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Research Article

# The engineering properties of silica fume and GGBS-based geopolymer mortars cured in elevated temperature

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**ABSTRACT**

Geopolymer, a promising alternative to traditional portland cement, offers a wide range of sustainable applications in the construction industry. Geopolymer mortar presents a sustainable future by mitigating carbon dioxide emissions associated with cement production. This study aims to investigate the effect of using different minerals admixtures and different curing methods on the engineering properties of geopolymer mortar. The study also investigates the possibility of incorporating geopolymer concrete to develop construction with sustainability features. Five different mixes were prepared by utilizing various mineral admixtures in different ratios of silica fume (SF) and granulated blast furnace slag (GGBS), M20-80 (20% SF and 80% GGBS), M80-20 (80% SF and 20% GGBS), M50-50 (50% SF and 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF). The curing methods for each sample were investigated separately under ambient and oven temperatures (65 °C) for 7 and 28 days to determine the compressive and flexural strength of the samples. The results revealed that the compressive strength value of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 and MSF100 cured in oven temperature shows similar compressive strength compared to the ambient temperature curing method.

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## 1. Introduction

Geopolymer concrete, initially developed by French Professor Davidovits in 1978, represents a cement-free type of concrete with mechanical and high-temperature resistances (Aleem and Arumairaj 2012). These alternatives gain prominence for its potential to mitigate environmental harm associated with traditional cement sources, particularly the pollutants found in fly ash (FA) and granulated blast furnace slag (GGBS) (Alcan et al. 2023; Alnahhal et al. 2018). The primary source of fly ash, a key component of geopolymer materials, contains alumina, ferric oxide, and silica, which, due to their structural behavior, pose environmental concerns (Khan et al. 2021). Notably, aluminosilicate materials like fly ash and GGBS, when properly harnessed, can serve as sustainable alternatives. The preference for F type fly ash over C type is attributed to its lower contamination and higher alumina oxide content (Fernández-Jiménez and Palomo 2003).

Utilizing FA as a binder in mortar enhances its eco-friendliness, reducing the need for Ordinary Portland Cement (OPC) and contributing to a more sustainable construction industry. The use of solid waste and by-prod-

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ucts in construction has gained the attention of many researchers (Abutaha et al. 2016, 2017; Ibrahim et al. 2017). Geopolymer mortar is a blend of source materials and alkaline liquids, with Si and Al serving as the main activators. Notably, the absence of additional water during manufacturing eliminates the hydration process, differentiating it from traditional mortar (Al-Bakri et al. 2012). The ecological balance benefits from reducing OPC production, making geopolymer mortar a crucial player in promoting sustainability. Approximately 600,000 tons of fly ash are produced, but only a fraction is utilized for concrete production, highlighting the underutilized potential of geopolymer materials (Van Chanh et al. 2008).

Geopolymer concrete, utilizing sodium hydroxide and sodium silicate as alkali activators, offers an eco-friendly alternative to OPC. The absence of a hydration process in geopolymer concrete eliminates the need for curing, contributing to its sustainability. Geopolymer mortar's suitability and sustainability in the compatibility of silica and alumina content, fostering reactions without the need for additional water (Mucsi et al. 2018). Geopolymers, being amenable to low-tech and high-tech applications, present a viable replacement for conventional materials in the building sector. Their ease of use, energy efficiency, eco friendliness, high durability, and good mechanical qualities position geopolymers as an environmentally conscious choice.

Geopolymer stands out as a promising candidate for replacing traditional Portland cement, offering a range of applications in sustainable construction, including concrete materials, fire-retardant coatings, fiber-reinforced composites, and waste-immobilization solutions for chemical and nuclear sectors. Extensive research has pointed out that Geopolymer (GP) concrete shares comparable properties with OPC concrete, indicating its suitability for civil engineering applications (Singh et al. 2015). Notably, the ceramic-like characteristics inherent in GP enable it to withstand high temperatures and fire, adding to its versatility (Kong and Sanjayan 2010).

Low-calcium (ASTM Class F) fly ash obtained from coal burning power stations, was successfully used in the production of geopolymer concrete (GPC) (Rangan 2014). However, the compressive strength of fly ash based geopolymer concrete can be also improved when FA is partially replaced with OPC. Among different replacement level of FA with OPC, the maximum strength was achieved at 20% replacement at all ages (Mehta and Siddique 2017). Superior durability was demonstrated with FA-based geopolymer. However, GGBS-based geopolymers are more acid resistant and have higher initial strengths (Duxson et al. 2007a).

After thermal curing, alkali-activated fly ash concrete reaches a compressive strength of 60 MPa as well as superior resistance to sulfate attack, aggressive acids, chlorides, and aggregate-alkali reaction, all of which make it a great alternative to OPC mortars in hazardous waste treatment and reinforcing steel bonding (Boonserm et al. 2012; Deb et al. 2016; Rashad and Zeedan 2011). Fly ash and GGBS work well together to provide strength and stability because the alumina silicate components dissolve, polymerize with alkali, condense, and solidify (Nagajothi and Elavenil 2021). Due to its nearly comparable compressive strength to conventional concrete, GGBS-fly ash-based geopolymer concrete can be used in place of traditional concrete (Nagajothi and Elavenil 2021).

Geopolymers' ceramic-like properties provide them with good fire resistance. As a result, geopolymer-based concrete is considered more fire resistant than traditional OPC-based concretes (Hussin et al. 2015). Recent developments in geopolymer concrete have made it popular because of its simplicity of use, better performance, and lower carbon footprint than traditional OPC concrete (Mathew and Joseph 2018).

Despite these promising attributes, there is a notable gap in the existing literature, particularly concerning the combined effects of silica fume (SF) and GGBS under different ambient and oven temperatures. The optimization of results in this context is essential for understanding the intricate correlation between temperature variations and the presence of mineral admixtures. Bridging this gap in knowledge will not only contribute to the comprehensive understanding of geopolymer materials but also offer insights into their optimal performance in diverse environmental conditions.

This study focuses on addressing this research gap, shedding light on the specific interactions and outcomes resulting from the combination of silica fume and GGBS at varying temperatures. By doing so, the study aims to provide valuable information for optimizing geopolymer formulations, considering both temperature effects and the presence of mineral admixtures. The study is designed to investigate the effect of using different minerals admixtures, and the effect of curing methods on the engineering properties of geopolymer mortar and investigate the possibility of incorporating geopolymer concrete to developed construction areas with sustainability features. This optimization is crucial for advancing the practical application of geopolymer materials and fostering their role in sustainable construction practices.

## 2. Sustainability of Geopolymer Concrete

Previously, concrete was considered as one of the most important construction materials with the best engineering properties, cost-efficiency and good durability, compared to the other construction materials (Srivastava et al. 2025; Urtekin and Çelik 2025; Narwade and Jadhav 2025). However, the production process of cement-based concrete causes harmful effects on the environment (Al-Safi et al. 2025; Shehata et al. 2022). Cement-based concrete such as OPC which is widely used construction material, significantly contribute to the greenhouse gases emission (Wasim et al. 2021). The production of cement contributes to almost 7% of the global emission of $CO_2$ (Mathew and Joseph 2018).

Recently, the adoption of geopolymer concrete as a construction material is showing promise option; as a sustainable replacement to the traditional cement-based concrete for green environment and reduce greenhouse gas emission by using raw materials like industrial wastes (Shehata et al. 2022). Geopolymer concrete (GPC) is becoming widely used in different industries due to the special properties of GPC like the significant mechanical properties and the improvement in chemical and thermal resistance.

The demand for concrete will increase in the future, indicating that the consumption of GPC using industrial by-product will provide an alternative solution to the increment of concrete demand (Sumajouw et al. 2007). More than 50% of the greenhouse gas emission resulted from the production of cement. Thereby, GPC is considered as an alternative sustainable construction materials compared to the traditional cement-based concrete (Danish et al. 2022). Furthermore, incorporating GGBS which is a waste by-product of steel fabrication, in the production of GPC contributes to reduce the carbon dioxide emission and the energy levels can be assumed to be zero (Qaidi et al. 2022).

## 3. Experimental Procedure

The properties of geopolymer mortar (GM) exhibit a correct correlation with the material properties involved. Each property plays a vital role in the strength of GM. Fig. 1 illustrates some of the factors affecting geopolymer mortar, emphasizing their significance in determining strength of the geopolymer concrete. Geopolymer is a type of aluminosilicate binder material formed through the activation of solid aluminosilicate-based materials, such as silica fume, ground granulated blast slag, and alkaline solutions like sodium hydroxide and silicate solutions. Geopolymers are produced by blending mineral admixtures with an alkaline activator solution, resulting in a substance referred to as geopolymer paste. This mixture typically forms a homogeneous slurry with a dark green color.

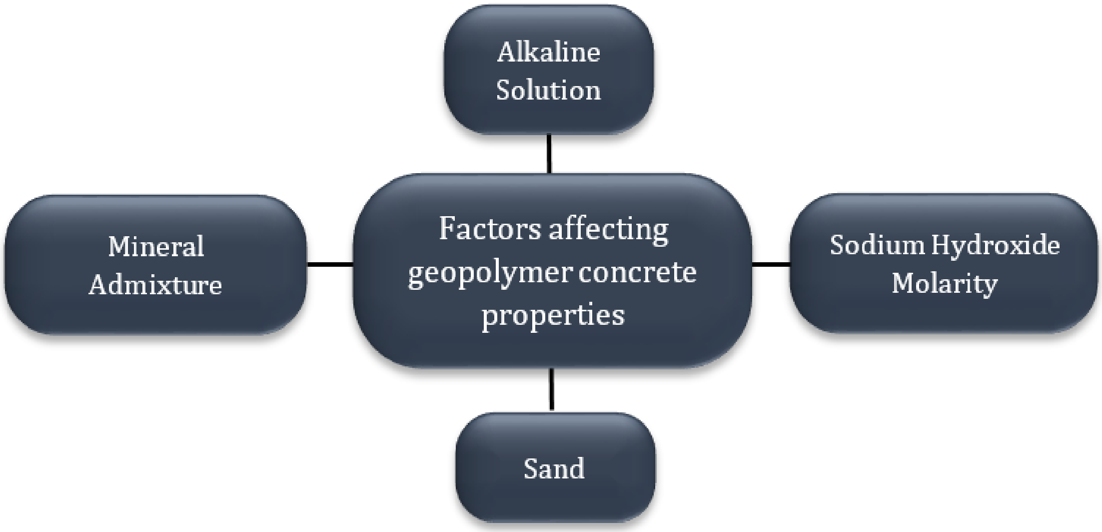


**Fig. 1.** Factors affecting geopolymer mortar properties.

## 4. Materials and Method

### *4.1. Mineral admixtures*

Considering the alarming one-to-one carbon dioxide emission ratio associated with cement production (Akbar and Liew 2021), geopolymer mortar, often referred to as "green mortar" (Zhao et al. 2021), emerges as a promising solution due to its cement-free composition and reliance on mineral admixtures. Inorganic polymers derived from aluminosilicates are referred to as geopolymers. These can be created by synthesising pozzolanic chemicals or aluminosilicate source materials with very alkaline solutions. Aluminosilicate materials like fly ash and GGBS, when properly harnessed, can serve as sustainable alternatives. These amorphous alumina silicates, produced through the reaction between silica and alumina silicate, exemplify eco-friendly features (Mucsi et al. 2018).

In the preparation of geopolymer mixes, this study demonstrates specific synthesizing parameters to highlight the effect of mineral admixtures on the engineering properties of GM. The inclusion of mineral admixtures significantly impacts the compressive strength and flexural strength of geopolymer mortar. Due to a lack of studies on the combination of SF and GGBS at both ambient and oven temperatures, this research was conducted to investigate their engineering properties cured at elevated temperatures. Their effect on the geopolymer mortar has been examined independently under the categories of mineral admixtures and alkaline activators.

Silica fume is a micro-sized material that can be utilized in concrete as a mineral additive due to its high Si and Al content and pozzolanic features. It improves granulometry by filling the spaces between cement grains. GGBS is a by-product of iron production in blast furnaces in iron and steel plants. The blast furnace slag is granulated through abrupt cooling and subsequently ground.

This study examines the impact of different additives, such as silica fume and ground granulated blast slag, on the mechanical properties of geopolymer mortar. Each sample exhibits distinct properties based on the materials used. These properties are a result of the mineral admixture content utilized in geopolymer mortar. The general materials used in the production of geopolymer mortar in this study are shown in Fig. 2.

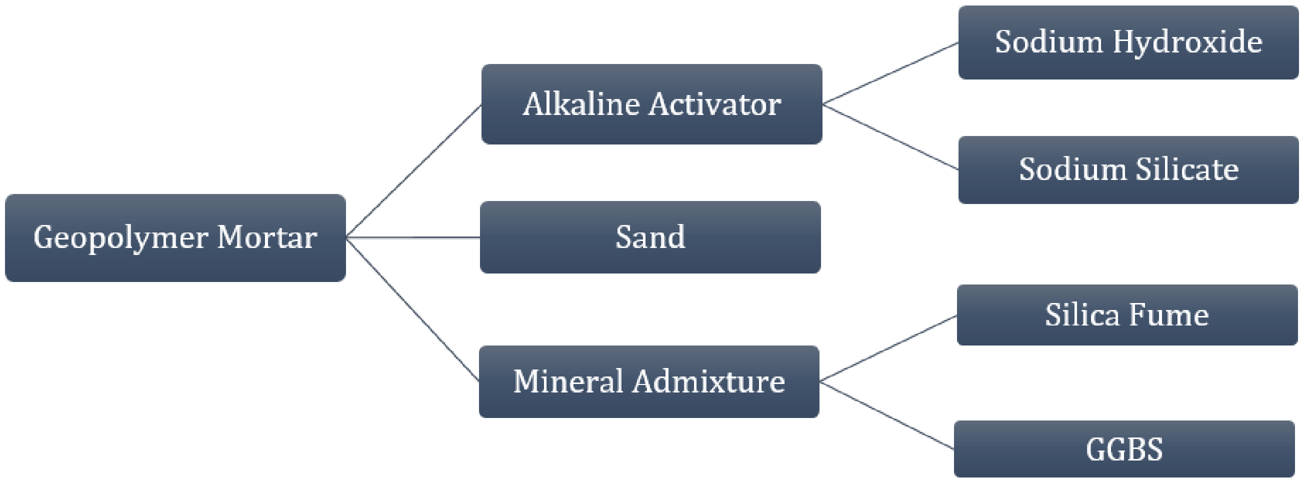


**Fig. 2.** Geopolymer mortar mixture demonstration.

### *4.2. Alkaline solutions*

A mixture of sodium silicate and sodium hydroxide were used as the alkaline solution in the production of GM. The ratio of sodium hydroxide to sodium silicate was maintained throughout the entire study. Alkaline solution ratio for each sample was also maintained constantly to observe only the effect of mineral admixtures on the engineering properties of GM.

Sodium silicate ($Na_2SiO_3$), also known as waterglass, is available in the market in both gel and solid forms. Sodium hydroxide (NaOH) is also commonly available in the market in pellet or flake form, and the cost of the product is dependent on the purity of its ingredients. In this study, sodium hydroxide (NaOH) solution with a molarity of 8M was prepared by dissolving it in pure water.

NaOH with 8M molarity was consistent for each specimen to determine only the effect of different mineral admixture on the engineering properties of geopolymer mortar samples. The concentration of 8M denotes that the amount of sodium hydroxide (NaOH) in one liter of water is 8×40=320g, where 40 is the molecular weight of NaOH. Dissolved sodium hydroxide (NaOH) pellets were used to achieve this concentration.

The NaOH solution was prepared at the planned concentrations and allowed to stand at room temperature for 24 hours, covered with nylon to prevent heat dissipation and water evaporation as shown in Fig. 3.

### *4.3. Preparation of geopolymer mortars*

The mix proportion used in the preparation of the geopolymer mortar specimens are shown in Table 1. Five different mixes were prepared by using various mineral admixtures in different ratios of silica fume (SF) and granulated blast furnace slag (GGBS), M20-80 (20% SF and 80% GGBS), M80-20 (80% SF and 20% GGBS), M50-50 (50% SF and 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF).

**Fig. 3.** Preparation of 8M sodium hydroxide solution.

**Table 1.** Mixture proportion of geopolymer mortars.

| Mixture proportions | Mix code | Silica fume (g) | GGBS (g) | Sodium silicate (ml) | Sodium hydroxide (ml) | Sand (g) | Liquid/Powder ratio |
|---|---|---|---|---|---|---|---|
| 1th mix | M20-80 | 90 (20%) | 360 (80%) | 66 | 134 (8M) | 1350 | 0.44 |
| 2nd mix | M80-20 | 360 (80%) | 90 (20%) | | | | |
| 3rd mix | M50-50 | 225 (50%) | 225 (50%) | | | | |
| 4th mix | MS100 | NA | 450 (100%) | | | | |
| 5th mix | MSF100 | 450 (100%) | NA | | | | |

The fundamental step involves preparing materials properly to obtain the most effective final test results. A programmable mortar mixer (Fig. 4) is used with properties designed to meet standard requirements for mixing mortars and cement pastes. The mixing paddle employs a planetary motion and is driven by a motor with a microprocessor-based speed. The mixer features preset programs complying with (EN 196-1, 2016) standards. The mixer includes an automated sand dispenser for automatic sand discharge. The user can monitor the mixed time on the display, and a lamp signals critical time.


**Fig. 4.** Automatic programmable mortar mixer.

The alkaline solution was prepared by converting milliliters into grams using density. Sodium silicate has a density of 1.38 kg/m$^3$, and sodium hydroxide has a density of 1.28 kg/m$^3$. The conversion results in 91 grams of sodium silicate and 171 grams of sodium hydroxide used in this study.

Silica fume, ground granulated blast slag, and sand were mixed for 5 minutes to prepare geopolymer specimens. Afterward, the activating solution was added and mixed sequentially. The mortar was then cast into prismatic molds of 40 mm × 40 mm × 160 mm (Fig. 5). Subsequently, the samples were then vibrated for 1 minute to remove entrained air, the samples were then sealed with a film to prevent moisture loss from the surface. After proper casting, the specimens were left at ambient temperature for 24 hours and demolded the next day then placed in the laboratory until the day of testing.

**Fig. 5.** Prism mold demonstration.

The geopolymer mortar samples were tested at the age of seven (7) and twenty-eight (28) days cured in ambient and elevated temperature (Figs. 6 and 7), representing early and final strength, respectively. Part of the specimens were cured in oven temperature at 65C until the age of testing (Fig. 8).

Three samples were taken from each sample group, and the results were determined by taking the average of three samples in the flexural strength test and an average of 6 samples in the compressive strength test. This methodology, employing 5 different ratios of raw materials with the same alkaline activator and sand content, elucidates the impact on compressive and flexural strength.

It also highlights the fundamental role of mineral admixtures in the geopolymer mortar structure. The testing age along with the corresponding number of samples are shown in Table 2. A total of 60 samples were utilized in the experimental phase, enabling a comprehensive comparison of results across various mineral admixtures cured in ambient and elevated temperatures.

### *4.4. Experimental investigation*

The flexural test measures the force presupposed to bend a beam under three-point loading conditions. The data is generally utilized to distinguish the materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed. Typically, a prism-shaped specimen is placed between the plates of a compression-testing machine (Fig. 9), applying a gradually increasing load until fracture occurs. After the flexural strength test, each sample was splitter into two pieces due to the fracture. The samples were then used for compressive strength tests. The compressive strength test measures the maximum compressive load a material can withstand before fracture. Each test requires three samples, and the average of the three samples determines the compressive and flexural strength.

In this study, each geopolymer mortar sample undergoes compressive and flexural strength testing at 7 and

28 days. The results illustrate the impact of mineral admixture content on the mortar. Both compressive and flexural strength tests were conducted on the formulated geopolymer mortar. In the flexural testing, samples were positioned in the compression machines with one side facing the supporting rollers, and the longitudinal axis parallel to the supports. Vertical loads were applied by the loading rollers on the opposite side of the prism/sample's face, with a uniform load increase. After specimens' failure, half of the prism/sample were then used for compressive strength testing was laterally centered on the machine's platen. The maximum force applied was recorded, along with the specimen's dimensions, the compressive strength was then calculated. The final compressive strength value represents the average of six individual test samples. For early strength, each specimen underwent separate testing. The final strength at 28 days was obtained for this testing phase. Additionally, the impact of heat was observed separately for 7 and 28 days.

**Fig. 6.** 7-day ambient temperature specimen samples.

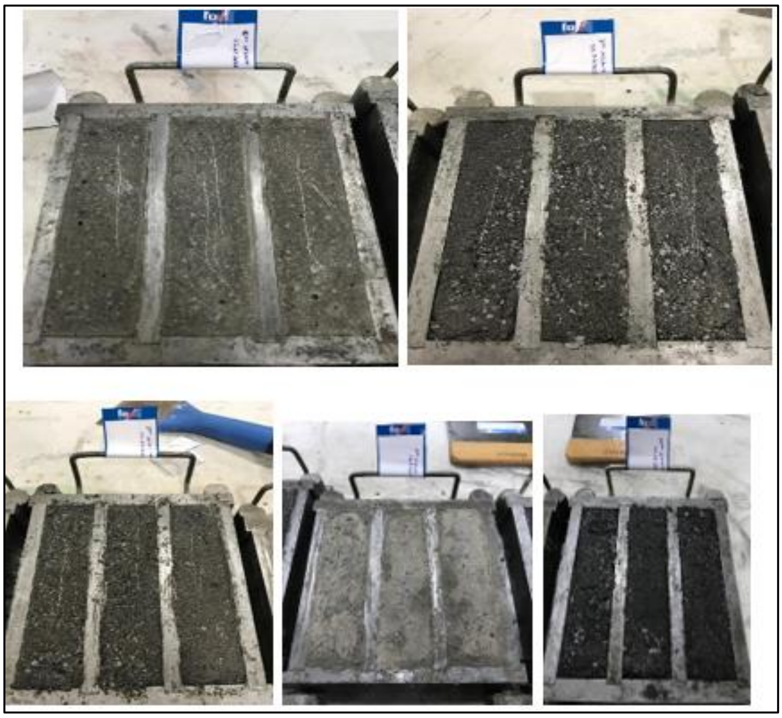

**Fig. 7.** 28-day ambient temperature specimen samples.

**Fig. 8.** 7-day specimen samples cured in 65 °C oven temperature.

**Table 2.** Number of samples required for compressive and flexural strength tests.

| Age | Curing method | Compressive strength/Flexural strength | | | | |
|---|---|---|---|---|---|---|
| | | M20-.80 | M80-20 | M50-50 | MS100 | MSF100 |
| 7 days | Ambient | 3 | 3 | 3 | 3 | 3 |
| | Oven temp. | 3 | 3 | 3 | 3 | 3 |
| 28 days | Ambient | 3 | 3 | 3 | 3 | 3 |
| | Oven temp. | 3 | 3 | 3 | 3 | 3 |

**Fig. 9.** Flexural and compressive strength test setup.

## 5. Results and Discussion

This section presents and discusses experimental results, specifically focusing on the strength development of geopolymer mortar under ambient and oven curing methods. The factors determined in the previous methodology section are considered. For all specimens, the liquid/powder ratio remained constant at 0.44, with only the percentages of mineral admixtures varying. Results for each test are presented separately based on their mineral admixture content and curing method.

### *5.1. Compressive strength results*

The mixtures were prepared to study the effect of various parameters on compressive strength. Part of the mixtures were prepared to study the effect of curing temperature on the compressive strength of geopolymer mortar. Each mixture is separately discussed below.

Table 3 shows the compressive strength values of the 7 days' samples cured at ambient and oven temperatures. The 7-day compressive strength results of the samples cured in ambient temperature ranged between

14.67 to 58.79 MPa as shown in Fig. 10. The maximum compressive strength was for the mix of MS100, and the minimum compressive strength value was for the mix of MSF100.

The compressive strength of MS100 was 4.7%, 40.3%, 41.5% and 75% higher than M20-80, M80-20, M50-50 and MSF100, respectively. However, the 7-day compressive strength results of the samples cured in oven temperature were in the range between 18.4–70.8 MPa. The results revealed that the maximum compressive strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100. The compressive strength of M20-80 was 66.6%, 65.2%, 41.6% and 73.9% higher than M80-20, M50-50, MS100 and MSF100, respectively. The comparison between the Seven-day compressive strength results of oven and ambient curing methods is shown in Fig. 12. The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 29.6%, 28.2% and 32.5% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 cured in oven temperature shows higher compressive strength compared to the ambient temperature curing method.

**Table 3.** 7-day compressive strength values.

| Curing method | 7-day compressive strength (MPa) | | | | |
|---|---|---|---|---|---|
| | M20-80 | M80-20 | M50-50 | MS100 | MSF100 |
| Ambient temperature | 52.85 | 30.01 | 31.22 | 58.02 | 17.36 |
| | 63.89 | 39.98 | 37.75 | 59.08 | 11.18 |
| | 51.82 | 31.05 | 37.01 | 57.68 | 17.98 |
| | 61.28 | 40.02 | 30.15 | 59.02 | 11.28 |
| | 50.05 | 29.87 | 31.98 | 58.88 | 18.05 |
| | 59.98 | 39.50 | 37.98 | 59.35 | 12.22 |
| Average | 56.65 | 35.07 | 34.33 | 58.67 | 14.67 |
| Oven temperature (65 °C) | 62.95 | 18.12 | 23.83 | 42.73 | 17.06 |
| | 65.86 | 23.28 | 25.51 | 42.31 | 18.93 |
| | 74.88 | 22.45 | 25.31 | 39.75 | 18.76 |
| | 75.89 | 24.59 | 24.89 | 40.09 | 19.34 |
| | 71.45 | 29.95 | 23.88 | 39.98 | 17.98 |
| | 69.67 | 23.56 | 24.5 | 43.21 | 18.55 |
| Average | 70.11 | 23.66 | 24.65 | 41.35 | 18.44 |

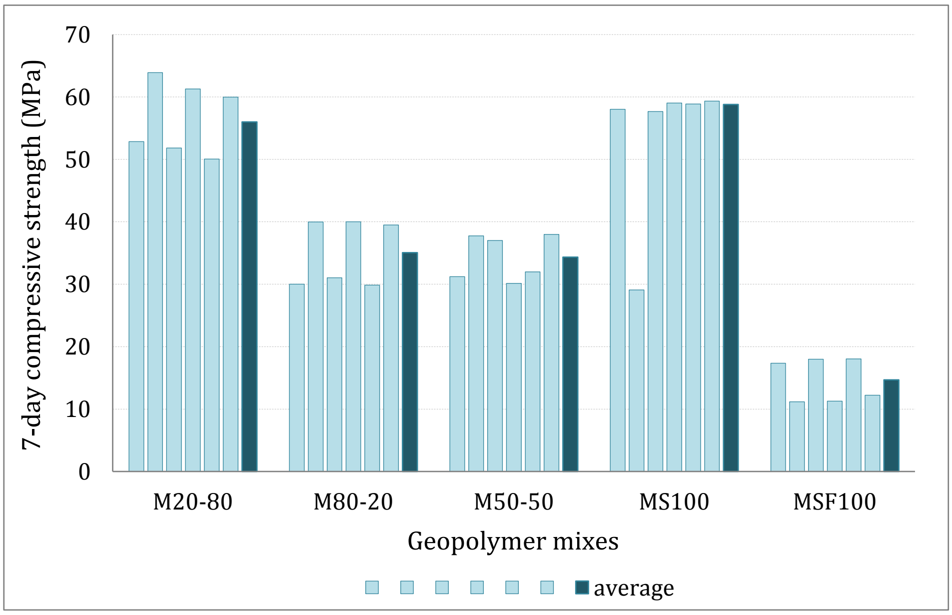


**Fig. 10.** 7-day compressive strength for ambient temperature.

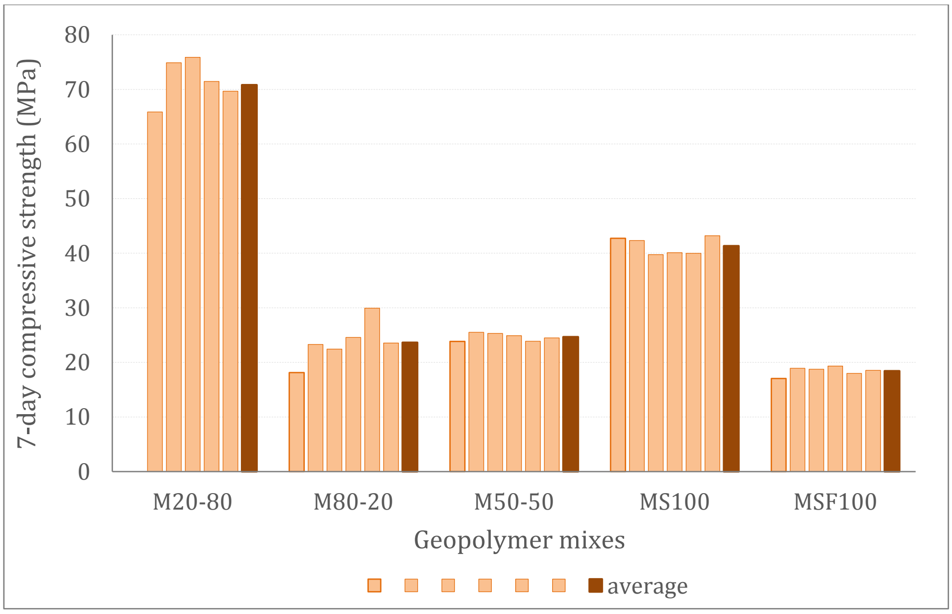


**Fig. 11.** 7-day compressive strength for oven temperature.

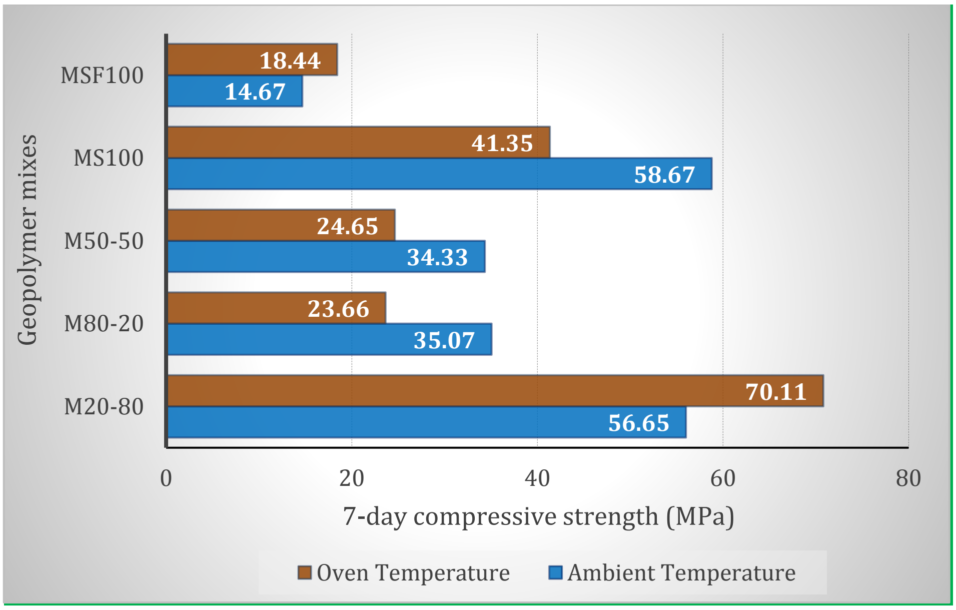


**Fig. 12.** 7-day compressive strength comparison.

Fig. 13 shows the 28-day compressive strength results of the samples cured in ambient temperature. The compressive strength values ranged between 19.2 to 70.7 MPa. The results revealed that the maximum strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100. The compressive strength of M20-80 was 27.9%, 26.5%, 14.5% and 72.8% higher than M80-20, M50-50, MS100 and MSF100, respectively. Fig. 14 shows the 28-day compressive strength results of the samples cured in oven temperature. The compressive strength values of the mixes were in the range between 21.1–70.6 MPa. The maximum compressive strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100. The maximum compressive strength of M20-80 was 61.3%, 44.3%, 26.75% and 70.2% higher than M80-20, M50-50, MS100 and MSF100, respectively.

The comparison between the 28-day compressive strength results of oven and ambient curing methods is shown on Fig. 15. The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 and MSF100 cured in oven temperature shows similar compressive strength compared to the ambient temperature curing method. Thus, there is no significant change that was observed in compressive strength values of the oven temperature and the ambient temperature curing method.

According to Shukor Lim et al. (2018), geopolymer mortar samples were immediately placed in an oven at 90 °C after casting, the compressive strength was decreasing as the heat curing duration increased. Rapid strength was observed up to 24 hours, then the strength became moderate or weak. For 24 hours of heat curing, the compressive strength was 31.46 MPa, slightly increasing to 32.1 MPa for 48 hours. Prolonged heat curing may weaken the mineral structure, and it is suggested not to exceed 24 hours in practical applications. The general assumption is that GGBS content is more effective, while SF results in lower workability and lower strength values. The study indicates that oven and room temperatures do not directly correlate with results. GGBS content penetrates alkaline solutions more than SF, providing durability to geopolymer mortar. The result of this study are with agreement of previous studies, geopolymers demonstrated a high degree of chemical stability when exposed to high temperatures (Duxson et al. 2006; Duxson et al. 2007b; Krivenko and Kovalchuk 2007). When exposed to high temperatures, geopolymer concrete exhibits remarkable stability, low shrinkage, and good resistance to freeze/thaw (Hussin et al. 2015; Rashad and Zeedan 2011). Further, the properties of GPC including the compressive strength and workability are affected by the properties of the ingredients that make the GP paste (Rangan 2014). Heat-cured geopolymer concrete based on Metakaolin and low calcium fly ash is thought to be a model building material (Luhar et al. 2021). Geopolymer specimens demonstrated lower compressive strength after high-temperature exposure to 900 °C (Mathew and Joseph 2018). Referring to the study by Narayanan and Shanmugasundaram (2017), geopolymer mortar develops sufficient strength even under ambient temperature conditions without conventional curing. Industrial by-products like GGBS and silica fume can be advantageously used in producing ambient-cured geopolymer composites. In general, the strength of ambient-cured geopolymer mortar increases with the rise in GGBS content. Parameters such as alkaline activator molarity, liquid/powder ratio, and binder/aggregate ratio influence the strength development of ambient-cured geopolymer mortar. Rangan (2014) investigated the effect of curing method on the properties of GPC, the study demonstrated that GPC cured in elevated temperature significantly assists the chemical process that takes place within the geopolymer paste. The improvement of compressive strength of the geopolymer concrete mixes cured in high temperature is attributed to the geopolymer mechanism of the polymerization reaction of the silica and the alumina released form the alkaline activation solution with FA (Mehta and Siddique 2017). Furthermore, GGBS may be added to the mixture of FA GPC to promote room-temperature curing and accelerate the setting time of fresh geopolymer concrete (Rangan 2014). Therefore, geopolymer mortar holds promise as an eco-friendly and sustainable construction material to produce new-generation mortar or concrete.

**Table 4.** 28-day compressive strength values.

| Curing method | 28-day compressive strength (MPa) | | | | |
|---|---|---|---|---|---|
| | M20-80 | M80-20 | M50-50 | MS100 | MSF100 |
| Ambient temperature | 70.94 | 52.85 | 45.80 | 62.44 | 19.52 |
| | 68.55 | 51.41 | 51.09 | 56.78 | 18.77 |
| | 68.60 | 50.96 | 52.57 | 57.98 | 18.56 |
| | 72.77 | 51.95 | 68.75 | 63.35 | 18.98 |
| | 73.85 | 49.85 | 46.85 | 60.43 | 19.56 |
| | 69.97 | 48.79 | 46.89 | 61.85 | 20.02 |
| Average | 70.78 | 50.97 | 51.99 | 60.47 | 19.23 |
| Oven temperature (65 °C) | 69.92 | 26.85 | 38.48 | 55.56 | 23.44 |
| | 72.85 | 26.98 | 37.65 | 53.45 | 18.75 |
| | 69.55 | 27.78 | 39.79 | 52.12 | 19.87 |
| | 71.95 | 27.21 | 39.92 | 50.43 | 22.45 |
| | 68.44 | 25.95 | 38.44 | 49.65 | 21.77 |
| | 70.98 | 28.99 | 39.65 | 49.12 | 20.19 |
| Average | 70.61 | 27.29 | 39.32 | 51.72 | 21.08 |

### *5.2. Flexural strength results*

The 7-day flexural strength results of the samples cured in ambient temperature is shown on Fig. 16. The flexural strength values ranged between 1.7 to 5.8 MPa. The maximum flexural strength was for the mix of MS100, and the minimum flexural strength value was for the mix of MSF100.

The flexural strength of MS100 was 12.7%, 60.5%, 37.9% and 70.2% higher than M20-80, M80-20, M50-50 and MSF100, respectively. However, the 7-day flexural strength results of the samples cured in oven temperature were in the range between 1.8–6.8 MPa as shown in Fig. 17. The maximum flexural strength was for the mix of M20-80 and the minimum flexural strength value was for the mix of MSF100. The flexural strength value of M20-80 was 70%, 47.8%, 35.7% and 72.5% higher than M80-20, M50-50, MS100 and MSF100, respectively. The comparison between the 7-day flexural strength results of oven and ambient curing methods is shown in Table 5. The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 25.6%, 2.7% and 12% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the flexural strength value of the mix of M20-80 and MSF100 cured in oven temperature shows increment compared to the ambient temperature curing method. The increment in flexural strength of the oven curing method was 32.5% and 6.8% higher for the mixes of M20-80 and MSF100, compared to the oven curing method, respectively.


**Fig. 13.** 28-day compressive strength for ambient temperature.

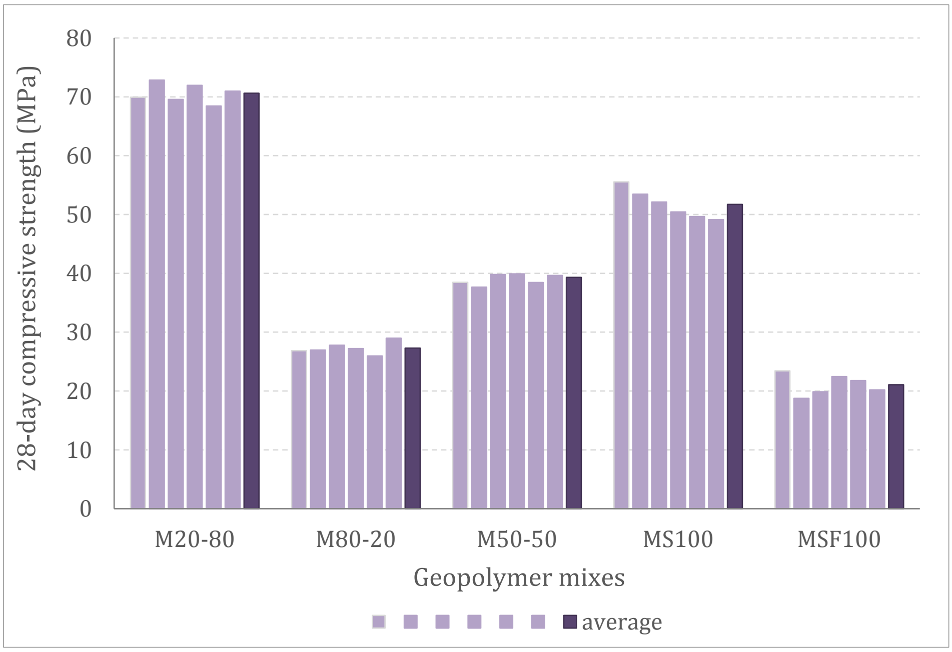


**Fig. 14.** 28-day compressive strength for oven temperature.

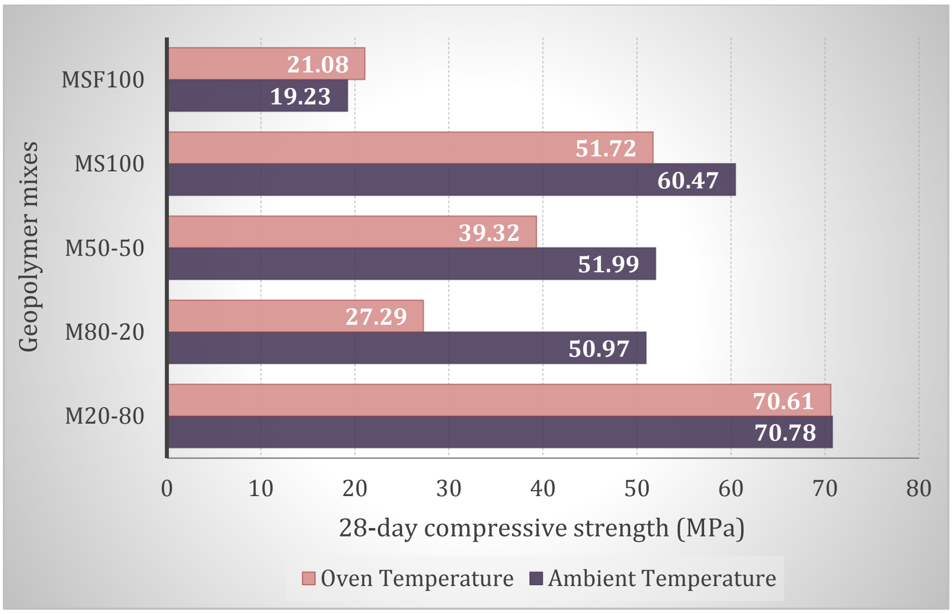


**Fig. 15.** 28-day compressive strength comparison.

**Table 5.** 7-day flexural strength values.

| Curing method | 7-day flexural strength (MPa) | | | | |
|---|---|---|---|---|---|
| | M20-80 | M80-20 | M50-50 | MS100 | MSF100 |
| Ambient temperature | 5.13 | 2.32 | 3.65 | 5.88 | 1.73 |
| | 5.18 | 2.3 | 3.67 | 5.85 | 1.75 |
| | 5.10 | 2.35 | 3.64 | 5.89 | 1.77 |
| Average | 5.14 | 2.32 | 3.65 | 5.87 | 1.75 |
| Oven temperature (65 °C) | 6.78 | 2.08 | 3.5 | 4.33 | 1.82 |
| | 6.82 | 2.10 | 3.5 | 4.38 | 1.93 |
| | 6.79 | 1.95 | 3.59 | 4.41 | 1.88 |
| Average | 6.80 | 2.04 | 3.53 | 4.37 | 1.88 |

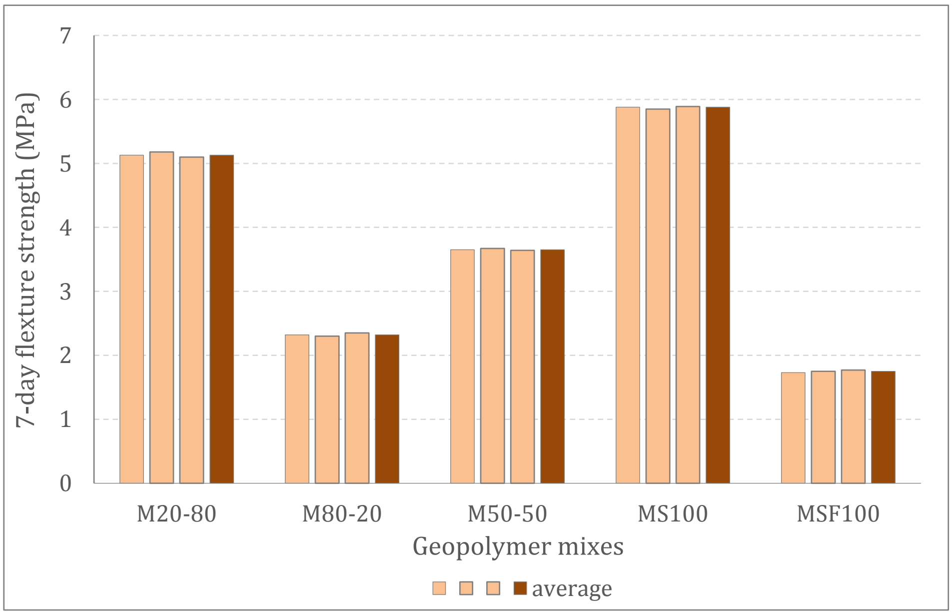


**Fig. 16.** 7-day flexural strength for ambient temperature.

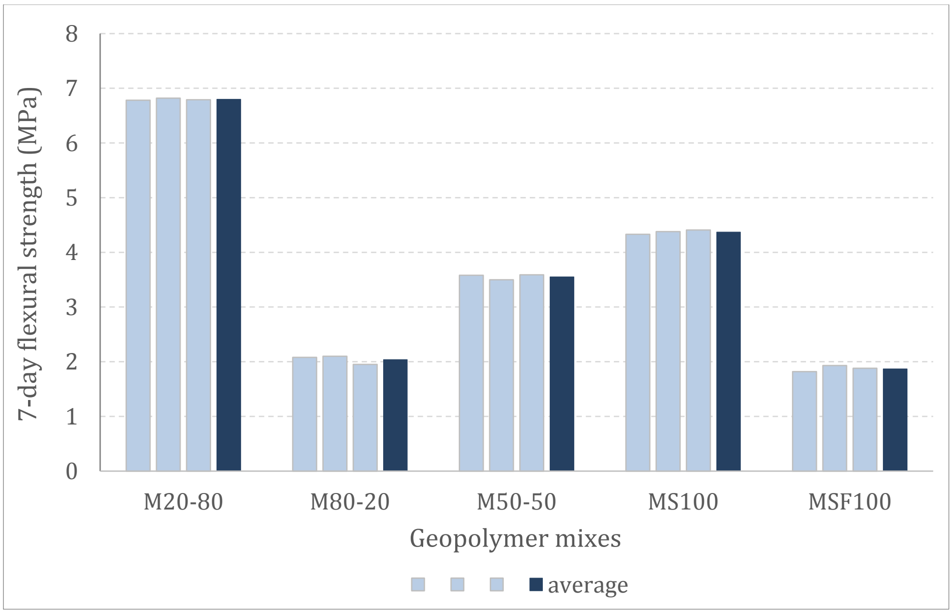


**Fig. 17.** 7-day flexural strength for oven temperature.

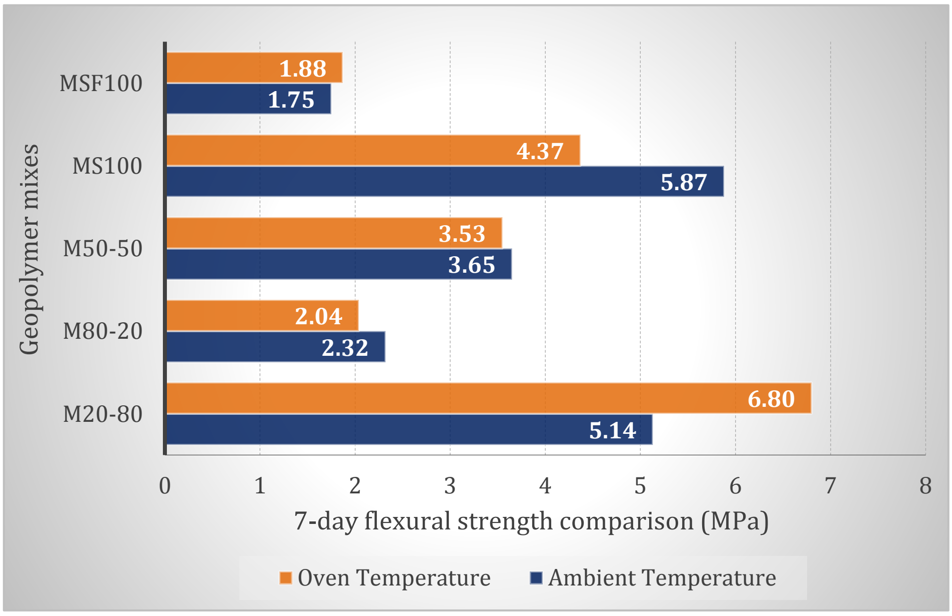


**Fig. 18.** 7-day flexural strength comparison.

The 28-day flexural strength results of the samples cured in ambient temperature are shown in Fig. 19. The flexural strength values ranged between 1.78 to 6.63 MPa. The maximum flexural strength value was recorded for the mix of M20-80 that considered 49.2%, 33.4%, 8.14% and 73.15% higher than M80-20, M50-50, MS100 and MSF100, respectively. However, the 28-day flexural strength results of the samples cured in oven temperature were in the range between 2.14–6.85 MPa. The maximum flexural strength was for the mix of M20-80 and the minimum flexural strength value was for the mix of MSF100. The maximum flexural strength of M20-80 was 68.3%, 38.2%, 18.4% and 68.7% higher than M80-20, M50-50, MS100 and MSF100, respectively.

The comparison between the 28-day flexural strength results of oven and ambient curing methods are shown on Fig. 21. The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment in the flexural strength compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 8.2%, 4% and 35.6% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the flexural strength value of the mix of M20-80 and MSF100 cured in oven temperature shows increment compared to the ambient temperature curing method. The increment in flexural strength of the oven curing method was 3.3% and 20.2% higher for the mixes of M20-80 and MSF100, compared to the oved curing method, respectively.

**Table 6.** 28-day flexural strength values.

| Curing method | 28-day flexural strength (MPa) | | | | |
|---|---|---|---|---|---|
| | M20-80 | M80-20 | M50-50 | MS100 | MSF100 |
| Ambient temperature | 6.65 | 3.37 | 4.39 | 6.05 | 1.78 |
| | 6.62 | 3.40 | 4.41 | 6.12 | 1.82 |
| | 6.64 | 3.36 | 4.43 | 6.10 | 1.79 |
| Average | 6.64 | 3.38 | 4.41 | 6.09 | 1.80 |
| Oven temperature (65 °C) | 6.85 | 2.15 | 4.23 | 5.62 | 2.10 |
| | 6.87 | 2.18 | 4.18 | 5.58 | 2.18 |
| | 6.83 | 2.20 | 4.20 | 5.57 | 2.15 |
| Average | 6.85 | 2.18 | 4.20 | 5.59 | 2.14 |

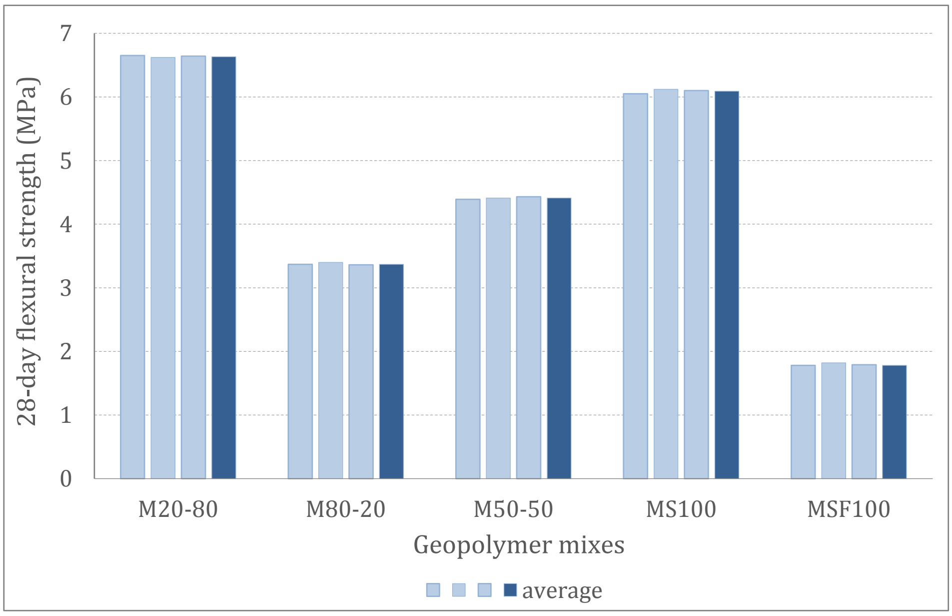


**Fig. 19.** 28-day flexural strength for ambient temperature.

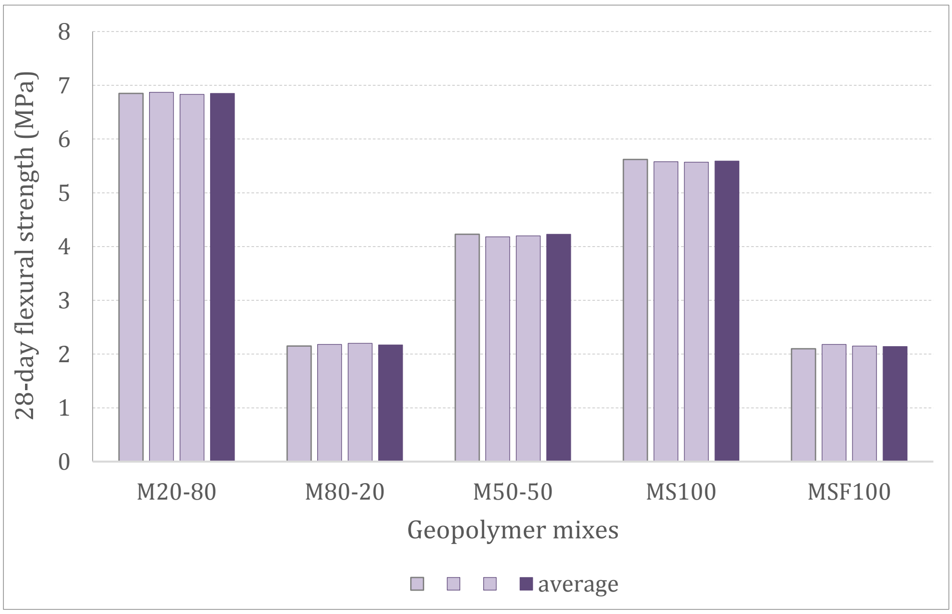


**Fig. 20.** 28-day flexural strength for oven temperature.

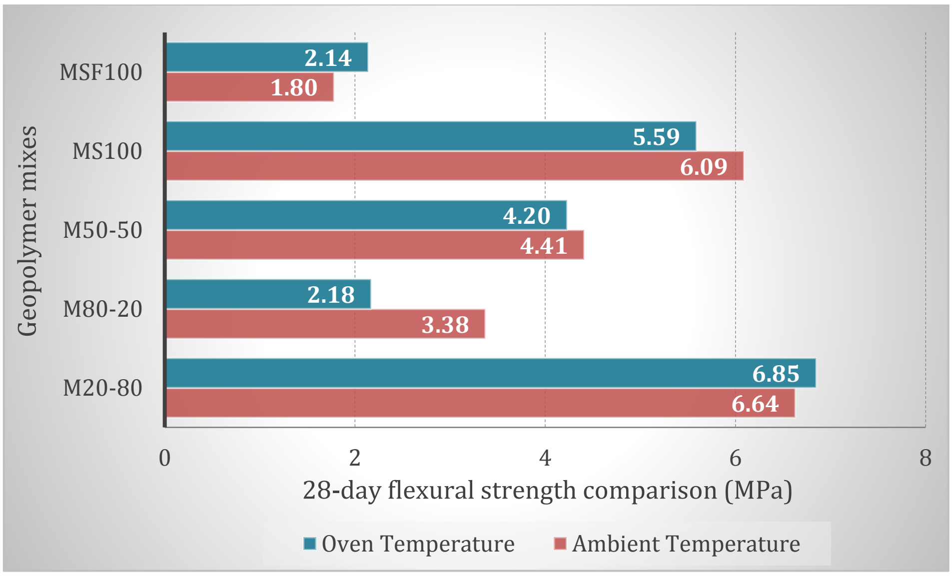


**Fig. 21.** 28-day flexural strength comparison.

## 6. Conclusions

This study aims to investigate the effect of using different minerals admixtures on the engineering properties of geopolymer mortar, and the effect of curing method of GM on the engineering properties of concrete. For the purpose of this study, five different mixes were prepared, each utilizing various mineral admixtures in different ratios: M20-80 (20% SF and 80% GGBS), M80-20 (80% SF and 20% GGBS), M50-50 (50% SF and 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF).The curing methods for each sample were investigated separately under ambient and oven temperatures (65 °C) for 7 and 28 days to determine the final values of compressive and flexural strength.

Based on the experimental work and test results, the following conclusions were derived:

- The twenty-eight-day ambient temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80, which is 27.9%, 26.5%, 14.5% and 72.8% higher than M80-20, M50-50, MS100 and MSF100, respectively. The maximum flexural strength values were recorded for the mix of M20-80, which is 49.2%, 33.4%, 8.14% and 73.15% higher than M80-20, M50-50, MS100 and MSF100, respectively.
- The twenty-eight-day oven temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80, which is 61.3%, 44.3%, 26.75% and 70.2% higher than M80-20, M50-50, MS100 and MSF100, respectively. The maximum flexural strength values were recorded for the mix of M20-80, which is 68.3%, 38.2%, 18.4% and 68.7% higher than M80-20, M50-50, MS100 and MSF100, respectively.
- The results revealed that the compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively.
- The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment in the flexural strength compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 8.2%, 4% and 35.6% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively.
- In summary, the results highlight the significant impact of different mineral admixtures and curing methods on the mechanical properties of geopolymer mortar, the mix of M20-80 demonstrating superior performance across various conditions.

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***Conflict of Interest***

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***Author Contributions***

*All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.*

***Data Availability***

*The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.*

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