposure is comparatively lower than under acid exposure. The curves show gradual deterioration with exposure duration, while the optimum SCBA mix consistently maintains higher residual strength.
Similarly, Percentage Strength loss results presented in Table 4.10 and illustrated in Graph. 4.13**.**

Table 4.10 :- Percentage Strength loss with sulphate exposure(%) at 28 and 56 Days

Mix ID	28 Days Exposure	56 Days Exposure
GPC-0	4.90%	15.49%
GPC-5	4.30%	13.91%
GPC-10	3.74%	12.55%
GPC-15	4.99%	13.82%

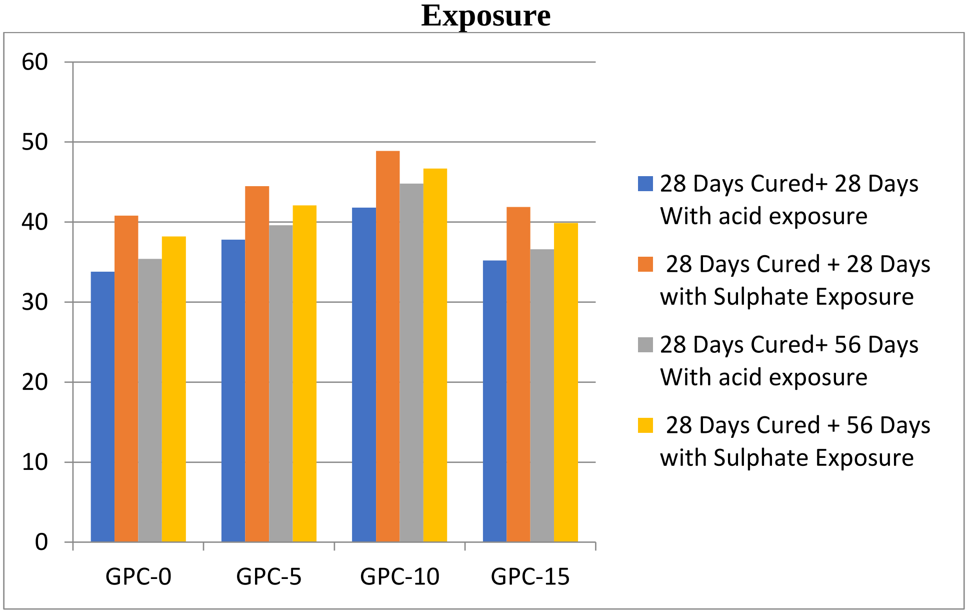
Graph 4.13 :- Percentage Strength loss with sulphate exposure(%) at 28 and 56 Days



4.6.1 Comparative Interpretation

A comparative graphical analysis presented in Graph. 4.14 demonstrates that acid exposure produces a steeper decline in strength compared to sulphate exposure.

Graph 4.14 :- Comparative Table For Residual Strength After Acid Exposure And Sulphate Exposure



The sharper degradation trend confirms the aggressive dissolution mechanism of acid attack, whereas sulphate attack causes relatively controlled deterioration in low-calcium geopolymer systems.

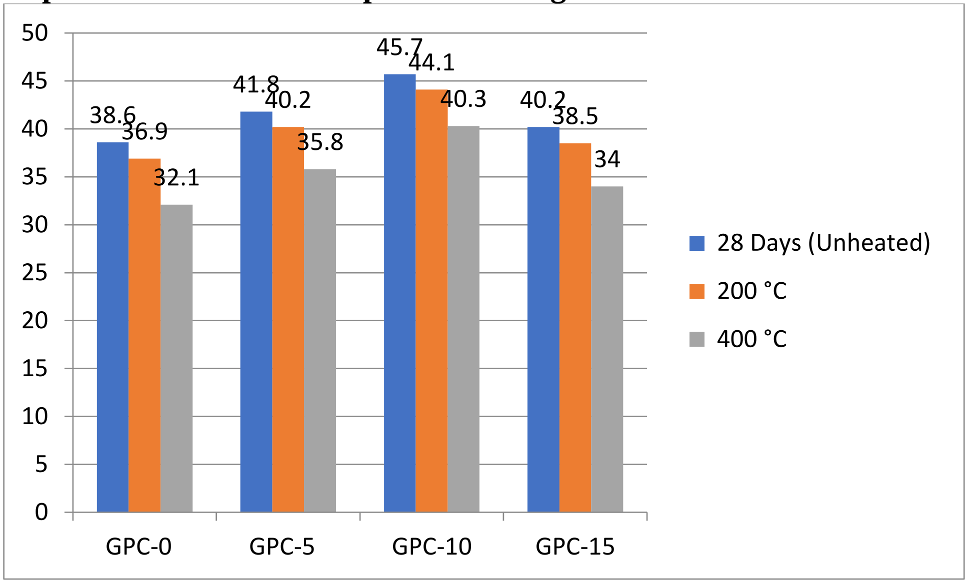
4.7 Thermal / Fire Resistance

The residual compressive strength of SCBA-blended geopolymer concrete after exposure to elevated temperatures (200 °C and 400 °C) is presented in Table 4.11, and the corresponding variation is illustrated in Graph 4.15.

Table 4.11 :- Residual compressive strength after thermal resistance test

Mix ID	28 Days (Unheated)	200 °C	400 °C
GPC-0	38.6	36.9	32.1
GPC-5	41.8	40.2	35.8
GPC-10	45.7	44.1	40.3
GPC-15	40.2	38.5	34

Graph 4.15 :- Residual compressive strength after thermal resistance test



As observed from Table 4.11 and Graph 4.15, compressive strength decreases progressively with increasing temperature for all mixes. The control mix (GPC-0) shows a reduction from 38.6 MPa (unheated) to 36.9 MPa at 200 °C and further to 32.1 MPa at 400 °C. A similar decreasing trend is evident for all SCBA-modified mixes; however, the magnitude of strength loss is comparatively lower in blended systems, particularly GPC-10.

The graphical trend in Graph 4.15 clearly indicates that the mix containing 10% SCBA retains the highest residual strength at both temperature levels. This enhanced thermal stability can be attributed to improved matrix densification, refined pore structure, and stronger paste–aggregate bonding resulting from optimal geopolymerization.

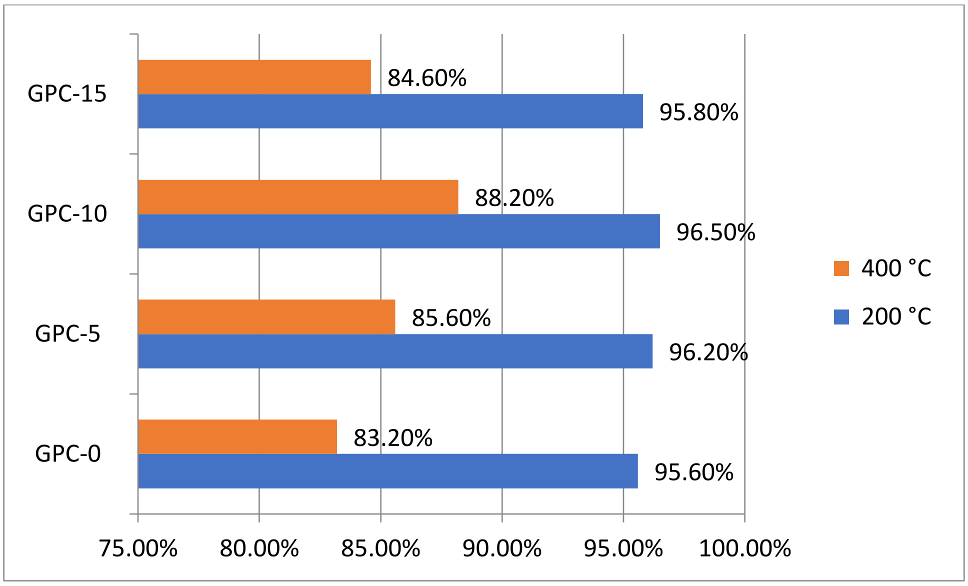
4.7.1 Percentage Strength Retention

The percentage strength retention values after thermal exposure are summarized in Table 4.12, and the corresponding graphical representation is shown in Graph 4.16

Table 4.12 :-Percentage Strength Retention after Thermal Exposure

Mix ID	200 °C	400 °C
GPC-0	95.60%	83.20%
GPC-5	96.20%	85.60%
GPC-10	96.50%	88.20%
GPC-15	95.80%	84.60%

Graph 4.16 :-Percentage Strength Retention after Thermal Exposure



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As evident from Table 4.12 and Graph 4.16**,** strength retention exceeds 95% at 200 °C for all mixes, confirming minimal thermal damage at this temperature level. The graphical trend shows that GPC-10 exhibits the highest retention (96.50%), followed closely by GPC-5 and GPC-15.

At 400 °C, strength retention decreases moderately, with values ranging between 83.20% and 88.20%. The highest retention is again observed for GPC-10 (88.20%), as clearly indicated in Graph 4.16. The comparative slope of decline in the graph confirms that thermal degradation increases progressively with temperature.

The improved performance of SCBA-modified mixes can be attributed to:

- Enhanced Si–Al polymerization
- Reduced calcium content
- Formation of thermally stable alumino-silicate gel phases
- Refined pore structure limiting crack propagation.

V. Conclusions

The present investigation evaluated the mechanical performance, durability characteristics, and thermal resistance of low-calcium fly ash-based geopolymer concrete partially blended with Sugarcane Bagasse Ash (SCBA). Based on the experimental findings, the following conclusions are drawn:

Incorporation of SCBA significantly influences both fresh and hardened properties of geopolymer concrete. Workability decreased slightly with increasing SCBA content due to the finer particle size and higher surface area of SCBA; however, all mixes remained within acceptable limits for structural applications.

Compressive strength increased progressively with curing age for all mixes, confirming continuous geopolymerization under ambient conditions. Among the investigated mixtures, the 10% SCBA blend (GPC-10) exhibited the highest compressive strength at all ages, achieving 45.7 MPa at 28 days and 53.4 MPa at 90 days. The strength enhancement up to 10% replacement is attributed to improved particle packing, pore refinement, and enhanced alumino-silicate gel formation. A further increase to 15% replacement resulted in marginal strength reduction, indicating dilution of reactive phases and incomplete geopolymerization.

Split tensile strength followed a trend similar to compressive strength, demonstrating a strong correlation between tensile and compressive behavior. The optimum 10% SCBA mix showed superior tensile performance, indicating improved crack resistance and better interfacial bonding within the geopolymer matrix.

Durability evaluation under aggressive environments revealed that acid exposure is considerably more detrimental than sulphate exposure. After 56 days of 3% H_2SO_4 exposure, the control mix exhibited higher strength and mass loss compared to SCBA-modified mixes. The 10% SCBA blend demonstrated the lowest deterioration, confirming that matrix densification and reduced permeability significantly enhance resistance to acid attack.

Under sulphate exposure, all mixes exhibited comparatively lower strength and mass loss. The improved performance of SCBA-modified mixes, particularly GPC-10, validates the superior chemical stability of low-calcium geopolymer systems in sulphate-rich environments.

Thermal resistance assessment further demonstrated that residual compressive strength decreases with increasing temperature; however, SCBA incorporation significantly improves strength retention. At 400 °C, the 10% SCBA blend consistently showed the highest residual strength. The improved fire resistance is attributed to reduced calcium content, stable alumino-silicate gel formation, refined pore structure, and enhanced thermal compatibility within the matrix.

Overall, the experimental results clearly establish that SCBA can be effectively utilized as a sustainable supplementary alumino-silicate source in geopolymer concrete. An optimum replacement level of 10% provides the best balance of mechanical strength, chemical durability, and thermal stability. Excessive replacement beyond this level leads to marginal reductions in performance due to reduced reactive phase availability.

The findings confirm that SCBA-blended geopolymer concrete is a durable, environmentally sustainable, and technically viable construction material suitable for applications exposed to aggressive chemical environments and elevated temperatures. The study contributes to sustainable waste utilization while promoting the development of low-carbon alternative binders for future infrastructure systems.

VI. Future Research Directions

Although the present study provides a comprehensive evaluation of SCBA-blended fly ash-based geopolymer concrete, several research directions remain open for further scientific advancement.

Future investigations may focus on the incorporation of nano-scale additives such as nano-silica, nano-alumina, or graphene oxide to enhance geopolymer gel densification and microstructural refinement. Nano-modification could potentially improve long-term durability, crack resistance, and chemical stability under aggressive environments.

The integration of fiber reinforcement, including steel, polypropylene, basalt, or natural fibers, represents another promising direction. Fiber addition may significantly enhance tensile and flexural performance, impact resistance, and thermal crack control, thereby improving structural reliability under combined mechanical and environmental loading.

While the present study adopted ambient curing conditions, controlled curing regimes such as steam curing, heat-assisted curing, or solar-assisted curing may be explored to accelerate geopolymerization and optimize early-age strength development for precast and industrial applications.

Extended durability assessment under realistic environmental exposures, including marine, chloride-rich, industrial, and freeze–thaw conditions, would provide deeper insight into long-term field performance. Evaluation of carbonation resistance, chloride penetration, and coupled deterioration mechanisms is particularly recommended.

Structural-scale investigations involving beams, slabs, and columns fabricated using SCBA-blended geopolymer concrete should be conducted to validate serviceability performance, load-carrying capacity, and fire resistance under realistic boundary conditions.

Comprehensive life cycle assessment (LCA) studies are also recommended to quantify carbon footprint reduction, embodied energy savings, and economic feasibility in comparison with conventional OPC systems. Such analyses would strengthen the case for large-scale implementation in sustainable infrastructure.

The synergistic use of SCBA with other supplementary cementitious materials such as rice husk ash, ground granulated blast furnace slag, or metakaolin may be explored to develop hybrid geopolymer systems with optimized mechanical and durability characteristics.

Finally, advanced microstructural characterization using SEM, XRD, FTIR, and mercury intrusion porosimetry (MIP) is recommended to establish quantitative correlations between gel chemistry, pore structure evolution, and macro-scale mechanical performance. Such studies would provide deeper understanding of SCBA reactivity and geopolymer network development.

The present research establishes Sugarcane Bagasse Ash as an effective and sustainable supplementary alumino-silicate source in fly ash-based geopolymer concrete. An optimum replacement level of 10% enhances mechanical strength, chemical durability, and thermal resistance while contributing to waste valorization and reduction of environmental impact.

The findings confirm that SCBA-blended geopolymer concrete represents a technically viable, eco-efficient, and durable alternative binder system suitable for aggressive environmental and fire-prone applications. By integrating performance enhancement with sustainability benefits, this material supports the transition toward low-carbon construction practices and circular economy principles.

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