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Development and Characterization of Bottom Ash–Fly Ash–GGBS-Based Geopolymer Composites for Sustainable Applications

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Abstract

The growing demand for sustainable construction materials has spotlighted geopolymer concrete (GPC) as an environmentally viable substitute for conventional cement-based systems. This study presents an innovative dual-waste valorization approach, integrating pulverized bottom ash (BA) and ground granulated blast furnace slag (GGBS) as binders while replacing sodium silicate (Na_2SiO_3) in the alkaline activator with treated textile effluent. Unlike prior works that focus solely on solid waste incorporation, this research pioneers the utilization of hazardous liquid effluent as a functional activator component, addressing both material performance and industrial wastewater remediation. Sixty GPC mixes were developed with varying BA: GGBS ratios (75:25, 50:50), sodium hydroxide (NaOH) concentrations (4M, 6M, 8M), and textile effluent replacements (0–100%), maintaining a constant alkaline-to-binder ratio. Ambient-cured specimens were evaluated for compressive strength, identifying two high-performing mixes for further mechanical and fire endurance testing. Notably, mix 6A2BG50E50 (6M NaOH, 50% BA, 50% effluent) achieved M40-grade strength and sustained fire exposure for four hours. This study demonstrates a robust, fire-resistant GPC formulation and introduces a novel method of repurposing both solid and liquid industrial wastes for sustainable infrastructure development.

Keywords: Geopolymer concrete; bottom ash; textile effluent; compressive strength; fire endurance

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INTRODUCTION

The increasing environmental degradation due to excessive natural resource consumption and the accumulation of industrial waste has raised urgent concerns globally, particularly in developing nations where rapid industrialization exacerbates the problem. One of the major contributors to environmental pollution is the cement industry, which is responsible for approximately 6–7% of global CO_2 emissions [1-2]. The production of one tonne of Portland cement emits approximately 0.87 tonnes of CO_2 and releases nitrogen oxides (NO_x), which contribute to global warming, smog formation, and severe respiratory hazards. To address these critical concerns, geopolymer concrete (GPC) has emerged as a promising alternative due to its significantly lower carbon footprint and ability to utilize industrial by-products as raw materials [3-4]. Moreover, the cement industry is among the top three energy-consuming industrial sectors worldwide, following steel and aluminum, further emphasizing the urgent need for sustainable alternatives in the construction sector [5]. Geopolymer concrete (GPC) has emerged as a promising eco-friendly substitute for conventional cement-based concrete to mitigate these adverse impacts [6-7]. GPC is synthesized through the geopolymerization process, which involves activating alumino-silicate-rich industrial by-products such as fly ash, bottom ash, and ground granulated blast furnace slag (GGBS) using alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [8-9]. This reaction forms a robust binder network without needing Portland cement, resulting in significantly lower carbon emissions and improved thermal and chemical resistance [10]. GPC not only addresses the problem of industrial waste disposal but also offers enhanced durability, early strength gain, and resistance to fire and aggressive environments [11]. Traditionally, the activator solution in GPC relies on synthetic sodium silicate, which, despite its effectiveness, remains costly and energy-intensive to produce [12]. In an innovative departure from conventional practice, the present study investigates the use of treated textile effluent—a hazardous waste stream from dyeing and finishing industries—as a partial or complete substitute for sodium silicate in the alkaline activator [13-14]. This dual-waste utilization approach uniquely combines solid industrial by-products (bottom ash and GGBS) and liquid waste (textile effluent) to develop a sustainable and economically viable GPC formulation. Pulverized bottom ash was used to improve its reactivity and, in conjunction with GGBS as the binder phase, in various mix ratios [15-16]. The activator solution was formulated with sodium hydroxide (4M, 6M, and 8M concentrations), while textile effluent replaced sodium silicate at varying levels from 0% to 100%. Sixty distinct GPC mixes were cast and ambient-cured before evaluating their compressive strength, and the optimal mixes were further examined for mechanical properties and fire endurance performance [17-18]. This research introduces a novel pathway for addressing environmental and material efficiency challenges in the construction industry by incorporating solid and liquid industrial wastes into a single geopolymer matrix [19]. The innovative use of textile effluent as a chemical substitute in GPC represents a significant step toward circular economy principles, reducing reliance on synthetic activators while transforming hazardous waste into value-added construction materials [20]. While most prior studies have focused on solid waste materials such as fly ash, bottom ash, and GGBS for geopolymer production, there is a lack of studies utilizing hazardous liquid industrial wastes as activator components. In this study, we introduce the novel concept of substituting sodium silicate with treated textile effluent from cotton industries, leveraging its silica and alumina content. This dual waste utilization strategy not only addresses hazardous effluent management but also reduces the cost of chemical activators, thereby offering an innovative solution with both environmental and economic benefits. The findings of this study not only contribute to the advancement of low-carbon construction technologies and provide a scalable model for sustainable waste management. The objective of this research is to develop a geopolymer concrete with enhanced mechanical strength and fire resistance by using pulverized bottom ash and GGBS as binder materials and replacing conventional sodium silicate with treated textile effluent. Thus, this concrete will offer an environmentally responsible and technically superior alternative to traditional cementitious systems.

MATERIALS AND METHODS

Geopolymer concrete (GPC), often called alkali-activated cement or inorganic polymer concrete, is increasingly recognized as a sustainable alternative to traditional Portland cement-based concrete. This study explores the use of bottom ash, a waste byproduct from thermal power plants, in the production of GPC, focusing on enhancing its properties and reducing environmental impact. Bottom ash, with its relatively larger particle size than fly ash, can be effectively utilized as a substitute for fine aggregates or even cement when ground to a finer particle size. In this study, bottom ash was ground to 15.7 µm, and when cured at ambient temperatures of 20°C and 80°C, the resulting geopolymer mortar demonstrated a 28-day compressive strength of 26.23 MPa. Bottom ash as a raw material is advantageous due to its chemical composition, which shares similarities with fly ash, particularly the concentration of silica and alumina, making it an ideal candidate for geopolymer activation. A significant challenge with traditional geopolymer concrete is the requirement for heat curing to achieve the desired strength. To address this issue, the study investigates the incorporation of Ground

Granulated Blast Furnace Slag (GGBS), a byproduct from the steel industry, which enhances the geopolymer's strength without needing heat curing. GGBS, composed primarily of calcium and magnesium silicates and alumino-silicates, has been proven to produce high-strength, durable concrete. Integrating GGBS into the geopolymer mix eliminates the need for heat curing, making the process more energy-efficient and environmentally friendly. Furthermore, the study addresses the cost-related challenge of using sodium hydroxide (NaOH) in geopolymer concrete production. NaOH, though effective, significantly increases the production cost, limiting its widespread application. As a solution, this research explores using effluent from cotton textile industries as an alternative to NaOH. Cotton textile industry effluents, rich in mineral fibers, share similar chemical characteristics to NaOH, specifically in their silica and alumina content, making them a viable substitute. This novel substitution could help lower the cost of geopolymer concrete production, making it more accessible for large-scale applications. Incorporating cotton textile effluent provides a cost-effective alternative to conventional alkaline solutions and introduces a sustainable approach by utilizing industrial waste that would otherwise contribute to environmental pollution.

This innovative strategy offers the dual benefit of reducing the environmental footprint of both the textile and construction industries, thus contributing to a circular economy model. This study highlights the potential of bottom ash, GGBS, and cotton textile industry effluent as sustainable materials for the production of geopolymer concrete. By utilizing these waste products, the research offers a novel solution to the challenges of cost, energy consumption, and environmental impact associated with traditional concrete production. This approach can transform the geopolymer concrete industry, offering a more sustainable and cost-effective alternative to conventional concrete.

Experimental Setting

To explore the sustainable substitution of commercial sodium silicate (Na_2SiO_3) in geopolymer concrete (GPC), effluent samples were collected from various cotton textile industries, specifically from mercerizing, washing, wetting, and bleaching processes. The sources include a mercerizing unit in Thalaivaipuram, Thenkasi district; a denim-manufacturing unit in Coimbatore; a cotton processing industry in Tirupur for washing and wetting; and a bleaching unit in Salem. Care was taken to ensure the effluents were free from colored chemicals before use. The chemical composition of these effluents was analyzed, and the effluent from the Mercerizing-1 process (Thenkasi) was selected for replacing Na_2SiO_3 due to its favorable alkaline characteristics and a molar ratio of 0.54, which supports optimal geopolymer binding. It was also available in bulk and presented as a viable alkaline liquid substitute.

Key chemical parameters of the effluents include pH (ranging from 6.63 to 12.70), specific gravity (approximately 1.52–1.53 g/cm^3), and constituents such as SiO_2, Na_2O, Fe_2O_3, K_2O, P_2O_5, and MgO. Al_2O_3 was below detectable limits in all samples. To assess the impact of this substitution, a systematic mix design was developed using two alkaline-to-binder ratios (A1 = 0.4 and A2 = 0.5) and two binder compositions: BG25 (75% bottom ash and 25% GGBS) and BG50 (50% bottom ash and 50% GGBS). Sodium hydroxide (NaOH) was used at three molarities—4 M, 6 M, and 8 M. Effluent was used to replace Na_2SiO_3 in five proportions: 0%, 25%, 50%, 75%, and 100%. This resulted in a total of 60 distinct mix combinations, labeled from 4A1BG25E0 to 8A2BG50E100. All specimens were cast and ambient-cured. Each mix was used to prepare test specimens for compressive strength (100 × 100 × 100 mm cubes), split tensile strength (100 × 200 mm cylinders), and flexural strength (100 × 100 × 500 mm prisms). Three cube specimens were tested at 7, 14, and 28 days for compressive strength, while two specimens each were tested at 28 days for tensile and flexural properties. Material quantities were computed for each batch based on the binder and alkaline liquid proportions, ensuring uniformity across the testing matrix. Table 1 shows that the textile effluents have varied pH levels, consistent specific gravity, and differing concentrations of key oxides like SiO_2, Na_2O, and MgO, indicating their potential as sodium silicate substitutes in geopolymer production.

Table 1. Chemical properties of textile effluent.

s.no	Parameters	Mercerizing- 1 process	Mercerizing- 2 process	Washing process	Wetting process	Bleaching process
1	pH	7.91	12.70	7.07	6.63	8.10
2	Colour	Yellowish	Yellowish	Yellowish	Yellowish	White
3	Specific gravity	1.53g/cm^3	1.53g/cm^3	1.52g/cm^3	1.52g/cm^3	1.52g/cm^3
4	SiO_2	95.00mg/l	28.73mg/l	38.38mg/l	73.86mg/l	137.80mg/l
5	Na_2O	177.93mg/l	1887.15mg/l	103.79mg/l	98.40mg/l	266.90mg/l
6	Fe_2O_3	1.92mg/l	1.11mg/l	1.02mg/l	2.24mg/l	0.33 mg/l
7	Al_2O_3	**BDL [D.L:0.01]**	**BDL [D.L:0.01]**	**BDL [D.L:0.01]**	**BDL [D.L:0.01]**	**BDL [D.L:0.01]**
8	K_2O	2.01mg/l	4.46mg/l	3.25mg/l	10.09mg/l	1.04mg/l
9	P_2O	36.00mg/l	24.54mg/l	45.83mg/l	249.85mg/l	2.82mg/l
10	MgO	88.04mg/l	16.77mg/l	117.36mg/l	184.47mg/l	238.96mg/l

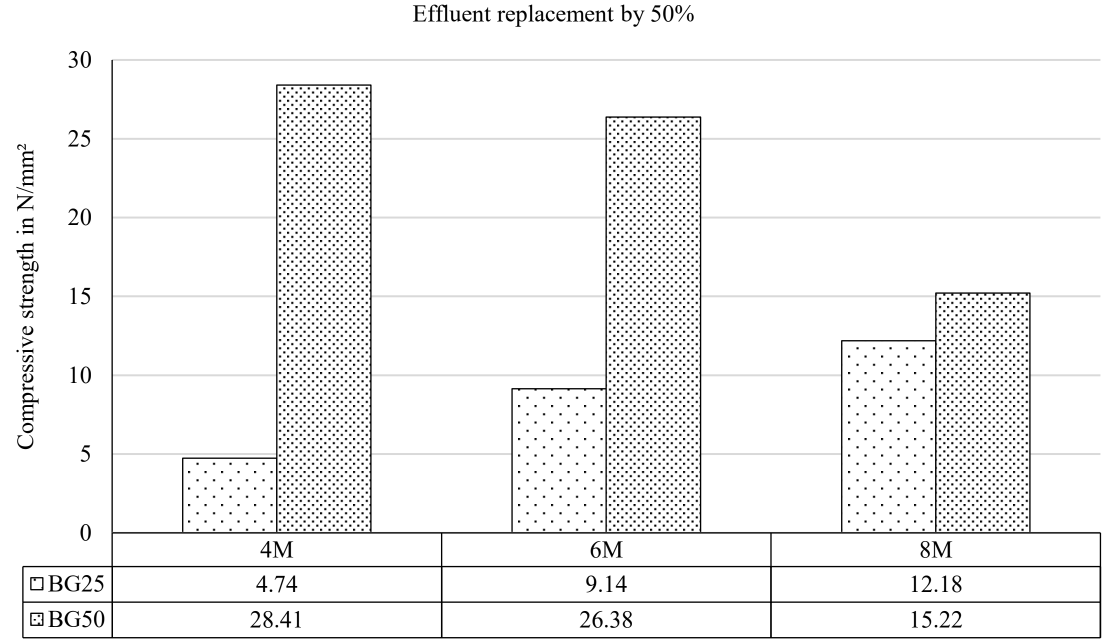
RESULT AND DISCUSSION

This study prepared two initial geopolymer mixes, A1 and A2, with alkaline-to-binder ratios of 0.4 and 0.5, respectively. Each mix incorporated three different sodium hydroxide molarities (4M, 6M, and 8M) and two binder combinations: 75% bottom ash with 25% GGBS (BG25) and 50% bottom ash with 50% GGBS (BG50). Sodium silicate (Na_2SiO_3) was progressively replaced with textile effluent at substitution levels of 0%, 25%, 50%, 75%, and 100%. This resulted in 60 unique mix formulations labeled accordingly—for example, 4A1BG25E0 to 8A2BG50E100. Mortar cubes were cast for all 60 mixes and cured under ambient conditions. Compressive strength tests were conducted, and the two best-performing mixes—one from A1 and one from A2—were identified. These optimal mixes were then used to cast concrete cubes, cylinders, and prisms to evaluate their mechanical properties, including compressive strength, split tensile strength, and flexural strength. Based on these results, the best-performing mix was selected for use in casting one-way slab panels. Finally, the structural performance and fire endurance of the geopolymer concrete (GPC) panels were assessed to validate their suitability for structural applications.

Geopolymer Mortars

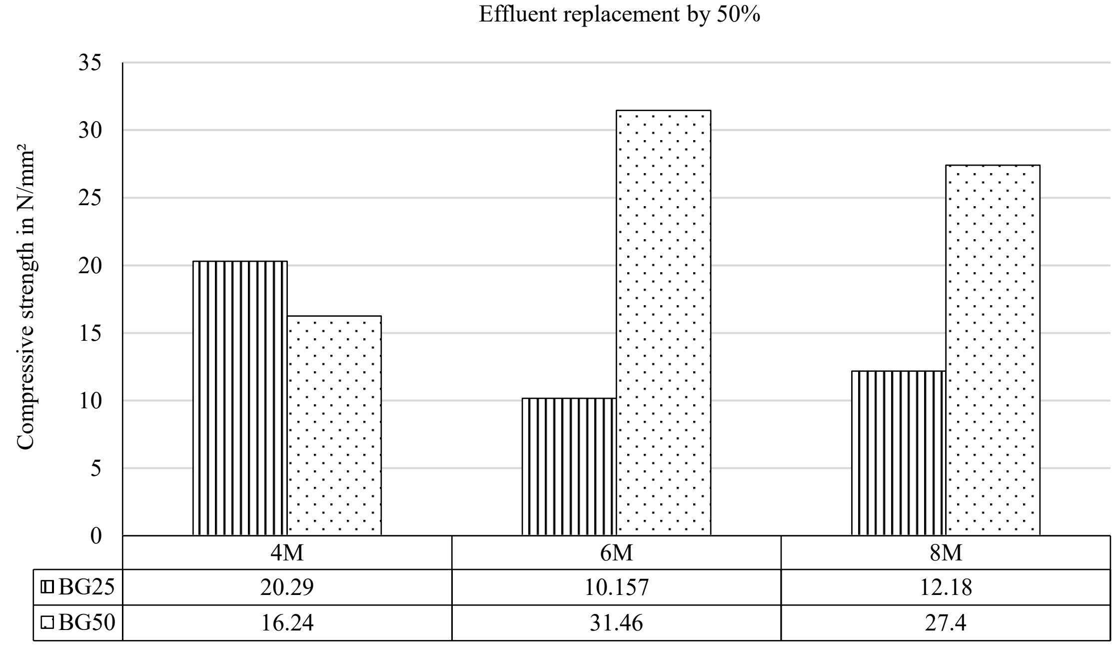
To identify the optimal geopolymer mortar compositions from Mix A1 and Mix A2, compressive strength tests were conducted on 60 mortar cube samples. These mixes were formulated using alkaline-to-binder ratios of 0.4 (A1) and 0.5 (A2), with sodium hydroxide at molarities of 4M, 6M, and 8M, and sodium silicate partially replaced by textile effluent derived from the mercerizing process-1. Effluent substitution was performed at 0%, 25%, 50%, 75%, and 100%. The binder phase consisted of finely ground bottom ash and GGBS in two proportions: 75% bottom ash with 25% GGBS (BG25) and 50% bottom ash with 50% GGBS (BG50).

All mortar specimens were cast and cured under ambient room temperature conditions. Compressive strength results of all 60 mixes were graphically analyzed to understand the effects of molarity, effluent replacement, and binder composition. It was observed that strength increased with effluent substitution up to 50%, with the highest strength recorded at this level for both A1 and A2 mixes. This improvement is attributed to a favorable increase in the molar ratio, from 1.0 to approximately 1.54, when sodium silicate was replaced by 50% textile effluent. Beyond this substitution level, a decline in the molar ratio and corresponding compressive strength was noted. Mixes A1 and A2, incorporating 6M NaOH and 50% effluent replacement, yielded superior compressive strength, establishing them as optimal formulations for further structural and durability evaluation. Figure 1 shows that 50% effluent replacement significantly improves the compressive strength in BG50 mixes, with the highest value of 28.41 N/mm^2 at 4M NaOH, demonstrating an effective synergy between effluent and GGBS.



	4M	6M	8M
□ BG25	4.74	9.14	12.18
⊡ BG50	28.41	26.38	15.22

Figure 1. Compressive strength for A1 effluent replacement by 50%.



	4M	6M	8M
▥ BG25	20.29	10.157	12.18
□ BG50	16.24	31.46	27.4

Figure 2. Compressive strength for A2 effluent replacement by 50%.

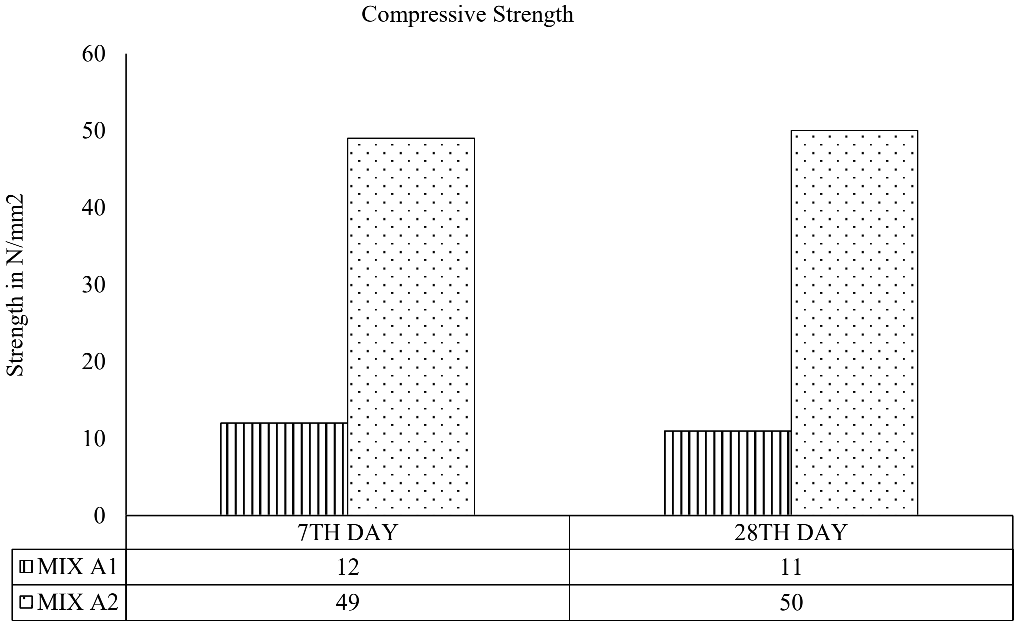
Figure 2 reveals that for A2 mixes with 50% effluent replacement, the BG50-6M combination yields the highest compressive strength of 31.46 N/mm², highlighting the optimal interaction between higher GGBS content and moderate alkalinity.

Geopolymer Concrete Specimens

Two optimized geopolymer concrete mixes, A1 and A2, were developed, cast, and cured at room temperature to evaluate their mechanical properties—specifically compressive, split tensile, and flexural strengths. The optimal mixture, 6A2BG50E50, was tested at 7 and 28 days using standard cube, prism, and cylinder specimens. Mix A2, with a binder-to-alkaline liquid ratio of 0.5, demonstrated significantly superior performance across all mechanical tests. It achieved compressive strengths of 49 N/mm² and 50 N/mm² at 7 and 28 days, respectively, compared to just 12 N/mm² and 11 N/mm² for mix A1, which had an alkaline-to-binder ratio of 0.4. Similarly, in the split tensile test, mix A2 recorded strengths of 2.548 N/mm² and 2.708 N/mm² at 7 and 28 days, respectively, substantially outperforming mix A1, which registered 1.5 N/mm² and 1.35 N/mm². Flexural strength results also confirmed the superior performance of mix A2, with values of 4.35 N/mm² on day 7 and 4.80 N/mm² on day 28. In contrast, mix A1 yielded 4.35 N/mm² and 4.05 N/mm² at the same time intervals. The enhanced performance of mix A2 is attributed to its balanced binder-to-alkaline ratio and the optimized molar ratio of the activating solution, which promotes better polymerization and denser microstructure.

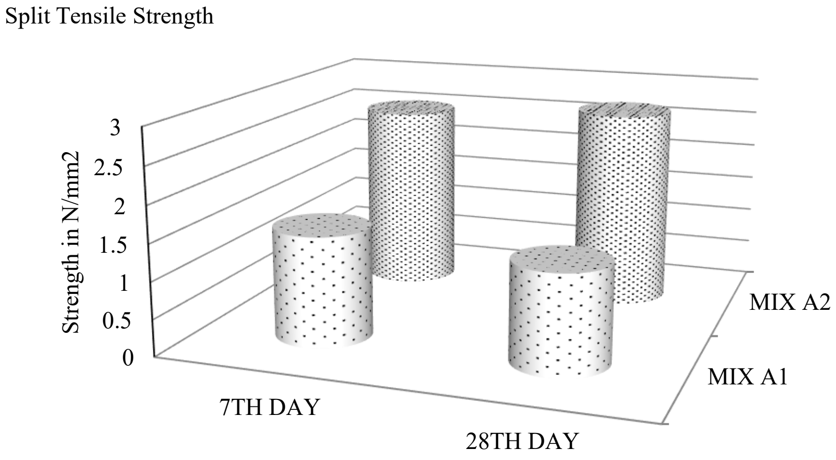
Figure 3 demonstrates a remarkable disparity in compressive strength between Mix A1 and Mix A2, with Mix A2 attaining 49 N/mm² on day 7 and 50 N/mm² on day 28, while Mix A1 shows significantly lower strengths of 12 N/mm² and 11 N/mm², respectively. This pronounced improvement in Mix A2 is primarily attributed to its optimized alkalinity-to-binder ratio of 0.5, which enhances the dissolution of aluminosilicate precursors and promotes the formation of a denser and more cohesive geopolymeric gel network. In contrast, Mix A1, with a lower ratio of 0.4, appears to have an insufficient alkaline activator, resulting in incomplete polymerization and poor matrix integrity. The sustained strength gain in A2 further indicates a stable polymeric structure with improved long-term bonding and minimal microstructural defects, validating the critical role of alkaline solution concentration in tailoring the performance of geopolymer concrete systems.

Figure 4 reveals that Mix A2 significantly outperforms Mix A1 in split tensile strength, recording values of 2.548 N/mm² and 2.708 N/mm² at 7 and 28 days, respectively, in contrast to Mix A1, which shows a declining trend from 1.5 N/mm² to 1.35 N/mm². This marked improvement in Mix A2 is attributed to the balanced binder-to-alkaline liquid ratio of 0.5, which facilitates enhanced geopolymerization and better microstructural integrity. The consistent tensile strength in Mix A2 implies the development of a stronger interfacial transition zone (ITZ) and improved fiber-matrix bonding, critical for resisting tensile stresses. Conversely, the suboptimal performance of Mix A1 suggests inadequate polymer chain development and weaker matrix cohesion due to an insufficient alkaline activator, resulting in poor tensile stress distribution and increased brittleness over time.



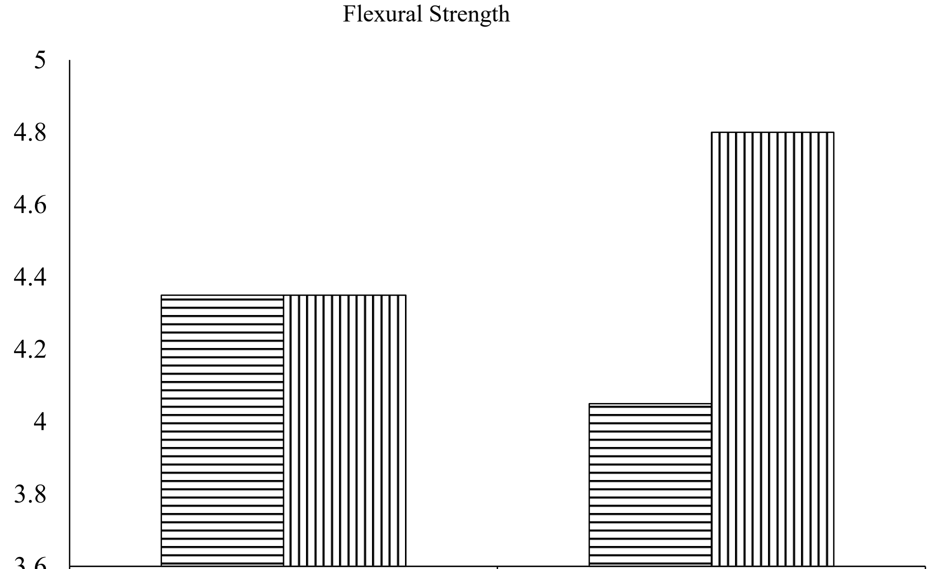
	7TH DAY	28TH DAY
▥ MIX A1	12	11
░ MIX A2	49	50

Figure 3. Compressive strength comparison for mixes A1 & A2 – Cubes.



	7TH DAY	28TH DAY
· MIX A1	1.5	1.35
⁘ MIX A2	2.548	2.708

Figure 4. Tensile strength comparison for mixes A1 and A2 – Cylinders.



	7TH DAY	28TH DAY
⊟ MIX A1	4.35	4.05
◫ MIX A2	4.35	4.8

Figure 5. Flexural strength Comparison of mixes A1 and A2 – Prisms.

Figure 5 illustrates that mixes A1 and A2 exhibit identical flexural strength (4.35 N/mm²) on the 7th day. However, by the 28th day, Mix A2 demonstrates a noticeable enhancement to 4.8 N/mm², surpassing Mix A1's marginal decline to 4.05 N/mm². This progression indicates that Mix A2 benefits from a prolonged geopolymeric reaction and structural densification due to its optimized binder-to-alkaline ratio of 0.5, which sustains polymer gel development and micro-crack resistance over time. In contrast, the declining trend in Mix A1 suggests inadequate gel continuity and poor long-term bond development, highlighting the significance of alkali content in improving flexural performance and post-curing strength retention in geopolymer matrices.

Geopolymer Concrete Panels

Building upon the superior mechanical performance of the A2 mix, this composition was selected for panel fabrication. The optimal formulation incorporated a SiO_2/Na_2O molar ratio of 1.54, 50% replacement of sodium silicate with industrial effluent, a binder-to-alkaline ratio of 0.5, and sodium hydroxide at a 6M concentration. The resultant geopolymer mix, denoted as A2BG50E50, satisfied the mechanical benchmarks for M40-grade concrete, making it suitable for structural applications. To evaluate their fire resistance, one-way slab panels were designed, cast, and reinforced with steel. After 28 days of ambient curing, the panels were subjected to elevated temperature exposure in a muffle furnace for 2, 4, and 8 hours. Post-heating, the specimens were cooled to room temperature under controlled conditions to mimic realistic thermal cycling. A comprehensive inspection revealed the extent of thermal cracking and spalling. Furthermore, residual compressive strength tests assessed structural degradation under thermal stress. Notably, the panels exhibited remarkable thermal resilience, attributed to the geopolymeric gel's inherent fire-retardant properties and the synergistic effect of effluent-based silicate bonding. This investigation emphasizes the potential of eco-engineered geopolymer systems in fire-resistant structural components, offering a sustainable alternative to conventional concrete.

Ultrasonic Pulse Velocity (UPV) Evaluation of Fire-Exposed Panels

Ultrasonic Pulse Velocity (UPV) testing was performed on geopolymer concrete (GPC) panels incorporating bottom ash and GGBS to assess internal integrity and quality degradation due to thermal exposure. Initial UPV measurements were taken on the 28th day of curing—before fire exposure—to establish baseline concrete quality. Subsequently, the panels were subjected to elevated temperatures in a muffle furnace for 2, 4, and 8 hours, followed by a 24-hour natural cooling period. Post-exposure UPV testing revealed that the GPC panels maintained good integrity and pulse velocity after two hours of thermal exposure, indicating the binder system's ability to resist early-stage thermal degradation. However, significant UPV values and concrete quality reductions were observed after 4 and 8 hours of heat exposure. This decline is attributed to the breakdown of polymeric bonds and microstructural deterioration due to the progressive volatilization of bound water and alteration of alkali-activated reaction products under prolonged heat. Despite these changes, the observed reduction in compressive strength remained within acceptable limits, highlighting the residual load-bearing capacity and thermal resilience of the optimized GPC system. These findings underscore the potential of bottom ash–GGBS-based geopolymer concrete as a fire-resistant construction material, particularly in applications where fire endurance of up to 2 hours is critical.

Compressive Strength Test

The compressive strength of geopolymer concrete panels (P1, P2, and P3) was evaluated after 28 days of ambient curing and subsequent exposure to fire for durations of 2, 4, and 8 hours, respectively. The compressive strength was estimated using a rebound hammer, and the panels measuring 500 × 200 × 62.5 mm were examined for mechanical and physical degradation. Results indicate that panel P1 (2-hour exposure) retained a substantial proportion of its original compressive strength, demonstrating that the bottom ash and GGBS-based geopolymer matrix maintains structural integrity under moderate thermal stress. However, panels P2 (4-hour exposure) and P3 (8-hour exposure) exhibited a pronounced decline in compressive strength. This degradation is primarily attributed to thermal-induced chemical changes in the geopolymer gel, particularly the breakdown of Si–O–Al linkages and the weakening of alkali-activated binding phases. In addition to strength loss, physical changes such as cracking, spalling, discoloration, and dimensional distortions were observed. P1 exhibited minor surface cracking on the top and bottom faces but no major structural damage. Panel P2 showed progressive deterioration, including edge cracks, corner breakage, and localized spalling. After 8 hours of fire exposure, panel P3 underwent severe degradation characterized by swelling, fragmentation at multiple corners, and extensive edge damage, indicating that the threshold of thermal endurance had been surpassed. These findings confirm that GPC panels incorporating bottom ash and GGBS can effectively resist fire-induced mechanical and physical degradation for up to two hours, making them suitable for structural applications requiring moderate fire resistance.

Table 2 presents the original and post-fire compressive strengths of GPC panels after furnace exposure for varying durations. Panel P1 retained approximately 70% of its original strength after 2 hours of fire exposure, indicating good thermal stability. However, a significant strength reduction was observed in P2 and P3 after 4 and 8 hours, respectively, with P3 retaining only about 31% of its original strength. This trend confirms that prolonged thermal exposure substantially degrades the mechanical integrity of geopolymer concrete, with a critical endurance limit of around 2 hours.

Table 2. Original and post-compressive strengths for panels.

Panels ID	Time in the furnace	Original compressive strength	Post-fire panel compressive strength
P1	2 hours	36	25
P2	4 hours	39	15
P3	8 hours	33	10.33

Figure 6. GPC slab P1 – Muffle furnace after 2 hours

Figure 7. GPC slab P2 – Muffle furnace after 4 hours.

Figure 8. GPC slab P3 – Muffle furnace after 8 hours.

Figures 6 to 8 illustrate the fire resistance performance of geopolymer concrete (GPC) slabs (P1, P2, and P3) subjected to elevated temperatures in a muffle furnace for 2, 4, and 8 hours, respectively. After 2 hours (Figure 6), minor surface cracking was observed, attributed to the material's inherent thermal stability and the strong aluminosilicate bonding formed by bottom ash and GGBS. At 4 hours (Figure 7), moderate cracking and initial spalling emerged due to thermal stress accumulation and moisture expansion within the matrix, initiating structural weakening. By 8 hours (Figure 8), severe spalling, edge fragmentation, and dimensional changes occurred, primarily due to prolonged exposure, causing extensive microstructural degradation, dehydration of reaction products, and breakdown of the polymeric gel. These findings indicate that while GPC maintains integrity under moderate heat, prolonged exposure compromises mechanical performance due to thermally induced material instability.

CONCLUSIONS

This study successfully demonstrates the feasibility of producing high-performance geopolymer concrete (GPC) by integrating industrial solid and liquid wastes. By utilizing 50% ground bottom ash (BA) and 50% ground granulated blast furnace slag (GGBS) as binder materials and replacing 50% of sodium silicate with treated cotton textile effluent, an optimized mix (6A2BG50E50) was developed. This mixture achieved compressive strengths of 49 N/mm² and 50 N/mm² at 7 and 28 days, respectively, along with significant improvements in split tensile and flexural strengths. Notably, this GPC mix sustained fire exposure for up to two hours with only minor surface damage, confirming its superior fire resistance. The incorporation of treated textile effluent not only reduces reliance on costly conventional activators but also offers a sustainable approach for managing industrial effluents, contributing to circular economy practices. The use of ambient curing further enhances the energy efficiency of the process, making it viable for practical, large-scale construction. This research provides a novel pathway for producing cost-effective, environmentally friendly, and structurally reliable GPC, demonstrating its potential to replace conventional Portland cement concrete in various structural applications while addressing both solid and liquid industrial waste challenges.

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