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Research Article

An Experimental Study on the Thermal Behavior and Mechanical Properties of Fiber-Reinforced Geopolymer Composites Based on Fly Ash and Blast Furnace Slag

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Keywords

Geopolymer concrete,
Blast furnace slag,
Fly ash,
Waste marble dust,
Glass fiber,
Compressive strength,
High temperature.

Abstract

This study aims to develop environmentally friendly and sustainable geopolymer concrete (GBS) using industrial waste, and to investigate its physical, mechanical, and high-temperature performance. In the study, ground blast furnace slag (GBS) was used as the primary binder, and fly ash (FA) was substituted for the binder at varying rates (0%, 10%, 25%, 50%, and 75%). Additionally, waste marble dust was used as an aggregate, and glass fiber was used as a reinforcing element. To improve the workability of the prepared mixtures, a superplasticizer was used at a rate of 5%, and the water-to-binder ratio was maintained at 0.19 for all samples. The prepared geopolymer concrete samples were subjected to thermal curing at 70 °C for 24 hours. As a result of the experiments conducted, it was determined that as the fly ash content increased, the flow diameters of the concrete decreased and the dry density values dropped from 2136 kg/m³ (GBS 100%) to 1972 kg/m³ (FA 75%). In terms of mechanical properties, the 28-day compressive strength was measured at 50.4 MPa in samples containing 0% fly ash. In comparison, the samples containing 75% fly ash yielded a strength of 30.7 MPa, indicating that strength decreases as the fly ash content increases. In high-temperature tests, it was found that as the fly ash content increased, the loss of compressive strength decreased in samples exposed to 250, 500, and 750 °C. The compressive strength lost is 13.48% for 250 °C, 17.54% for 500 °C and 75.88% for 750 °C. At 250 and 500 °C, the compressive strength loss rate was relatively low, whereas it was significantly higher at 750 °C. The primary reason for this is the low calcium content of fly ash and the high thermal stability of amorphous aluminosilicate phases. Additionally, according to the results of the cost analysis, increasing the amount of fly ash reduces the production costs of geopolymer concrete. Although the materials used in geopolymer concrete are industrial by-products, the procurement costs of these materials are influenced by several factors, including geographical region, supply chain, usage quantity, and local industrial activities. In conclusion, it has been demonstrated that geopolymer concrete produced from industrial waste reduces environmental impacts and provides significant advantages in terms of sustainability.

1. Introduction

Concrete is a composite building material consisting of aggregate (sand, gravel, crushed stone, etc.), water, binding agent (cement), chemical admixture and mineral additives. Concrete is widely used in today's growing and developing construction sector. In terms of construction materials, concrete is the most commonly used choice worldwide. The widespread use of concrete has had a profound impact on the environment, both today and in the future. During the production of cement, carbon dioxide (CO_2) emissions are released. Approximately one ton of carbon dioxide (CO_2) is released into the atmosphere for every ton of Portland cement produced [1]. Nowadays, the population is increasing daily, and as a result, the need for concrete is also growing, leading to the release of more carbon dioxide (CO_2) into the atmosphere. Today's technologies are being developed to cause less damage to the environment and reduce current energy consumption in the cement production process. Additionally, a substantial amount of water is used in the production of concrete, resulting in a negative environmental impact. This creates problems in residential areas that lack sufficient water resources [2].

Environmentally friendly concrete production needs to be developed and increased. For this purpose, the materials used in concrete production must be sourced from recyclable resources rather than natural resources. Therefore, substitutes for Portland cement are essential [3]. For the disposal of materials that occur as industrial waste, they can be used as substitutes for cement. For example, there are many industrial wastes such as blast furnace slag (BFS) as iron industry waste, fly ash (FA) as thermal power plant waste, marble dust as marble production waste, silica fume (SF) as industrial waste, and red mud as aluminum production waste that can be an alternative in concrete production. Substituting such wastes for cement to act as binders in concrete is an effective way to utilize industrial wastes and mitigate global warming. These industrial wastes, used in cement production, are also employed in the production of geopolymer concrete by replacing Portland cement. The mechanical properties of geopolymer concretes produced with these materials were found to be good [4].

To better address this critical issue, the development of geopolymer concrete is examined. Geopolymers have been researched since they were discovered and described by French scientist Professor Joseph Davidovits in 1978 [5]. Geopolymer concrete is a type of concrete formed by the reaction of three-dimensional amorphous aluminosilicate source materials with various activators. The development of geopolymer concrete has been environmentally beneficial. Geopolymers have many advantages. For example, it emits less to the atmosphere, has high resistance to high temperatures, exhibits good thermal insulation properties, provides a usage area for waste materials, achieves sufficient strength in a short curing time, and is environmentally friendly [6].

Geopolymer concrete exhibits superior properties in various aspects compared to conventional concrete. Compared to regular concrete, geopolymer concrete requires less energy in production and releases approximately 6 times less carbon dioxide (CO_2). Therefore, geopolymer

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concrete shows positive behavior in terms of environmental friendliness, sustainability and renewability. Geopolymer concrete exhibits superior fire resistance and acid resistance compared to OPC concrete]. Geopolymer concrete is a type of concrete that can be used instead of regular Portland cement and emits the least carbon dioxide. Geopolymers do not release carbon dioxide (CO_2) during chemical reactions and emit less carbon dioxide (CO_2) than regular Portland cement due to the techniques used in their production [8].

The properties of the materials that enable the formation of these positive properties of geopolymer concrete have been examined. Blast furnace slag (BFS) is a waste material generated as a byproduct of various metal industries. Not all blast furnace slags exhibit the same chemical properties, due to differences in the primary product type and production methods. For example, blast furnace slag, a byproduct of iron and steel production, exhibits only binding properties, whereas slag produced from copper metal has only pozzolanic properties [9]. Using blast furnace slag instead of regular Portland cement in concrete production offers several benefits, including good workability and improved performance against physical and chemical influences. It also helps exhibit improved mechanical properties, reduced carbon dioxide (CO2) emissions into the atmosphere, enhanced compressive strength, and sustainability and environmental friendliness. Blast furnace slag is utilized in a variety of applications [10]. Direct uses of slag include concrete aggregate, lightweight filling material, insulation material and lightweight concrete production. The ground form of blast furnace slag is used in the glass industry, for soil stabilization, as a concrete aggregate, and in the production of cement. The hydration of Portland cement with water develops faster than the hydration of granulated blast furnace slag with water. Blast furnace slag is easier to store than regular Portland cement because it does not undergo a pre-hydration reaction when exposed to a humid environment [11].

The structure of ground granulated blast furnace slag (GGBFS) is an amorphous glass polymer. It is also a hydraulic cement material, and its chemical constituents are similar to those of concrete. Kuo et al. used ground granulated blast furnace slag to produce cementless concrete and found that two criteria primarily contributed to its early strength. These criteria include the main hydration products (i.e., ettringite, calcium hydroxide, and tobermorite gel) and the unhydrated clinker minerals [12].

Fly ash (FA) is a waste material generated as an industrial byproduct of the combustion of coal for power generation [13]. Fly ash is generally gray in color, abrasive, and mostly alkaline in nature. Since large-scale coal combustion for electricity generation began in the 1920s, millions of tons of ash have been produced. Fly ash can be considered the world's fifth-largest source of raw materials. Annual worldwide coal ash production is estimated at approximately 600 million tons, with fly ash accounting for around 500 million tons of the total ash produced. For this reason, the amount of fly ash produced by factories and thermal power plants is constantly increasing worldwide, and this fly ash is a major environmental problem. The storage of wet fly ash in ponds could lead to severe ecological degradation of valuable agricultural land within a short period (14 days). Today, the worldwide use of fly ash varies widely, ranging from 3% to 57%. Coal is an essential commercial fuel in India. India is the sixth-largest producer and consumer of electricity worldwide. An estimated 25% of the fly ash produced in India is used for cement production, brick manufacturing and road construction. Fly ash has been identified as a promising sorbent for removing various pollutants. Fly ash has also been found to have good properties for use in the construction industry. Research has also shown that the unburned carbon component in fly ash plays a crucial role in its adsorption capacity. The geotechnical properties of fly ash (e.g., specific gravity, permeability, internal angular friction) make it suitable for use in the construction of roads and structural embankments [15]. The pozzolanic properties of ash, including its lime-binding capacity, make it a valuable material in the production of cement, building materials, concrete, and concrete admixtures. Although fly ash offers significant environmental and economic advantages in the production of geopolymer concrete, its use in high proportions presents certain performance limitations. Primarily, increasing the fly ash content tends to reduce the workability of the mixture, leading to challenges in casting and compaction due to decreased flowability. Consequently, the reduced compactness and weaker binder formation can cause substantial reductions in early-age compressive strength, which may be critical for structural applications. While fly ash enhances thermal resistance at elevated temperatures, its excessive use may result in mechanical performance falling below the required standards under normal service conditions. Therefore, an optimal balance must be achieved when determining fly ash content, considering both mechanical and thermal performance requirements. Additionally, the chemical composition, reactivity, and particle size distribution of fly ash can vary significantly depending on its source, introducing uncertainty in mix design and performance prediction. In this context, quality control and mix optimization become particularly important when utilizing high fly ash content in geopolymer concrete [16].

2. Materials and methods

2.1. Materials

For this study, geopolymer concrete samples were produced using blast furnace slag, fly ash, waste marble powder, glass fiber, water, sodium hydroxide ($NaOH$), sodium silicate (Na_2SiO_3), and superplasticizer. Industrial waste materials were selected for the production of geopolymer concretes to reduce carbon dioxide (CO_2) emissions. Ground blast furnace slag was used as the primary binder in the production of geopolymer mortar. Fly ash was used as a substitute for blast furnace slag as the main binder in geopolymer concretes. The aim was to investigate the effect of materials on the strength of concrete in mortars prepared at different ratios. In terms of utilizing waste materials, waste marble dust was used as an alternative to aggregate in the production of geopolymer. Additionally, the water used for preparing the mixtures was potable municipal water. The physical and chemical properties of the materials are presented in Table 1. Also, KK* in the table gives the loss on ignition value. Figure 1 shows the visual appearance of the materials used in the mixtures.

Table 1. Physical and Chemical Properties of Materials

Chemical Properties			
	Blast Furnace Slag	Fly Ash	Waste Marble Powder
SiO_2	38,91	58,75	0,4
MgO	7,82	2,22	0,4
Al_2O_3	10,13	25,24	0,1
CaO	35,92	1,46	53,2
Fe_2O_3	3,11	5,76	0,1
K_2O	0,61	4,05	0,1
SO_3	2,32	0,08	0,1
Na_2O	0,49	0,60	0,2
KK*	0,42	-	45,1
Physical Properties			

Specific Gravity (g/cm^3)	2,91	2,23	2,65
Specific Surface (cm^2/g)	5462	2900	-

Figure 1. Materials used in the preparation of mixtures

2.2. Experimental Methods

When producing one-component geopolymer composites, ground blast-furnace slag was used as the primary binder. Different proportions of fly ash were used to replace the ground blast furnace slag in different mixtures prepared. With these different ratios, mechanical properties were observed, and the aim was to produce environmentally friendly, sustainable, and renewable concrete. In addition, waste marble dust, an industrial byproduct, was used as aggregate in the geopolymer concretes produced. Glass fiber was incorporated into the mixtures to enhance the strength and flexural values of the geopolymer concrete. The proportions of fly ash substituted for blast furnace slag were 0%, 10%, 25%, 50% and 75%. The water/binder ratio was determined to be 0.19 in all mixtures, and a superplasticizer was used at a rate of 5% of the binder amount to increase the workability of the mixtures. The prepared geopolymer concrete specimens were heat-cured in a 70 °C oven for 24 hours. The proportions and amounts of the materials used in this study are given in Table 2.

Table 2. Quantities of Materials Used in the Mixture (kg/m^3)

FA Rate (%)	BFA	FA	NaOH	Na_2SiO_3	Water	Superplasticizer	Marble Powder	Glass Fiber
0	750,0	0,0	85,8	214,2	145,0	37,5	853,2	26,0
10	675,0	75,0	85,8	214,2	145,0	37,5	835,8	26,0
25	562,5	187,5	85,8	214,2	145,0	37,5	809,8	26,0
50	375,0	375,0	85,8	214,2	145,0	37,5	766,4	26,0
75	187,5	562,5	85,8	214,2	145,0	37,5	723,0	26,0

The mixtures in Table 2 were prepared with a mixer. Flow diameters were first determined for the mixtures using ASTM C1437]. The prepared fresh geopolymer mixtures were placed in steel molds that had been previously lubricated with grease in three stages. In the first stage, part of the molds were filled and compacted for 30 seconds using a shaking table. In the second stage, the remaining molds were filled and compacted using the same method. In the third stage, the surface was smoothed, and final compaction was performed. To prevent moisture loss, the surfaces of the samples placed in the molds were wrapped with plastic wrap and then kept in a 70 °C oven for 24 hours. Figure 2 shows an overview of the demolded geopolymers. Afterward, they were removed from the molds. The mechanical properties of the specimens were determined by performing flexural (3-point) and compressive strength tests at 7 and 28 days. Flexural strength tests were conducted on 40 × 40 × 160 mm^3-sized specimens by TS EN 12390-5 (2019) [18]. Compressive strength tests were performed on 50 mm × 50 mm × 50 mm cube specimens by the TS EN 12390-3 (2019) standard. In the high-temperature effect experiment, a high-temperature oven capable of reaching temperatures of up to 1000°C and adjustable digitally for the desired time and temperature was used. The samples were heated to 250, 500, and 750 °C at an average heating rate of 7 °C/min and then maintained at the maximum temperature for 2 hours. The samples were left to cool in the oven after the oven was turned off.

Figure 2. General views of geopolymer

3. Results and Discussion

3.1. Fresh State Properties of Geopolymer Concretes

Depending on the change in the fly ash ratio in geopolymer concretes, the flow diameters also change. Figure 3 illustrates the flow diameters of geopolymer concretes for various fly ash percentages. As the fly ash content increases, the flow diameters of geopolymer concretes become smaller. Compared to the FA0 reference mixture for flow diameters, FA10 decreased by 7.76%, FA25 by 11.64%, FA50 by 15.95% and FA75 by 18.97%.

Increasing the fly ash content in geopolymer concrete increases the viscosity of the binder phase in the mixture, restricting the free movement of water and increasing the density of the gel phase formed during the geopolymerization reaction. This increases the consistency of the fresh geopolymer concrete, reducing its workability. The use of sodium hydroxide and sodium silicate solutions, which are more viscous than water, generally makes geopolymer concrete more cohesive and adhesive than conventional concrete. However, the higher slump of geopolymer concrete indicates that the mix has higher workability. This can adversely affect the workability of fresh geopolymer concrete, making it difficult to place the mix in molds and compact it homogeneously. The reduction in spreading diameter can increase the risk of voids and segregation, especially in complex reinforcement arrangements or in elements with narrow cross-sections, as it limits the concrete's ability to yield under its weight. Therefore, additional measures such as more effective compaction methods, mix modification or the use of superplasticizing admixtures may be required in the production and application processes [19].

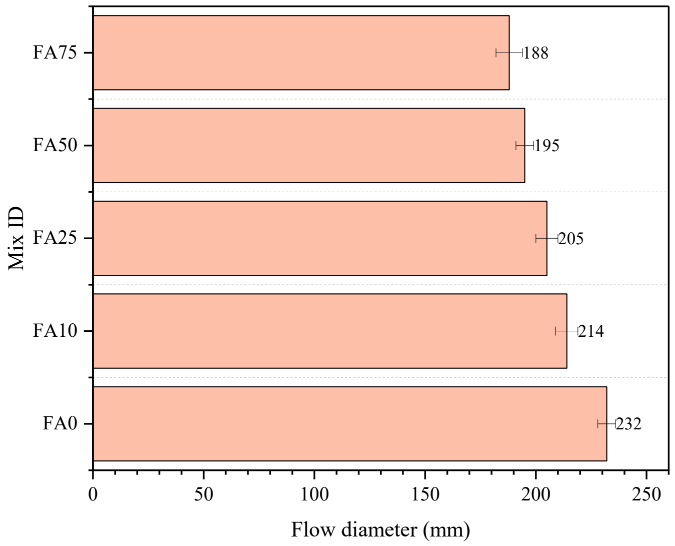

Figure 3. Flow diameter (mm)

3.2. Physical properties of geopolymer concretes

The oven dry density test was applied to evaluate the physical properties of the tested specimens. Figure 4 illustrates the oven-dry densities of geopolymer concretes with varying percentages of fly ash. The average oven-dry density is 2136 kg/m³ at 0%, 2109 kg/m³ at 10%, 2054 kg/m³ at 25%, 2003 kg/m³ at 50%, and 1972 kg/m³ at 75%. As the proportion of fly ash substituted for blast furnace slag in the mixtures increases, the furnace dry density decreases. According to the results, the fly ash ratio plays a vital role in reducing the density of geopolymer concrete in the matrix. Oven dry density depends on the specific gravity and fineness of the materials used. Since blast furnace slag has a higher specific gravity and fineness than fly ash, the furnace dry density increased as the fly ash ratio decreased.

Kaplan et al. (2022) concluded that the hardened unit weight decreased as the curing time and temperature increased. The unit weights decreased as the increase in temperature and heat curing time increased the evaporation of the liquid phase. 80 °C The capillary water absorption value of the cured mixtures generally stabilized after a specific period, and it was observed that capillary water absorption stabilized especially in geopolymer mixtures cured for 10 hours. Curing time and temperature positively affected geopolymerization, thereby reducing carbon dioxide (CO_2) emissions [20].

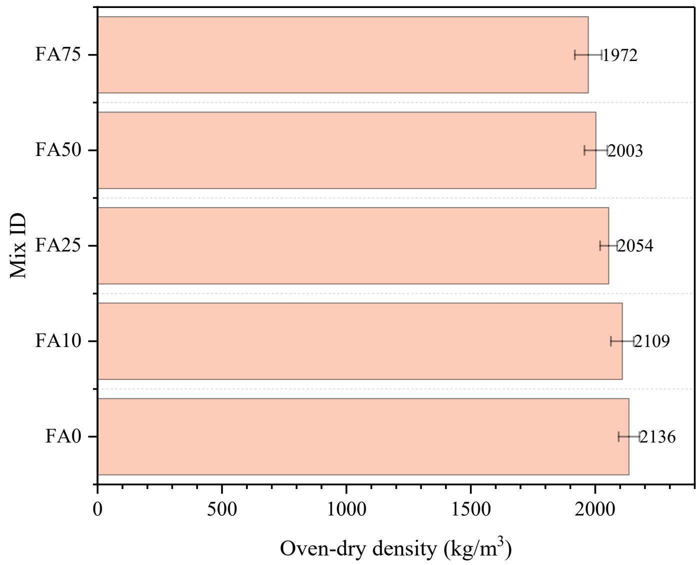

Figure 4. Oven-dry density

3.3. Mechanical properties of geopolymer concretes

The compressive strengths of geopolymer concretes at 7 and 28 days are presented in Figure 5. The compressive strengths of geopolymer concretes at 7 days ranged from 25.7 to 43.4 MPa, and at 28 days, they ranged from 30.7 to 50.4 MPa. The increase in fly ash content in the specimens decreased both the 7-day and 28-day compressive strengths. Geopolymer concretes produced using only ground blast furnace slag as the main binder showed the highest values in 7 and 28-day compressive strengths. Compared to the 7-day compressive strength of the FA0 reference mix, FA10 decreased by 10.60%, FA25 by 18.43%, FA50 by 29.95% and FA75 by 40.78%. Compared to the 28-day compressive strength of FA0 reference mix; FA10 decreased by 5.75%, FA25 by 11.51%, FA50 by 25.40% and FA75 by 39.09%. Glass fiber was used to support the compressive strength of the prepared specimens. Glass fiber was used to improve the less brittle structure, high strength and crack resistance in geopolymer concrete. In addition, according to the data, as the fly ash ratio decreases, the compressive strength increases in parallel with the increase in oven-dry density. Geopolymer concretes can exhibit compressive Strength equivalent to or higher than that of normal Portland cement. Curing conditions and material composition also significantly affect the compressive strength values of the geopolymer samples produced.

Bellum et al. demonstrated that the addition of blast furnace slag to fly ash enables the achievement of higher compressive strength compared to ordinary Portland cement. It was concluded that the combination of fly ash and ground blast furnace slag tends to form a successful, stable geopolymer concrete with high mechanical strength properties [21].

In the study by Zuaiter et al., two types of glass fibers were used alone and in hybrid combinations, with the emphasis that hybrid glass fibers exhibited superior mechanical and durability properties compared to single-type glass fiber blends, even at higher volume ratios [22]. Ganesh and Muthukannan reported a significant increase in the energy absorption capacity of geopolymer concrete, approximately ten times, and a notable reduction in brittleness with the addition of glass fiber [23].

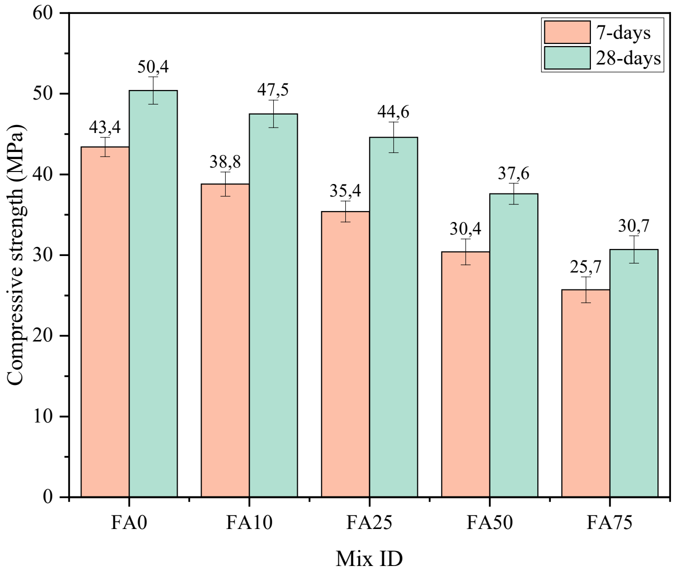

Figure 5. Compressive strength

3.4. High temperature effect on geopolymer concrete

In the high-temperature effect experiment, a high-temperature oven was used, which can reach a temperature of up to 1000°C and is digitally adjustable for the desired time and temperature. The specimens were heated to temperatures of 250, 500, and 750°C at an average heating rate of 7°C/min and then maintained at the maximum temperature for 2 hours. The samples were left to cool in the oven after the oven was turned off. Figure 6 shows the compressive strength results obtained after applying the high-temperature effect to geopolymer concretes. In specimens exposed to temperatures of 250, 500, and 750°C, it was observed that the reduction in compressive strength decreased as the fly ash content increased. This is mainly due to the high thermal stability of the amorphous aluminosilicate phases in the chemical and mineralogical structure of fly ash. The low calcium content of fly ash leads to a reduction in calcium-based compounds undergoing thermal degradation at elevated temperatures, so the microstructure remains more robust. Additionally, increasing the fly ash content makes the concrete's microstructure denser and firmer, thereby reducing the effects of internal pressure and microcracks caused by water evaporation at high temperatures. In the study by Wang et al. (2024), a tight structure and a decrease in pore volume were observed in the microstructure of the geopolymer matrix, as the activator modulus increased with the fly ash content. This finding suggests that fly ash contributes to the densification of the binder phases 24. Similarly, Zhao & Wang (2023) reported that the microstructure of fly ash geopolymers activated with a binary activator system became more compact, and the binder gel gained continuity [25].

On the other hand, blast furnace slag with high calcium content is more prone to thermal degradation and may cause loss of strength at high temperatures. For these reasons, geopolymer concretes with a high fly ash content exhibit superior thermal strength at high temperatures. At 250 and 500 °C, the compressive strength loss rate was relatively low, whereas it was significantly higher at 750 °C. This can be explained by the evaporation of both free and bound water in the concrete at these temperatures, as well as the limited thermal expansion effects. Within this temperature range, the structural integrity between the binder phase and the aggregate is largely preserved, and the microstructure remains largely intact. However, a significant and sudden decrease in compressive strength occurred at temperatures of 750 °C and above. The primary reason for this is that the chemical structure of the geopolymer binder phase begins to deteriorate at high temperatures, and the thermal expansion differences between the aggregates and the binder result in microcracks. These cracks weaken the structural integrity and cause a significant reduction in compressive strength. Additionally, phase changes in minerals and deterioration of binder phases at temperatures above 750 °C are also factors that contribute to the loss of strength. Therefore, when evaluating the high-temperature performance of geopolymer concretes, it is essential to note that the strength is largely maintained up to 500 °C, but it decreases rapidly at temperatures above 750 °C.

When concrete produced with ordinary Portland cement (OPC) is exposed to elevated temperatures, the dihydroxylation of $Ca(OH)_2$ occurs at approximately 400-500 °C. Stress occurs at the interface transition zone of the aggregate. In the cement paste, stress occurs due to the differential expansion and contraction of the two components caused by changes in temperature. As these cracks develop and increase in size, the concrete's strength decreases. The existing cracks in the concrete accelerate the transfer of heat and exacerbate the damage. It has been observed that the loss of strength of concrete at a temperature of 1000 °C can reach up to 95% [26].

Qu et al. investigated the effect of high temperatures on geopolymer mortars with initial damage induced by mechanical load. A geopolymer mortar was prepared using different proportions of fly ash and ground granulated blast-furnace slag. The results showed that the use of ground granulated blast furnace slag in the production of geopolymer concrete improves the compressive strength but increases its susceptibility to preload damage, leading to greater strength loss. In the study, it was observed that the most resistant sample to the high temperature effect was the geopolymer sample produced with a low percentage (less than 20%) of ground granulated blast furnace slag [27].

In the study by Kürklü, geopolymer mortars were made by substituting blast furnace slag mixtures with coarse fly ash at different ratios. The mortar sample with the highest compressive strength was subjected to temperatures of 200, 400, 600, 800, and 1000 °C, and the changes in physical and mechanical properties were analyzed. As a result of the high-temperature tests, 400°C and 600°C were determined to be the critical temperatures for changes in mechanical and physical properties, respectively. However, the geopolymer mortar lost approximately 58% of its Strength at the last temperature, 1000 °C [28].

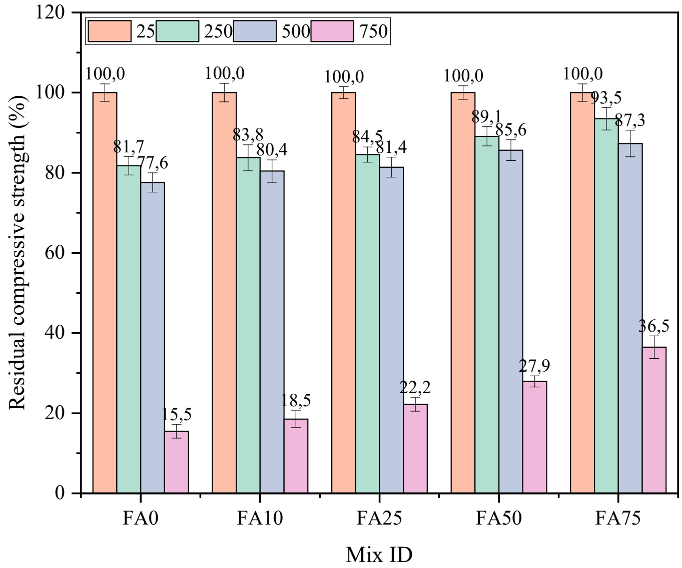

Figure 6. Changes in compressive strength as a result of the high temperature effect

3.5. Cost analysis

The cost of the geopolymer concrete produced may vary according to the material ratios used. Table 3 presents the cost table for the materials used in the experiment. Additionally, Figure 7 illustrates the cost of geopolymer concrete produced at varying ratios. For cost, FA0 was reduced by 2.10%, FA10 by 2.10%, FA25 by 3.76%, FA50 by 8.27% and FA75 by 12.68%. The cost of geopolymer decreased as the ratio of fly ash used increased. Although the materials used in geopolymer concrete are industrial byproducts, the procurement costs of these materials vary depending on the geographical region, supply chain, amount of use and local industrial activities. For example, in areas where industrial byproducts such as fly ash or blast furnace slag are available from local industrial organizations, the costs of these raw materials can be pretty low. However, in regions where such wastes are not available, transportation and procurement costs increase significantly. The cost of alkali activators is generally higher than that of other materials and constitutes a significant portion of the total cost of geopolymer concrete. In particular, the prices of chemicals such as sodium silicate and sodium hydroxide can vary depending on both the chemical purity and the quantity of the product. In this context, the economic viability of geopolymer concrete depends on the type of material used, the means of procurement, the availability of local resources and the scale of production. Therefore, when conducting an economic analysis, not only the unit price, but also factors such as logistics, sustainability, and the use of local resources should be considered.

Table 3. Unit prices ($ /kg) of materials used in the geopolymer mixture

GBFS	FA	NaOH	Na_2SiO_3	Water	SP	WMP	Glass fiber
0.10	0.075	1.00	0.55	0.0015	3.25	0.045	2.75

The main components of geopolymer concrete, such as fly ash and ground granulated blast-furnace slag, these materials are industrial by-products that already exist as waste products. Their utilization helps reduce waste management issues and decreases the consumption of natural resources. This leads to a reduction in the use of virgin raw materials, thereby lowering the environmental footprint [29]. However, the alkali activators used in geopolymer concrete production—particularly sodium silicate and sodium hydroxide—require high energy for their manufacture, resulting in environmental costs during this process. The ecological impact of these chemicals constitutes a significant portion of the total carbon footprint of geopolymer concrete [30].

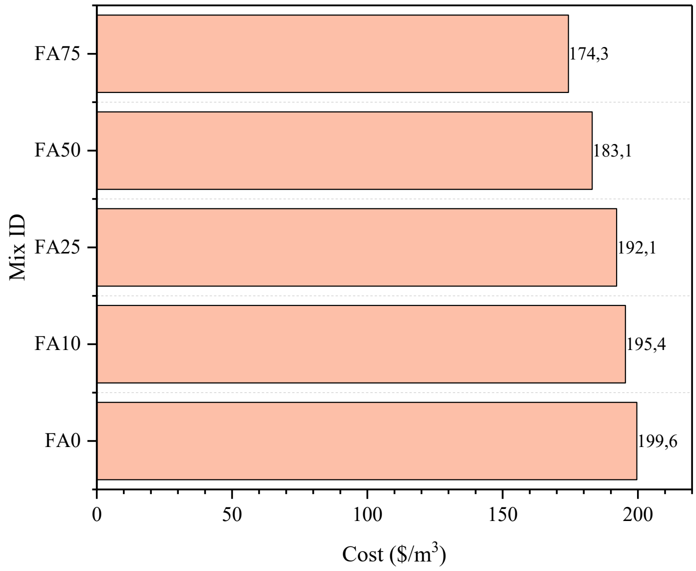

Figure 7. Cost analysis

Indeed, some studies have reported that logistics costs in such cases can exceed 50% of the total material cost [31]. In this context, the prices of fly ash and slag are considered low to medium if local suppliers are available and high if the supply is from distant sources. Alkali activators stand out as one of the most expensive components of geopolymer concrete. Commercial sodium silicate prices generally range between USD 250 and USD 400 per ton, and sodium hydroxide (approximately 98% purity) between USD 500 and USD 800 per ton. These prices can increase depending on the purity of the product, the volume of supply and market availability (Davidovits, 2008; [Mehta & Monteiro, 2014]). Therefore, the analysis assumes that activators account for approximately 40% to 60% of the total binder cost. Furthermore, since the production of these chemicals requires high energy, their environmental impact should also be considered in the economic analysis [32].

4. Conclusions

Flow diameters decrease as the fly ash content increases in the production of geopolymer concrete.

The oven-dry density values of geopolymer concretes range from 1972 to 2136 kg/m³. As the fly ash ratio increases, the oven-dry density value decreases. Oven dry density varies depending on the specific gravity and fineness of the materials used. Since blast furnace slag has a higher specific gravity and fineness compared to fly ash, it increased the oven dry density as the fly ash ratio decreased.

The increase in fly ash decreases the mechanical properties of geopolymer concretes. The 28-day compressive strength of geopolymer concretes with a 75% fly ash content, substituted for blast furnace slag, was 30.7 MPa, whereas it was 50.4 MPa with 0% fly ash content. Increasing the fly ash content reduces the geopolymerization potential, resulting in a more porous microstructure and a decrease in the effectiveness of the binder phase. The combination of these factors results in a significant reduction in the material's compressive strength.

As the fly ash content increases, the loss of compressive strength is less pronounced in samples exposed to temperatures of 250, 500, and 750 °C. Fly ash has thermal stability and a robust microstructure. Additionally, increasing the fly ash content makes the concrete's microstructure denser and tighter, thereby reducing the effects of internal pressure and microcracks caused by water evaporation at high temperatures. Blast furnace slag is more prone to thermal degradation, which causes a loss of strength at high temperatures. For these reasons, geopolymer concretes with a high fly ash content exhibit superior thermal stability at high temperatures. The compressive strength lost is 13.48% for 250 °C, 17.54% for 500 °C and 75.88% for 750 °C. At 250 and 500 °C, the compressive strength loss rate was relatively low, whereas it was significantly higher at 750 °C. At high temperatures, the chemical structure of the geopolymer binder phase begins to deteriorate, and the thermal expansion differences between the aggregates and the binder lead to microcracks. These cracks weaken the structural integrity and cause a significant decrease in compressive strength.

The cost of geopolymer concrete decreased as the fly ash content increased. The procurement costs of the materials used vary depending on the geographical region, supply chain, quantity of use and local industrial activities.

In conclusion, geopolymer concrete produced using industrial waste instead of regular Portland cement is a significant alternative in terms of sustainability, durability, and economics. Geopolymer concrete production reduces environmental impacts by promoting the recycling of industrial waste and offers innovative solutions in the building materials industry.

This study presents a comprehensive investigation into the mechanical and thermal properties of geopolymer concrete produced by partially replacing ground granulated blast furnace slag with varying proportions of fly ash. This topic has been relatively underexplored in the literature. It aims to contribute to the growing body of knowledge in the field of sustainable construction materials.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1.] Bayrak, B., Alcan, H. G., Özelmacı Durmaz, Ö. Ç., İpek, S., Kaplan, G., Güneyisi, E., & Aydın, A. C. (2024). Studying the metakaolin content, fiber type, and high-temperature effects on the physico-mechanical properties of fly ash-based geopolymer composites. Archives of Civil and Mechanical Engineering, 25(1), 2. https://doi.org/10.1007/s43452-024-01071-9

[2.] Gartner, E. (2004). Industrially interesting approaches to "low-CO2" cements. Cement and Concrete Research, 34(9), 1489–1498. https://doi.org/10.1016/J.CEMCONRES.2004.01.021

[3.] Meyer, C. (2009). The greening of the concrete industry. Cement and Concrete Composites, 31(8), 601–605. https://doi.org/10.1016/J.CEMCONCOMP.2008.12.010

[4.] G.L. Golewski, T. Sadowski, The fracture toughness the KIIIc of concretes with F fly ash (FA) additive, Constr. Build. Mater. 143 (2017) 444–454, http://dx.doi.org/10. 1016/j.conbuildmat.2017.03.137.

[5.] Davidovits, J. (1991). GEOPOLYMERS Inorganic polymerie new materials. Journal OfThamalAnalysis, 37, 1633–1656.

[6.] Davidovits, J. (1994, October). Properties of geopolymer cements. In First international conference on alkaline cements and concretes (Vol. 1, pp. 131-149).

[7.] Motorwala, A., Shah, V., Kammula, R., Nannapaneni, P. & Raijiwala, D. (2008). "ALKALI Activated FLY-ASH Based Geopolymer Concrete,".

[8.] Flower, D. J., & Sanjayan, J. G. (2007). Green house gas emissions due to concrete manufacture. The international Journal of life cycle assessment, 12, 282-288. http://dx.doi.org/10.1065/lca2007.05.327

[9.] Xu, D., & Li, H. (2009). Future resources for eco-building materials: I. Metallurgical slag. Journal of Wuhan University of Technology-Mater. Sci. Ed., 24(3), 451-456.

[10.] Liu, Y., Su, Y., Xu, G., Chen, Y., & You, G. (2022). Research progress on controlled low-strength materials: metallurgical waste slag as cementitious materials. Materials, 15(3), 727. https://doi.org/10.3390/ma15030727

[11.] Zhao, D., Zhang, Z., Tang, X., Liu, L., & Wang, X. (2014). Preparation of slag wool by integrated waste-heat recovery and resource recycling of molten blast furnace slags: from fundamental to industrial application. Energies, 7(5), 3121-3135. https://doi.org/10.3390/en7053121

[12.] Kuo, W. T., Liu, M. Y., & Juang, C. U. (2019). Bonding behavior of repair material using fly-ash/ground granulated blast furnace slag-based geopolymer. Materials, 12(10), 1697. https://doi.org/10.3390/ma12101697

[13.] Luhar, I., & Luhar, S. (2022). A comprehensive review on fly ash-based geopolymer. Journal of Composites Science, 6(8), 219. https://doi.org/10.3390/jcs6080219

[14.] Hardjito, D., Wallah, S. E., Sumajouw, D. M., & Rangan, B. V. (2005). Fly ash-based geopolymer concrete. Australian Journal of Structural Engineering, 6(1), 77-86. https://doi.org/10.1080/13287982.2005.11464946

[15.] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. Progress in energy and combustion science, 36(3), 327-363. https://doi.org/10.1016/j.pecs.2009.11.003

[16.] Golewski, G. L. (2022). The role of pozzolanic activity of siliceous fly ash in the formation of the structure of sustainable cementitious composites. Sustainable Chemistry, 3(4), 520-534. https://doi.org/10.3390/suschem3040032

[17.] ASTM C1437 (2013). Standard test method for flow of hydraulic cement mortar, ASTM International.

[18.] TS EN 12390-5 (2019). Testing hardened concrete — Part 5: Flexural Strength of test specimens, Turkish Standards Institution (TSE).

[19.] Deb, P. S., Nath, P., & Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. Materials & Design (1980-2015), 62, 32-39. https://doi.org/10.1016/j.matdes.2014.05.001

[20.] Kaplan, G., Öz, A., Bayrak, B., Alcan, H. G., Çelebi, O., & Aydın, A. C. (2022). Effect of quartz powder on mid-strength fly ash geopolymers at short curing time and low curing temperature. Construction and Building Materials, 329, 127153. https://doi.org/10.1016/j.conbuildmat.2022.127153

[21.] Bellum, R. R., Al Khazaleh, M., Pilla, R. K., Choudhary, S., & Venkatesh, C. (2022). Effect of slag on Strength, durability and microstructural characteristics of fly ash-based geopolymer concrete. Journal of Building Pathology and Rehabilitation, 7(1), 25. https://doi.org/10.1007/s41024-022-00163-4

[22.] Zuaiter, M., El-Hassan, H., El-Maaddawy, T., & El-Ariss, B. (2022). Properties of slag-fly ash blended geopolymer concrete reinforced with hybrid glass fibers. Buildings, 12(8), 1114. https://doi.org/10.3390/buildings12081114

[23.] Ganesh, A. C., & Muthukannan, M. (2021). Development of high performance sustainable optimized fiber reinforced geopolymer concrete and prediction of compressive Strength. Journal of Cleaner Production, 282, 124543. https://doi.org/10.1016/j.jclepro.2020.124543

[24.] Wang, Y., Zhao, J., Zheng, D., Hua, K., Wang, D., & Zheng, Y. (2024). Study on the relation between macro-mechanical properties and micro-structure of geopolymers with different activator modulus. *Environmental Science and Pollution Research*, *31*(3), 4671-4685.

[25.] Zhao, J., & Wang, Y. (2023). Microstructure evaluation of fly ash geopolymers alkali-activated by binary composite activators. Minerals, 13(7), 910. https://doi.org/10.3390/min13070910

[26.] Manzoor, T., Bhat, J. A., & Shah, A. H. (2024). Performance of geopolymer concrete at elevated temperature− A critical review. Construction and Building Materials, 420, 135578. https://doi.org/10.1016/j.conbuildmat.2024.135578

[27.] Qu, F., Li, W., Tao, Z., Castel, A., & Wang, K. (2020). High temperature resistance of fly ash/GGBFS-based geopolymer mortar with load-induced damage. Materials and structures, 53, 1-21. https://doi.org/10.1617/s11527-020-01544-2

[28.] Kürklü, G. (2016). The effect of high temperature on the design of blast furnace slag and coarse fly ash-based geopolymer mortar. Composites part b: engineering, 92, 9-18. https://doi.org/10.1016/j.compositesb.2016.02.043

[29.] Van Deventer, J. S., Provis, J. L., & Duxson, P. (2012). Technical and commercial progress in the adoption of geopolymer cement. Minerals Engineering, 29, 89-104. https://doi.org/10.1016/j.mineng.2011.09.009

[30.] Zhuang, X. Y., Chen, L., Komarneni, S., Zhou, C. H., Tong, D. S., Yang, H. M., ... & Wang, H. (2016). Fly ash-based geopolymer: clean production, properties and applications. Journal of cleaner production, 125, 253-267. https://doi.org/10.1016/j.jclepro.2016.03.019

[31.] Provis, J. L. (2014). Geopolymers and other alkali activated materials: why, how, and what?. Materials and structures, 47(1), 11-25.

[32.] Mehta, P. K., & Monteiro, P. J. M. (2014). Concrete: Microstructure, properties, and materials (4th ed.). McGraw-Hill Education.

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