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Examination of the Mechanical Properties of Geopolymer Concrete: A Review

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ABSTRACT

The growing population and advancements in human lifestyle have led to a significant surge in energy demands for contemporary buildings. The increasing demand for energy, depletion of fossil fuel resources, and pressing environmental concerns serve as significant drivers for the advancement of sustainable and effective infrastructure. Geopolymer (GP) composite, devoid of cement and composed of diverse materials rich in Al_2SiO_3 and Na_2SiO_3/NaOH (alkali-activated silica), is emerging as a significant material for sustainability initiatives. Their preference is attributed to the reduced emission of greenhouse gases in comparison to ordinary Portland cement (OPC). This paper seeks to provide a comprehensive overview of current advancements in the field of GP composites, focusing on sustainability. The characteristics of composites formulated with different geopolymeric binders are discussed. Additionally, the discussion includes the microstructure and chemical characteristics of GP composites. The resilience of GP composites is emphasised, particularly in relation to their degradation in diverse, harsh environments. A comprehensive assessment of global warming potential (GWP) was carried out, and the practical applications of GP composites within the building industry are also presented.

1. Introduction

The cement industry significantly contributes to carbon emissions, accounting for 5–8% of total global emissions. The industry is experiencing growth, especially in emerging economies, with projections indicating a 4% increase in CO_2 emissions by the year 2050. **[1]** Numerous environmental problems linked to the cement production process prompt concerns regarding sustainability. The cement production process entails the extraction and processing of raw materials, including limestone, clay, and shale, which are subsequently heated in a kiln at elevated temperatures to produce clinker. The clinker is meticulously pulverised with gypsum and additional ingredients to manufacture cement. This process expends considerable energy, predominantly from fossil fuels, resulting in substantial carbon dioxide (CO_2) emissions. **[2]** Fig. (1) illustrates CO_2 emissions across various sectors [3] Scientific studies have shown that cement production has far-reaching negative effects on the

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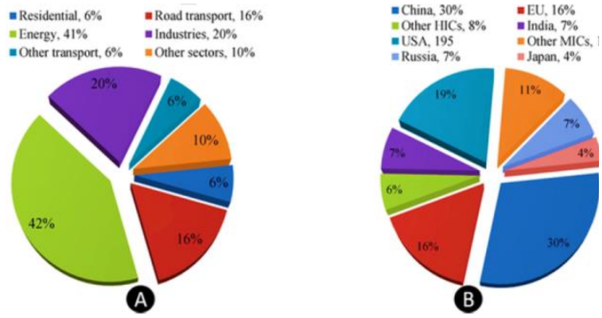

Fig. 1. Carbon dioxide emissions categorised by several sectors; (a) by countries; (b) worldwide [3]

environment, particularly in the areas of air, soil, water, and noise pollution. A plethora of studies have also offered various strategies to try to lessen the impact of these problems. [4] in There are several methods to decrease CO_2 emissions: (1) substitution of cement with alternative raw materials and supplementary cementitious materials,[5] (2) utilisation of civil construction waste as a substitute raw material in the manufacture of Portland clinker, with partial substitution of limestone–clay composites [6] Geopolymer concrete (GPC) is a form of sustainable concrete. [7] has developed as a sustainable and high-performance alternative to classic Portland cement concrete (PCC), sometimes referred to as ordinary Portland cement (OPC), providing considerable environmental and engineering benefits. [8] that GPC is both economically viable in the long run and facilitates material reuse rates of up to 70%, hence endorsing circular economy concepts. [9] The utilisation of geopolymer (GP) in concrete as a sustainable material has recently risen, as illustrated in Fig. 2. [10]

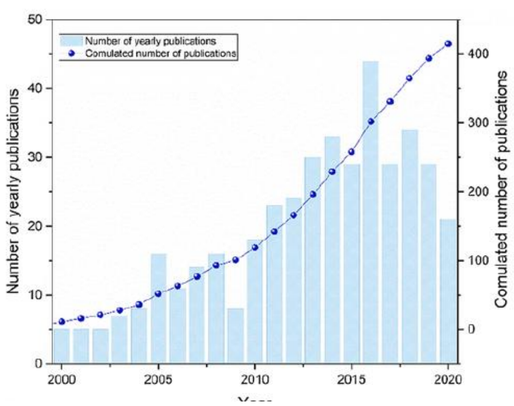

Fig. 2. Annual publication trend of geopolymer concrete (GPC) **[10]**

2. Significance of research

Researching geopolymer concrete (GPC) is essential for developing sustainable, low-carbon construction materials that mitigate the substantial CO_2 emissions associated with conventional cement. GPC provides enhanced durability, fire resistance, and chemical resilience by incorporating industrial byproducts such as fly ash and slag, positioning it as a critical eco-friendly alternative for rigorous applications and sustainable development. The fundamental objective of this work is to evaluate and analyse recent experimental results in the field of geopolymer concrete. The study focuses on the materials employed in GPC and the formulation design. Moreover, it highlights the essential attributes of GPC that profoundly influence the structural performance and longevity of concrete under severe climatic conditions.

3. Sustainability of geopolemar concrete

Sustainable development is attained through the use of geopolymers in the construction industry, as it leads to reduced CO2 emissions, optimal resource utilisation, incorporation of waste materials, cost-effectiveness in long-lasting infrastructure, and social advantages such as financial benefits and job creation.[11]

GPC relies on the activation of high-silica content in natural or industrial byproducts, such as fly ash, utilising an alkaline solution to generate three-dimensional polymers that bind the aggregate in lieu of hydrated Portland cement. Consequently, cement consumption may be diminished or potentially eradicated. Besides its environmental benefits, geopolymer water-free activation produces concrete mixtures that exhibit enhanced resistance to alkali-aggregate reactivity, increased durability against chloride attacks, and reduced susceptibility to shrinkage and early-age cracking. [12] The distinction between ordinary concrete and polymer concrete is presented in Table 1

Table 2 : Defferent between GPC and OPC

Properties	Notes	Ref.
Compressive strength	The compressive strength of geopolymer concrete develops rapidly at an early age compared to regular concrete, and the results demonstrate that the bond performance of geopolymer concrete exceeds that of normal concrete.	**[13]** **[14]**
Brittleness	At a specified strength level, geopolymer paste and concrete exhibit greater brittleness compared to their corresponding OPC paste and concrete.	**[15]**
water absorption rate	Ordinary Portland Cement (OPC) concrete exhibits a significantly reduced water absorption rate compared to the equivalent fly ash geopolymer concrete.	**[16]**
Setting time (NaOH &temperature)	GPC set more rapidly with an increase in NaOH molarity. Upon the reduction in temperature	**[17]** **[18]**
Setting time (effect of alkaline concentrations)	It exhibited variations based on alkaline content and initial curing temperature. The setting time of pastes decreases with increasing alkaline concentrations.	**[19]**
CO2 Emotions	Geopolymer concrete is frequently asserted to possess a reduced global warming potential compared to(OPC)	**[20]**
environmental management	Geopolymer materials in the advancement of alternative cement for enhanced environmental management.	**[21]**
low-carbon and environmentally friendly	Geopolymer concrete is more sustainable and environmentally benign than ordinary Portland cement concrete	**[22]**

4. Constituent of Geopolymer Concrete

The components of geopolymer concrete include a binding agent, activators, aggregates, and requisite admixtures. Figure 3 illustrates the components of geopolymer concrete along with many commonly utilised examples. **[23]**

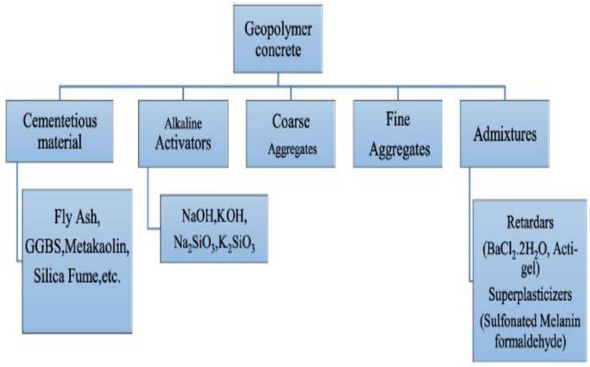

Fig.3. The components of geopolymer concrete**[23]**

4.1. Fly ash

Fly ash is a by-product mostly derived from thermal power plants, consisting of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). Additional oxides found in fly ash comprise Fe_2O_3, CaO, MgO, among others. It may also include trace elements such as arsenic (As), zinc (Zn), lead (Pb), selenium (Se), gallium (Ga), germanium (Ge), and minor quantities of rare-earth elements. [24] Assi et al .[25] indicated that the source of fly ash substantially influences the compressive strength of fly ash-based geopolymer concrete. The particle size distribution (PSD) directly influences the compressive strength. Furthermore The origin of fly ash substantially influences the microstructure of fly ash-based geopolymer concrete.A finer particle size distribution of fly ash greatly reduces the permeability void ratio. Reduced microcracks were noted with the utilisation of finer fly ash. Wardhono **etal. [26]** study The influence of water-to-binder ratio on the strength of fly ash geopolymer as a sustainable green material The findings indicate that the water-to-binder ratio considerably influences the strength of FGP. The maximum strength was attained using a 0.30 water-to-binder ratio. Increasing the water-to-binder ratio further generally resulted in a reduction of strength and an expedited initial setting time. The results indicated that an appropriate water-to-binder ratio allows for the use of fly ash as a sustainable green material to combat global climate change.

4.2. Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag serves as a viable substitute for typical Portland cement owing to its capacity to diminish CO_2 emissions. Nonetheless, the restricted binding capacity of pure GGBS requires the use of alkaline activators to improve its hydration properties. [27]

Bellum et al . [28] revealed that the incorporation of GGBFS as an addition in FA-based geopolymer concrete enhanced its mechanical qualities. The reduction in porosity and water absorption, coupled with an increase in compressive strength, is attributed to the creation of more C–A–S–H gel, which enhances the microstructure and produces a more rigid matrix. The enhanced mechanical characteristics of the GC samples were noted with the increased GGBFS content, attributed to the creation of C–A–S–H gel, which contributes to the development of denser structures. The peak strength values were achieved with 50% FA incorporation via GGBFS**.**

4.3. Alkaline solution

In geopolymerization, the alkaline solution is crucial. The predominant alkaline solution utilised in geopolymerization comprises a mixture of sodium hydroxide (NaOH) or potassium hydroxide (KOH) alongside sodium silicate (Na2SiO3) or potassium silicate (K2SiO3).[29]

Memon et al. [30] examined the influence of sodium hydroxide content on the fresh characteristics and compressive strength of fly ash-based self-compacting concrete geopolymer (SCGC). The quantitative measurements and ocular observations indicated that variations in sodium hydroxide content had minimal impact on the fresh qualities of SCGC. The incorporation of sodium hydroxide, increasing from 8 M to 14 M in various SCGC mixtures, led to a mere 3.6% decrease in slump flow (from 700 mm to 675 mm). An elevation in sodium hydroxide concentration from 8 M to 14 M augmented the viscosity and cohesiveness of concrete while diminishing the fluidity and flowability of various SCGC mixtures. Ghafoor et al [31] examine the influence of sodium hydroxide (NaOH) content on the performance of fly ash-slag blended ambient-cured geopolymer concrete (GPC). The NaOH content was adjusted between 8 molar and 14 molar to examine its effect on both fresh and hardened mechanical characteristics. The elevation in NaOH concentration from 8 molar to 16 molar led to a persistent decline in the workability of GPC. The goal slump exceeding 150 mm was attained even at elevated NaOH concentrations, attributable to the inclusion of a high-range water-reducing admixture. The elevation of NaOH concentration significantly affects the strength development of fly ash slag-based ambient cured geopolymer concrete.Islam et al. [32] examine the impact of the sodium silicate to sodium hydroxide (SS/SH) ratio on the splitting tensile strength, utilising four ratios (1.5, 2.0, 2.5, and 3.0) in this investigation.

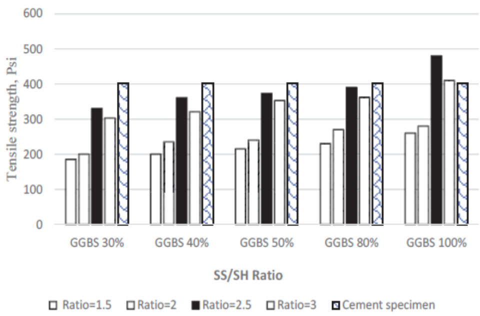

Fig 4. Splitting tensile strength at 28 days for 6 molarity of sodium hydroxide[32]

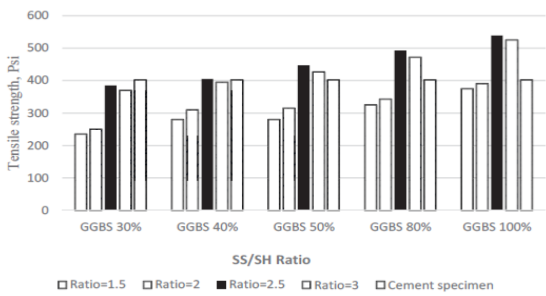

Fig 5. Splitting tensile strength at 28 days for 10 molarity of sodium hydroxide[32]

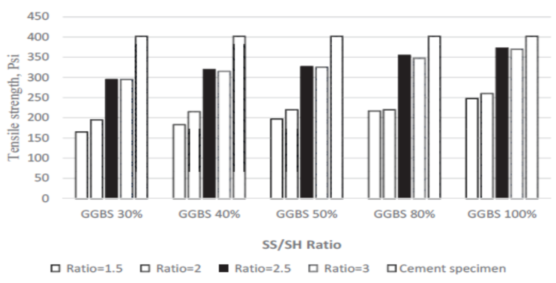

Fig 6. Splitting tensile strength at 28 days for 14 molarity sodium hydroxide[32]

Figures 4, 5, and 6 demonstrate that the splitting tensile strength value rises with an increasing ratio of sodium silicate to sodium hydroxide (SS/SH). The maximum strength value was observed at a ratio of 2.5.

5. Properties of geo polymer concrete

5.1. Compressive strength

The compressive strength of geopolymer concrete is mostly determined by curing temperature, mix design ratios, and the chemical composition of the alumino silicate and alkaline constituents. Increased curing temperatures and regulated humidity markedly accelerate the rate and degree of geopolymerization, thus enhancing strength development. (Tan Nguyen et al., 2014; Ye & Xu, 2014) cited by [33]. The molarity of alkaline activators, especially sodium hydroxide (NaOH), is crucial. Increased NaOH molarity, up to an optimal level, enhances the activation of fly ash or metakaolin, hence boosting compressive strength. Numerous factors influence compressive strength, including **:**

5.1.2 Particle size distribution

Assi et al. [34] demonstrated that the resultant compressive strength is linearly influenced by the average particle size distribution. The compressive strength of geopolymer concrete diminished with the utilisation of McMeekin fly ash.

5.1.3 Sources of material

He et al. [35] observed in their investigation that, for a specific Si/Al ratio, the geopolymer formed from metakaolin demonstrates superior compressive strength compared to the waste-based geopolymer (red mud). Both geopolymers exhibit a considerable presence of voids and unreacted phases as inactive fillers inside the geopolymer binder, leading to complexity and heterogeneity in their mechanical properties. The disparity in strength between the two geopolymers is ascribed to the varying reactivity of source materials, the proportion of nonreactive fillers, and the alkalinity involved in geopolymerization reactions.

5.1.4 Curing period

Kim et al. [36] showed that compressive strengths of 31 N/mm² and 45 N/mm² may be attained for the 10 M alkali-activated geopolymer mortar after 7 and 28 days of casting, respectively, when cured for 24 hours at 60°C. The researchers determined that an extended curing period and a higher concentration of alkali activator enhanced the compressive strength. Yılmaz et al. [37] demonstrated that curing specimens for extended durations and at elevated temperatures enhances compressive strength outcomes. The maximum compressive strength was attained at 80°C following 72 hours of curing.

5.2. Durability

Khan et al. [38] examine the integration of high-volume rice husk ash (RHA) into geopolymer bricks in their study. The mixes were immersed in sulphuric acid with a pH of 1.34. For comparative purposes, mixes were additionally submerged in water. The compressive strengths of the acid-immersed mixes were compared to those of the water-immersed mixtures. The findings demonstrated that prolonging the curing duration in acid and water diminished the compressive strength of the combination. After a seven-day exposure, the compressive strength of the controlled combination diminished by 14.7%, but the mixture with RHA exhibited no reduction in compressive strength. After 28 days of acid exposure, the geopolymer combinations containing RHA exhibited a compressive strength reduction of 31%, in contrast to the 17.5% reduction observed in the control mixtures. The increased porosity of the RHA-based combinations facilitated the infiltration of moisture and sulphate ions, leading to greater deterioration of these mixtures in comparison to the control mixtures. Figure (7): illustrates the comparison of compressive strength following acid exposure on RHA–GP mixes.

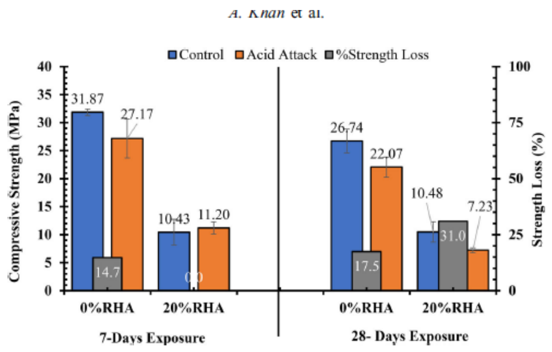

Fig 7 Compressive strength comparison after acid attack on RHA–GP mixtures.[38]

Vogt et al. [39] illustrated the significance of the Si/Al ratio in geopolymer mix designs for acid resistance, wherein a metakaolin-based geopolymer was altered by substituting the aforementioned precursor with varying percentages of silica fume. Durability assessments were conducted by subjecting geopolymers containing different proportions of silica fume (up to 9%) to a sulphuric acid solution (pH 1) for a duration of 84 days. The findings indicate that above a specific silica fume threshold, the total dissolution-induced erosion of the sample surface can be mitigated, and increased silica fume quantities result in substantial densification of extensive protective regions inside the corroded layer, hence impeding the advancement of corrosion.

Zhang et al. **[40]** indicated that the resistance of geopolymer composites to freezing and thawing can be improved by suitably elevating the curing temperature to around 50 ◦C to 80 ◦C, especially for low-Ca geopolymers. Optimal outcomes can be achieved when the curing temperature is maintained between 50 °C and 70 °C

5.3. Microstructure of Geopolymer concrete (GPC)

The microstructure of Geopolymer concrete (GPC) exhibited a higher proportion of amorphous phases, reduced porosity, and an increased number of mesopores compared to ordinary Portland cement concrete (OPCC). A literature review indicated that the manufacturing of geopolymer concrete necessitates meticulous attention and precise material compositions. The activation process in geopolymer production necessitates high alkalinity, which poses safety risks, increases energy consumption, and contributes to greenhouse gas emissions. The generation of GPC is influenced by both curing time and curing temperature. [41] Geopolymerization inhibits the interconnectivity of micropores by creating a denser matrix of geopolymer gel. The use of 12M sodium hydroxide solution, a low liquid-to-binder ratio of roughly 0.4, and a curing temperature of around 70 °C for a minimum of 24 h resulted in high-strength geopolymers. The binders combined with a sodium silicate to sodium hydroxide mass ratio of 2.0–2.5 exhibit enhanced reactivity. [42]

Ashfaq et al. [43] utilised SEM images to succinctly illustrate the morphology of Fly Ash and Metakaolin-based Geopolymer concrete, as depicted in Fig. 29. The use of metakaolin evidently enhances the density of the geopolymerization structure. The white particles are composed of metakaolin, whereas the black particles consist of fly ash. All these specimens exhibit heterogeneous and inconsistent porosity. It is also anticipated that a portion of the metakaolin and fly ash will remain unreacted

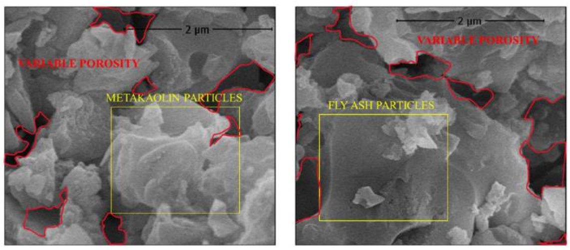

Fig 8.Scanning Electron Microscope picture of fly ash and metakaolin-based Geopolymer Concrete[43]

Albidah et al. [44] investigate the behaviour of metakaolin-based geopolymer concrete at ambient and increased temperatures. Their work includes scanning electron microscope (SEM) pictures of three geopolymer mixes, P1, P3, and

P4, at ambient conditions and following exposure to 400 °C, captured at a magnification of × 1000, as depicted in Figure 13. Table 2 illustrates the proportions of the blends.

Table 2. Geo polymer mix proportions (44)

Mix ID	MK (kg/m3)	NaOH solution (kg/m3)	Na_2SiO_3 solution (kg/m3)	Extra water (kg/m3)
P1	369.7	116.2	208.1	6.1
P3	383.4	98.6	215.8	2.2
P4	355.9	83.1	261.0	0.0

Not : Coarse aggregate (kg/m3)= 1224.0,Fine aggregate (kg/m3)= 575.8

At ambient conditions, the micrographs exhibit the characteristic microstructure of a dense and uniform geopolymer gel. The samples for SEM analysis were derived from the cracked segments of compressive strength testing, revealing visible cracks in the micrographs. A meticulous analysis of these micrographs reveals the absence of unreacted MK particles in P4. Nevertheless, a few unreacted MK particles remain in P1 and P3. Nonetheless, the geopolymerization reaction is nearly complete in all three mixtures. The microstructure of all three mixtures is uniform, compact, and dense, which accounts for the superior strength attained by these mixtures. The micrographs obtained after heating at 400 ◦C exhibit a somewhat porous and sponge-like structure in the three geopolymer mixtures, which contributed to the reduction in strength.

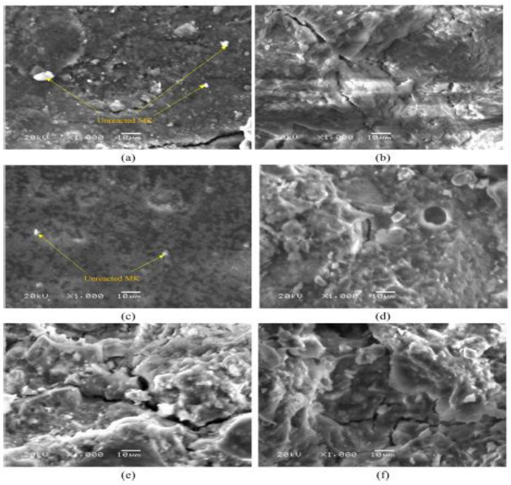

Fig 9. SEM of geopolymer mixtures: (a) P1 at ambient temperature; (b) P1 at 400 °C (c) P3 at ambient temperature; (d) P3 at 400 °C (e) P4 at ambient temperature (f) P4 at 400 °C.[44]

6. Application of geo polymer

The sustainability of infrastructure projects is an increasingly significant concern in engineering practice. In the future, construction materials will be chosen based on their capacity to fulfil sustainability criteria. Geopolymers are materials derived from industrial by-products. Utilising geopolymer concrete technology enables waste reduction and the environmentally sustainable production of concrete. [45] Fig [10] demonstrated the utility of GPC in building [46]

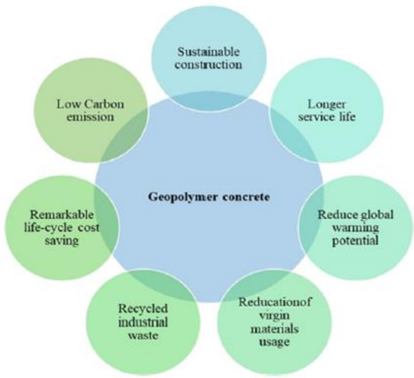

Fig 10. The utility of GPC in construction [46]

Geopolymer concrete (GPC) is utilised in sustainable building for infrastructure, including bridges,[47] and highways[48]. The adaptability of GPC has been evidenced by its effective utilisation in infrastructure projects, high-rise construction, precast components, and specialised applications such as marine constructions and fire-resistant barriers. [49] Geopolymers can mitigate environmental problems and have diverse applications in various domains, including water purification, waste treatment, and fire-resistant buildings. [50]

7. Conclusion

Sustainable development is realised through the use of geopolymers in the construction industry, as they lead to reduced CO_2 emissions, optimal resource utilisation, the incorporation of waste materials, cost-effectiveness in long-lasting infrastructure, and social advantages in terms of financial gains and job creation. The source of fly ash significantly influences the compressive strength of fly ash-based geopolymer concrete. The particle size distribution (PSD) directly influences the compressive strength. Furthermore, the origin of fly ash substantially influences the microstructure of fly ash-based geopolymer concrete. A finer particle size distribution of fly ash resulted in a more substantial reduction of the permeability void ratio.

In geopolymerisation, the alkaline solution is crucial. The predominant alkaline solution used in geopolymerization comprises a mixture of sodium hydroxide (NaOH) or potassium hydroxide (KOH) alongside sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3). The compressive strength of geopolymer concrete is mostly determined by curing temperature, mix design ratios, and the chemistry of the aluminosilicate and alkaline constituents. Increased curing temperatures and regulated humidity markedly accelerate the rate and degree of geopolymerisation, thus enhancing strength development.

Geopolymerization inhibits the interconnectivity of micropores by creating a denser matrix of geopolymer gel. The application of a 12M sodium hydroxide solution, a low liquid-to-binder ratio of roughly 0.4, and a curing temperature of around 70°C for a minimum of 24 h resulted in the formation of high-strength geopolymers.

The microstructure of geopolymer concrete (GPC) exhibited a higher presence of amorphous phases, reduced porosity, and an increased number of mesopores compared to ordinary Portland cement concrete (OPCC).

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