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RESEARCH PAPER

Effect of Expanded Glass Lightweight Aggregate on the Performance of Geopolymer Mortar at Elevated Temperatures

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Abstract
The greenhouse gas emissions associated with conventional concrete as a result of the cement industry have prompted scientists to search for eco-friendly alternatives. Among these promising alternatives is geopolymer concrete or mortar. This work studies the impact of using polyvinyl alcohol (PVA) fibers and lightweight expanded glass (EG) aggregate on the mechanical behaviour of lightweight geopolymer mortar (LWGM) at various temperatures (room temperature, 250 °C, and 500 °C). EG was utilized to partially replace the sand by 10 and 20%. Limited studies dealt with geopolymer mortar based on such composition at high temperatures. The geopolymer mortar was created using slag as the main precursor activated by a mixed solution of sodium hydroxide and sodium silicate. Various combinations were produced, and their behaviour was observed at room and high temperatures. Several tests such as workability, compressive and flexural strengths, density, stress-strain relationship, load-displacement behaviour, and uniaxial tensile strength were performed. The findings of the study indicate that the density and compressive strength of geopolymer mortar reduced with increasing the replacement level by the EG. However, the utilization of 10% EG can produce a lightweight mortar with a compressive strength of 17.9 at 28 days. Moreover, the use of 1% PVA significantly improves the mechanical performance. Furthermore, the mechanical characteristics of the materials were considerably altered when subjected to extreme temperatures of 500 °C as observed from experimental data.

Keywords Elevated temperature · Lightweight expanded glass aggregate · Geopolymer mortar · PVA fibers

1 Introduction

Climate change has emerged as a critical global concern in recent decades, with severe consequences such as wildfires, hurricanes, extreme rainfall, and melted ice cap (Coffetti et al. 2022). The emission of carbon dioxide (CO_2) represents a significant risk to climate change mitigation, causing ecosystem destruction, losses in economic and lives, and even planetary emergencies. The growth of urbanization creates conflicting human issues of promoting development while minimizing environmental damages (Abdullah et al. 2019). On the other hand, Ordinary Portland Cement (OPC) is the prime construction material globally in terms of mass. The production of OPC involves energy-intensive pyro processing, leading to significant CO_2 emissions, approximately 0.85–0.92 tonnes per tonne of OPC manufactured (Prakasan et al. 2020). Thus, the development of sustainable concrete becomes crucial to meet construction demands while mitigating environmental impacts (Jiang et al. 2020a). To mitigate the environmental impact of cement, researchers and

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practitioners have been actively exploring the substitution of cement with more environmentally friendly binders over the last two decades (Shobeiri et al. 2021). On the other hand, with an increasing population, there is also a rise in waste generation. It was estimated that about 10.4 billion tonnes of waste were generated globally in 2010 and is projected that this number will reach 148 billion tonnes by 2025 (Alam and Qiao 2020; Patwa et al. 2020). Proper reusing or recycling of waste can minimize such issues (Xiao et al. 2022). Recently, municipal and industrial wastes such as glass waste, ground blast-furnace slag (GGBS), and fly ash (FA) have been utilized in producing green concrete, aiming to improve sustainability (Jiang et al. 2020b; Lu et al. 2022). However, merely reducing the environmental impact of concrete production may not ensure long-term sustainability and performance improvement (Coffetti et al. 2022). Finding comprehensive solutions to make concrete truly sustainable remains a challenging task for both academia and industry (Jiang et al. 2023).

Geopolymers have emerged as an innovative cement/binder alternative, revolutionizing the construction industry. Geopolymer materials form by blending an aluminosilicate precursor with an alkaline activator. The chemistry behind the geopolymerization process relies mainly on the dissolution and reorganization of aluminium (Al) and silicon (Si) atoms from the raw materials that lead to the formation of polymeric networks (Davidovits 2020).

The formation of calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels polymerization process are responsible for the formation of dense microstructure that leads to enhancing the mechanical and durability performance of geopolymer materials (Hakeem et al. 2024; Keskin-Topan et al. 2024; Shilar et al. 2022a; Shilar, Ganachari, Patil, & NisaShilar et al. 2022a, b, 2023). The formation of C-A-S-H and N-A-S-H gels involved the following processes: (a) monomer rearrangement where the reorganization of the Al and Si monomers happens; (b) Matrix formation when a cohesive gel matrix forms; (c) amorphous structure where the formed gel become predominantly amorphous; (d) polymeric chain growth this growth happen due to the ongoing polycondensation reactions; (e) curing kinetics where the setting and hardening of geopolymer materials happens and this process significantly affected by the chemical composition of the raw materials and the temperature of curing.

Similar to the normal concrete, many chemical laws/theories such as Abrams' law, Bolomey's law, fluid-binder ratio, variability of source materials, and theory of particle packing applied to geopolymer materials (Pacheco-Torgal et al. 2014, 2021; Radhakrishna et al. 2013). It is suggested by Prof. Joseph Davidovits that the ancient pyramids of Egypt were constructed using a form of geopolymer binder (Davidovits 2008).

Geopolymer materials from different resources offer a reduction in the CO_2 emissions of up to 80% relative to OPC (Kanagaraj et al. 2023; Kanagaraj et al. 2023b; Kanagaraj et al. 2023b). Thus, they offer a sustainable approach to reducing CO_2 emissions of OPC usage and also serve as an eco-friendly means of disposing of industrial waste, such as GGBS, FA, rice husk ash, sugarcane bagasse ash, metakaolin, and more (Adak et al. 2017; Jiang et al. 2023; Kurtoglu et al. 2018; Mehta and Siddique 2018; Nuaklong et al. 2018; Pasupathy et al. 2018; Pradhan et al. 2023a; Pradhan et al. 2023b , Singh et al. 2022; Tanu and Unnikrishnan 2022, 2023b). Additionally, demolition and construction wastes such as recycled concrete or clay bricks, ceramic and roof tiles, and glass have been used to develop geopolymers (Alhawat et al. 2022; Dadsetan et al. 2022; Mahmoodi et al. 2022; Mir et al. 2022). The waste materials contain significant amounts of aluminosilicate and thus serve as valuable precursors in the production of geopolymers. Generally, the production of geopolymers involves the polymerization of aluminosilicate materials with the use of alkali activators, mainly sodium silicate (Na_2SiO_3), potassium hydroxide (KOH) and sodium hydroxide (NaOH) (Farooq et al. 2021; Singh and Middendorf 2020).

In recent decades, numerous studies have focused on fibrous concrete (Jan et al. 2018, 2024). Adding fibers to the concrete mixture is an effective technique for improving its mechanical characteristics, including toughness, ductility, tensile and flexural strengths, and control of cracking distribution (Jan et al. 2021, 2022b; Niş et al. 2020; Shaukat et al. 2020). Polyvinyl alcohol (PVA) fiber is a synthetic fiber extensively utilized for reinforcing geopolymers as it poses a considerable ease of dispersion, chemical resistance, and mechanical characteristics. Additionally, the small diameter of the PVA fiber, approximately 40 μm, enhances the interfacial zone between the matrix and fiber, resulting in improved ductility of geopolymers (Shoji et al. 2022; Zhong and Zhang 2023). For example, Arisoy and Wu (Arisoy and Wu 2008) conducted a study on PVA fiber-reinforced lightweight concrete, which exhibited remarkable toughness and enhanced flexural strength in comparison with lightweight concrete without fibers. Another study by Li and Du (2018) focused on developing a FA-geopolymer mortar with PVA fibers and reported enhanced flexural toughness by bridging cracks. Whereas, Tanyildizi and Yonar (2016) investigated the impact of high temperatures on the FA-geoplymer concrete with PVA fibers and found increased flexural and compressive strengths with the increase in the content of the fiber.

Lightweight aggregate concrete (LWAC) possesses higher porosity compared to conventional concrete,

Table 1 Properties of GGBS.

Compounds	SiO_2	CaO	Fe_2O_3	Al_2O_3	SO_3	MgO	TiO_2	Na_2O	K_2O	L.O.I
Content (%)	36.4	34.12	0.69	10.39	0.49	10.3	-	0.35	0.97	1.64

Table 2 Chemical compositions of the expanded glass

Item	SiO_2	CaO	Fe_2O_3	Al_2O_3	SO_3	MgO	TiO_2	Mn_2O_3	Na_2O	K_2O	L.O.I
Content %	72.95	4.35	0.09	0.41	0	0.89	0.03	0	18.74	0.2	2.33

primarily because of the inclusion of porous lightweight aggregates. The choice of suitable lightweight aggregates plays a vital role in the physical characteristics and durability of LWAC (Chung et al. 2021). The process of manufacturing expanded glass aggregate entails mixing suitable expansive agents with finely ground waste glass and subjecting it to elevated temperatures until it reaches a viscosity of less than 106.6 Pa, close to the softening point of glass. Glass products, with a relatively short lifespan, contribute to about 5% of municipal waste generated, with recycling rates varying across different regions (Harrison et al. 2020). Although recycling technologies have improved, not all glass can be recycled and ends up as non-recyclable waste. Researchers have found that the concrete industry provides a promising approach for this unrecyclable waste glass. Cleaning and crushing the waste glass and using a special production method with suitable expansive agents can transform it into effective lightweight expanded glass aggregate (Adhikary et al. 2021). Several research studies have investigated the incorporation of EG into lightweight aggregate concrete. These studies have found that the EG causes small expansion as a result of alkali-silica reaction (ASR) and does not show any significant effects like efflorescence. This behavior can be attributed to the porous structure of expanded glass, which provides sufficient room for the ASR products without causing noticeable issues (Adhikary and Rudzionis 2020; Carsana and Bertolini 2017).

Regarding elevated temperatures, Jiang et al. (2020b) conducted a study on the bonding between FA-geopolymer and steel at high temperatures. They found that the developed geopolymer exhibited superior performance in comparison with cement concrete, even when exposed to temperatures exceeding 800 °C. Additionally, Tanu and Unnikrishnan, (2023a) investigated the effect of elevated temperature on durability properties of geopolymer concrete developed with GGBS and sugarcane bagasse ash. Results indicated that geopolymer concrete could maintain up to 50% of its mechanical properties at a temperature of 600°C. Kanagaraj et al. (Kanagaraj et al. 2024, 2023a) investigated the effect of elevated temperature on the strength behaviour of binary blend high-strength geopolymer concrete (HSGC). Resulted indicated that HSGC specimens subjected to 1029 °C resulted in a considerable reduction in strength due to the formation of large cracks. On the other hand, Tayeh et al. (2021) compare the influence of high temperatures (100 °C to 800 °C) on lightweight ordinary concrete (LWOC) and lightweight GGBS-FA-geopolymer (LWGC) from expanded clay aggregate. LWGC with a combination of 50% GBSF and 50% FA demonstrates the most favourable compressive strength results. Interestingly, the behavior of LWGC appears similar to LWOC across all variables examined in this study. Additionally, Abdulkareem et al. (2014) investigated the effect of artificial lightweight aggregates in geopolymer mortars subjected to high temperatures. The authors reported improved durability and mechanical characteristics due to the minimal thermal conductivity of the aggregates.

According to the above, limited research was conducted on investigating the effect of expanded lightweight aggregate and PVA fibers on the mechanical properties of lightweight geopolymer mortar at elevated temperatures. Therefore, the novelty of this research is to investigate the combined effect of using lightweight expanded glass aggregate and PVA fibers on the mechanical characteristics of LWGM under elevated temperatures.

2 Methodology

2.1 Materials

The study focused on producing lightweight geopolymer mortars using GGBS. The properties of GGBS are presented in Table 1. Local natural river sand was used, along with artificial fly ash aggregates manufactured through a cold bonding process. The used river sand has a specific gravity of 2.68, bulk density of 1840 kg/m^3, and water absorption of 0.58%. Expanded glass granules that are made from recycled glass residues were used as lightweight aggregates. The used expanded glass has a specific gravity of 0.55, bulk density of 340 kg/m^3, and water absorption of 25%. Table 2 shows the chemical compositions of the expanded glass. As can be seen from Table 2, the EG has high SiO_2 content (72.95%). It is expected that the high SiO_2 content of the EG could significantly increase reactivity and contribute to the formation of a more robust geopolymer network (Davidovits 1994, 2020). (For activating the geopolymerization process, a mixture of sodium silicate and sodium hydroxide

Table 3 Properties of superplasticizer (SP).

Structure of material	Name	Density	Color	Chloride content (%)	Alkali (%)
Poly-carboxylic Ether Based	Master Glenium RMC 303	(1.023 to 1.063) kg/lt	Light Green	< 0.10	< 3.00

was utilized. The sodium silicate solution employed had a mass chemical composition of 14.7% sodium oxide, 29.4% silicon dioxide, and 55.99% water. Additionally, all mixes incorporated superplasticizer to achieve the desired workability. The properties of the superplasticizer are in Table 3. Further, a volume fraction of 1% of PVA fibers was used in some samples as per (Kadhim et al. 2022; Li et al. 2002). The characteristics of the utilized PVA fiber are shown in Table 4. Particle size distribution of river sand and EG are presented in Fig. 1.

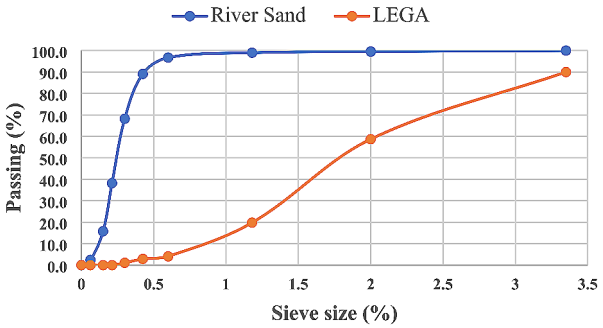

Fig. 1 Particle size distribution graph of river sand and EG.

2.2 Sample Preparations

The study involved the preparation of three GGBS-lightweight geopolymer mortars (LGPM). Table 5 shows the LWGM mixture proportions. The naming convention of LWGM mixes was based on the level of lightweight expanded glass aggregate replacement. In other words, 10% expanded glass (EG) and 20%EG represented the replacement level of 10% and 20% without the inclusion of fibers, respectively while 20%EG-1%PVA represented a mix with 20% replacement by EG and a 1% PVA fibers. Multiple LWGM trials were prepared and tested, and the samples with optimal cohesiveness and workability were chosen for further detailed analysis.

To create the alkaline solution, a solution of 12 M NaOH flakes with water was prepared at ambient temperature. This alkaline solution was then mixed with Na_2SiO_3 solution using a 2.5 ratio of sodium silicate/sodium hydroxide. The prepared activator was left for 24 h in plastic containers to dissipate heat prior to usage. All LWGM mixes were formulated with GGBS, activator, and expanded aggregates at ratios of 1:3 binder/aggregates, and 0.8 activator to GGBS. The volume fraction of the 1% PVA fiber was chosen for economic reasons and according to exiting literature (Kadhim et al. 2022; Li et al. 2002). The mixing process involved gradually adding the alkali activator solution to the dry ingredients, followed by the addition of water and superplasticizer for proper workability. Additional water was used to enhance workability and geopolymerization, but its quantity was limited to prevent a reduction in mechanical characteristics. The fiber samples were prepared by a slow addition of the fiber to ensure uniform dispersion. Mixtures were cast into two layers in oiled moulds and the compaction was carried out using a table vibrator for removing air voids. Following curing for 24 h, the mixtures were demoulded. Then, the mixtures were cured at ambient temperature after storing in plastic bags, since GGBS-geopolymer can be utilized in structural elements with no need for water or high-temperature curing (Niş and Altındal 2021).

2.3 Experimental Tests

The workability of prepared mortars was assessed using a flow table test, following the ASTM C1437 (ASTM C1437-13 2013). Fresh density measurements were taken immediately after the mixing process, while hardened density measurements were recorded just before conducting compressive strength tests. According to ASTM C 138– 01a (ASTM C 138– 01a 2017), a fresh density test for geopolymer mortar was performed. To determine the compressive strength, three cubes with sides measuring 70 mm were subjected to tests, and the average value was computed.

Table 4 Properties of PVA fibers

Property	Length (mm)	Diameter (μ_m)	Density (g/ cm^3)	Nominal strength (MPa)	l/d ratio	Young's modulus (GPa)	Elongation (%)
Value	12	39	1.3	1600	308	41	6

Table 5 Geopolymer lightweight mortar mix designs

Mixture ID	Binder	Aggregates		SP (kg)	Na_2SiO_3/ NaOH	Total Solution (kg)	Extra Water (kg)
	Slag (kg)	Sand (kg)	EG (kg)				
10%EG	15	40.5	4.5	1.12	2.5	10	2.5
20%EG	7.5	18	4.5	0.860	2.5	6	1
20%EG -1%PVA	15	36	9	2.25267	2.5	12	2

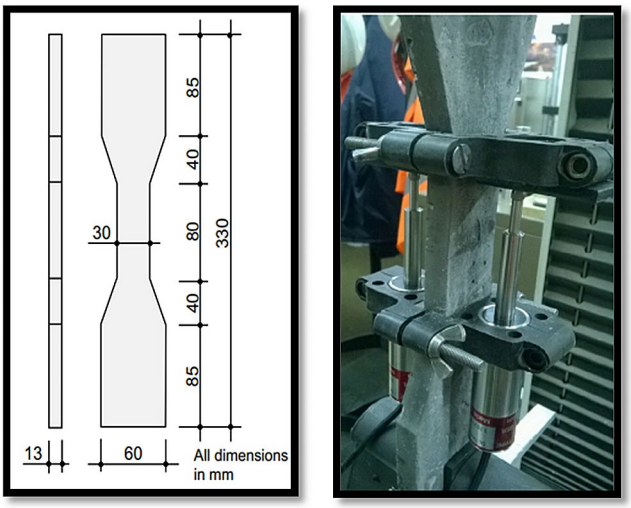

Fig. 2 Test dimensions for dog-bone tensile and Dog-bone Test Setup (Pourfalah 2018)

Table 6 The number of specimens were cast and tested for each mixture

Test	Number of specimens cast and tested
Density	3
Compressive Strength	3
Cylinder Samples for Stress-Strain Relationship	3
Flexural Behavior (Prisms)	3
Flexural Behavior (beams)	3
Uniaxial Tensile Strength	3

Moreover, three cylindrical specimens with a diameter of 100 mm and a height of 200 mm were utilized for displacement-controlled compressive strength tests. A universal testing machine was employed with a testing rate of 0.5 mm/min. Before conducting the tests, a sulphur capping procedure was implemented to ensure uniform surfaces for each sample. Following a 28-day curing period, flexural testing was conducted on prism and beam samples measuring 160 mm × 40 mm × 40 mm and 350 mm × 75 mm × 45 mm, respectively. The three-point bending experiments were performed at a 0.3 mm/min constant rate until failure. Linear variable displacement transducers were used for measuring the central displacement and recording the loads vs. displacements. To assess the uniaxial tensile characteristics of LWGM samples, dog-bone-shaped specimens were employed (as depicted in Fig. 2), with the majority of cracks developing in the narrower 80 mm section located in the middle of the specimen. Quasistatic uniaxial tension loads were applied to the specimens until failure, and the resulting stress-strain curves were recorded and analysed throughout the tests. Table 6 presents the number of specimens cast and tested for each mixture for each test.

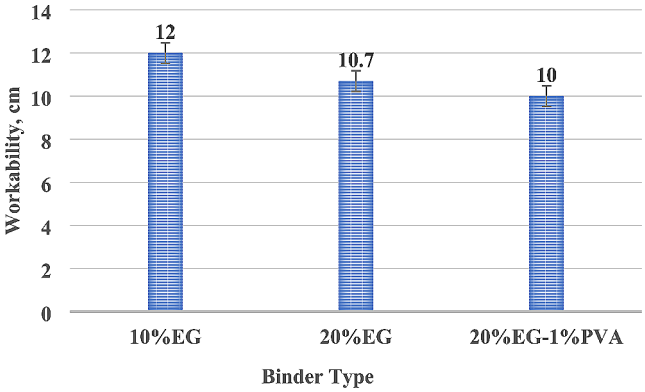

Fig. 3 Results of workability test

2.4 Impact of High Temperatures

To study the impact of high temperatures, a set of specimens, both with and without PVA fibers, were subjected to temperatures of 250 °C and 500 °C. The mixtures were heated gradually in an oven at a rate of 25 °C per minute until reaching the desired temperature. They were then maintained at each elevated temperature for 30 min. Subsequently, the samples were cooled gradually inside the oven until they reached room temperature to avoid thermal shock. In order to facilitate comparison, tests were conducted on the mixtures both before and after subjecting to the high temperatures.

3 Results and Discussions

3.1 Workability

The flow rate results are shown in Fig. 3. It is observed that the workability of the 10%EG, with a flow rate of 120 mm, is higher compared to the 20%EG mix, which has a rate of 107 mm. Lightweight aggregates have a rougher surface texture compared to traditional aggregates. This increased roughness can lead to greater friction between particles, as the proportion of lightweight aggregates in the mixture increases. Moreover, when compared to normal-weight aggregates, lightweight aggregates usually have higher porosity and absorption capacity. This implies that they have a greater capacity to absorb water from the combination, which lowers the amount of free water available to lubricate the mixture and makes it stiffer and less workable (Adhikary et al. 2021). The flow rate of the 20%EG -1%PVA mix is measured at 100 mm. The study findings indicate that the addition of PVA fibers to cementitious composites reduces the workability. The incorporation of PVA fibers in lightweight geopolymer mortar improves the cohesiveness of the mortar, as the large surface area of PVA fibers allows

them to adhere to aggregates. The presence of fibers creates a more interconnected network within the matrix, which can restrict the movement of the cement particles and reduce the fluidity of the mixture. Similar results were reported in a previous investigation (Bhogayata and Arora 2019). Additionally, it is noteworthy that the LWGM mixes, with or without fibers, did not exhibit any segregation or bleeding. Generally, lightweight aggregates with rounded particles have a low tendency to bleed. This is mostly because lightweight aggregates have excellent absorption capacity, enhanced cohesiveness, homogenous mixture, and internal curing qualities. Together, these elements preserve a consistent, stable mixture and avoid the problems that are frequently linked to traditional concrete mixes (Bui 2012).

3.2 Density

The findings presented in Fig. 4 illustrate the results obtained for GGBS-geopolymer mortar. The fresh density of the mortar was assessed after mixing. For all mixtures and in comparison with fresh mixture, it was observed that the density gradually decreases over time until 28 days, primarily due to evaporation. Comparing the 10%EG and the 20%EG, the fresh unit weight of the former was 2.02 g/cm^3, higher than the latter, which measured 1.734 g/cm^3. The 20% EG specimen exhibited a fresh density that was 14.16% lower than that of the 10% EG specimen. The decrease in density as the proportion of lightweight aggregates increases is primarily due to the lower specific gravity of lightweight aggregates compared to normal-weight aggregates. Furthermore, as the age of the LWGM increased from 1 to 28 days, there was a slight decrease in dry density values. When comparing the 20% EG sample's dry density to that of the 1-day sample, a 3.22% drop was observed at 28 days. Consequently, the fresh unit weight% increases as the percentage of lightweight aggregates in the mixture decreases, leading to a reduction in the overall mixture weight. Additionally, as the volume of sand replaced by lightweight aggregates increases, the density of the mixtures decreases. This reduction in density occurs due to the physical properties of lightweight aggregates, which mainly are lower specific gravity, high porosity, reduced bulk density, and higher water absorption. Furthermore, the use of fibers increases the unit weight% at the same percentage of lightweight aggregates in the mixture. Fibers can reduce the spaces between particles in the matrix and make it more linked, which raises the mix's overall density. The enhanced packaging may increase the composite's unit weight (Jan et al. 2024). Hence, the weight of the mixture is directly proportional to the unit weight of GGBS-geopolymer mortar.

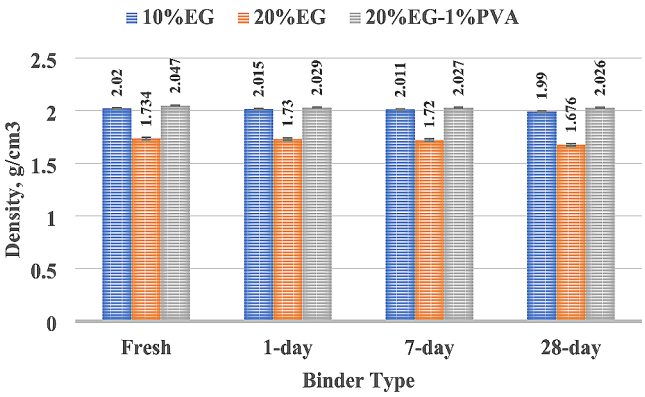

Fig. 4 Results of density test

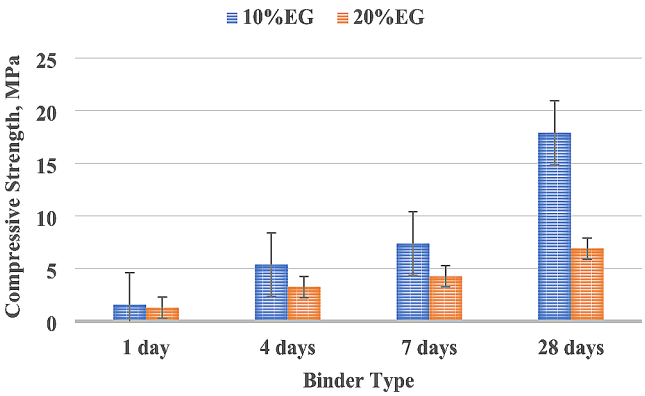

Fig. 5 Results of compressive strength of cube specimens

3.3 Compressive Strength

Figure 5 displays the compressive strengths of geopolymer mortars at various curing ages with varying levels of EG replacement. In general, longer curing times tend to increase compressive strengths. However, as the level of aggregate replacement with EG increases, there is a gradual reduction in strength. Mortars with longer curing times and low levels of EG replacement exhibit the highest compressive strengths. For instance, the 28-day compressive strength of geopolymer mortar with 10% EG was 17.9 MPa, while the mortar with 20% EG was only 6.9 MPa, indicating a 61.45% drop in strength. This reduction was due to the EG lower crushing resistance compared to sand. This is also because EG has different mechanical properties and a lower density than typical aggregates, which might lead to a composite material that is weaker overall. When more sand is replaced by EG, the strength growth slows after 7 days due to EG water absorption, resulting in a porous microstructure and decreased compressive strength. These findings align with previous research (Mermerdaş et al. 2020; Nematollahi et al. 2017). Furthermore, the addition of PVA fibers (1%) in geopolymer specimens enhanced the compressive strength at 28 days, as depicted in Fig. 6. The presence of fibers

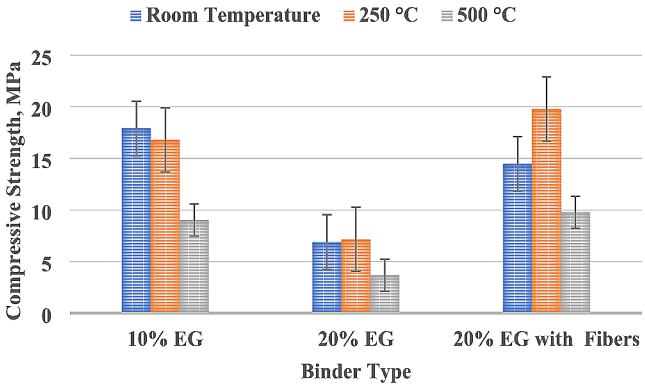

Fig. 6 Results of compressive strength of cube specimens post and pre-exposure to high temperatures

limited fracture growth and prevent crack propagation as a result of the fibers' bridging impact, providing in enhanced compressive strength. Better load distribution inside the specimen as a result of this enhanced crack resistance may raise the compressive strength. PVA fibers have the potential to improve the geopolymer matrix's microstructure. PVA fibers can create a denser and more homogeneous matrix by bridging microcracks and reducing the size and connectivity of pores, which increases the matrix's compressive strength (Ahmad et al. 2021; Rashidi et al. 2024).

Figure 6 also illustrates the impact of high temperatures on the compressive strengths of geopolymer mortars. The figure compares the compressive strengths of geopolymer mortars cured at room temperature and at various temperatures. Both 10% and 20% EG samples show their highest compressive strengths at room temperature, with a reduction in compressive strength is observed as the temperature continues to rise apart from 20% EG at 250 °C. Specifically, the compressive strength of the 10% EG samples at room temperature was 6.26% and 49.61% higher than the same samples at 250 °C and 500 °C, respectively. However, the compressive strength values for samples with 20% EG at 250 °C were higher than the strengths observed after exposure to room temperature and 500 °C. The compressive strength of the 20% EG samples at 250 °C was 3.63% and 48.6% higher than the same samples at room temperature and 500 °C, respectively. The decrease in strength at 500 °C was caused by water vaporization from the matrix of mortars which led to substantial thermal shrinkage. As the temperature increased, water converted into vapor, leading to increased vapor pressure. With the highest vapor pressure, the matrix having lower permeability was unable to endure the thermal stresses, leading to severe thermal cracks and reduced strength. Chemically bonded water begins to evaporate as the temperature rises. This involves dehydrating calcium silicate hydrates (C-S-H), which are essential to the mortar's strength. The cohesive forces inside the matrix are reduced as a result of this water loss, which lowers the compressive strength. The dissimilarity in thermal expansion between the aggregates and the matrix also played a role in the strength deterioration (Abdulkareem et al. 2014). This is similar to the finding by (Ameri et al. 2019).

The greatest compressive strength percentage for 20% EG sample was 7.16 MPa at 250 °C. At room temperature and 500 °C, the compressive strength reduced to 3.63% and 48.6%, respectively. The strength improvement observed at 250 °C can be attributed to several factors, including the evaporation of free water, sintering processes, enhanced bonding, and increased overall strength. This implies that a 20% EG sample heated to a moderate temperature of 250 °C can marginally increase its compressive strength. This is probably because the matrix is strengthened by the continuing curing process, the removal of excess moisture, and better pore structure modification.

When 1% PVA fibers were added to 20% EG samples, the greatest compressive strength percentage was 19.79 MPa at 250 °C. At room temperature and 500 °C, the compressive strength reduced to 23.89% and 50.63%, respectively. The enhanced strength observed at 250 °C in the 20% EG-1% PVA sample can be attributed to additional geopolymerization, which strengthens the bonding between the fibers and the matrix (Chandrakanth and Koniki 2020). The addition of PVA fibers helped prevent cracking in mortar even after exposure to 250 °C. The fibers aided in cementing the aggregate particles together after melting, explaining their role in preventing cracking at higher temperatures. However, at 500 °C, the strength of all samples declined. The geopolymer matrix may undergo chemical alterations at high temperatures, which could result in some loss of bonding between the matrix and the PVA fibers. This bonding loss may lead to less load transfer between the fibers and matrix, which would weaken the material's compressive strength (Jan et al. 2022a). However, the lightweight geopolymer mortar with PVA fibers experienced a lower rate of loss in strength in comparison with samples without fibers as illustrated in Fig. 7, indicating that PVA fibers exhibit higher mechanical strength and are more resistant to spalling at high temperatures (Malik et al. 2019).

3.4 Cylinder Samples for Stress-Strain Relationship

Figure 8 shows the stress-strain curves of cylindrical samples at various temperatures. These curves generally show three distinct areas: the first and second areas represent the elastic and plastic deformations, respectively, and the third area is a subsequent reduction in load after peak load. Temperature has a significant impact on the stress-strain behavior of cylindrical geopolymer mortar samples, both with and without PVA fibers. PVA fibers improve ductility and

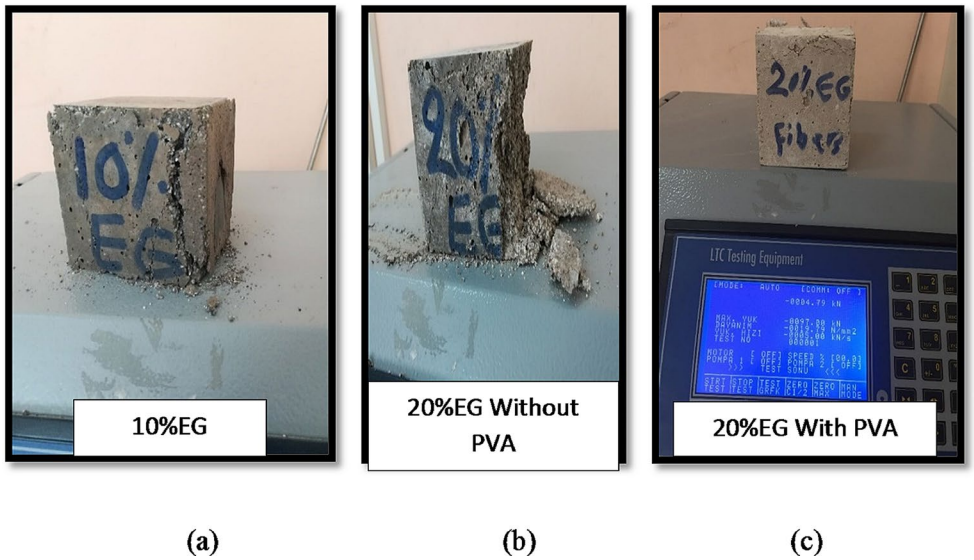

Fig. 7 Failure characteristics of samples after subjected to 250 °C. (**a**) 10%EG; (**b**) 20%EG; (**c**) 20%EG-1%PVA.

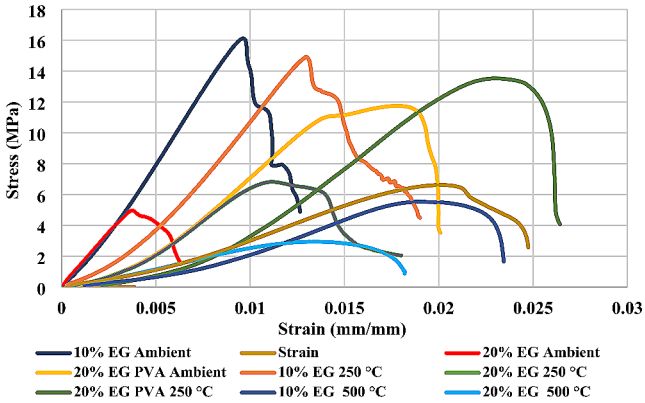

Fig. 8 Cylinder samples' stress-strain curves at different temperatures

postpone failure in geopolymer mortars, which show a linear elastic zone and peak stress at room temperature. The peak stress lowers and the mortars show more noticeable plastic behavior as temperatures rise to 500 °C. In comparison to other samples, the specimen with 10% EG demonstrated the greatest peak load at room temperature. However, the PVA sample displayed the maximum compressive strain in comparison with the fiber-free sample. Even after reaching peak strength, the fiber-reinforced samples continued to deform and sustain a high load, indicating steady-state cracking. Fibers prevented sudden and brittle failure by bridging the cracks (Kan et al. 2020).

After exposure to 250 °C, all specimens, except the 10% EG sample, exhibited increased compressive stress compared to room temperature. This increase in performance is due to the removal of excess water through evaporation and the subsequent process of geopolymerization, which results in a more compact matrix (Zhong and Zhang 2023). Similar to the ambient temperature condition, the 10% EG sample displayed the highest compressive stress. Furthermore, when the temperature was raised to 500 °C, all samples demonstrated a lower rate of compressive stress compared to ambient temperature and 250 °C. This decrease is due to the expansion of water vapor, which results in increased pressure within the geopolymer mortar, leading to cracking and material weakening. The specimens reinforced with fibers also exhibited the highest compressive strain. However, when exposed to a temperature of 500 °C, the PVA fiber-reinforced samples no longer showed a ductile failure mode as a result of the physical transformations that occurred in the fibers as a result of the high temperatures (Masi et al. 2015). Figure 9 illustrates the fracture or failure patterns of the cylindrical samples. Mortars without fibers exhibited significant cracking and spalling, characterized by extensive crack networks and material loss due to the brittle nature of the material. On the other hand, samples that have fibers exhibit minimal degradation, as the fibers limit the spread of cracks and reduce spalling. Fibers improve surface stability and create finer crack patterns, which increase the overall toughness and structural integrity of the mortar by minimizing damage (Jan et al. 2024). At both room temperature and 250 °C, the PVA fibers demonstrated effective crack resistance and preserved the structural integrity of the specimens. However, when exposed to 500 °C, spalling is observed, specifically above the range of 250–300 °C. This suggests that, even in the presence of fibers, the material's integrity begins to deteriorate at higher temperatures, resulting in surface layer separation and increasing material loss (Jan et al. 2022a).

Fig. 9 Cylinder sample failure patterns at various temperatures

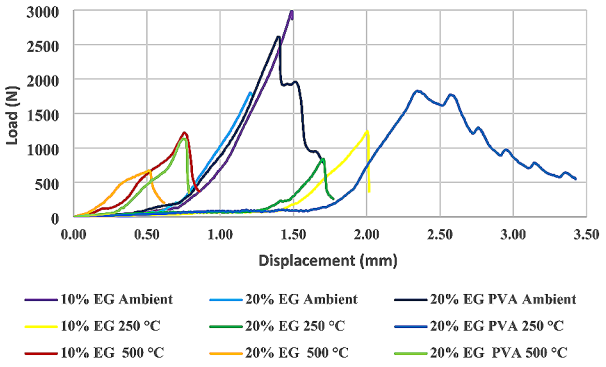

Fig. 10 Prism sample load-displacement curves at various temperatures

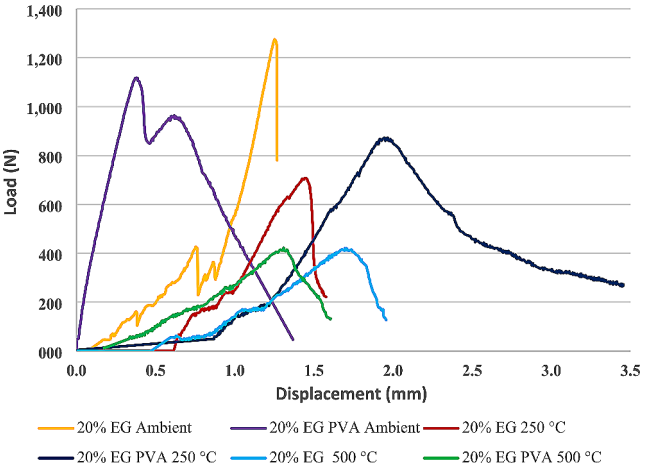

Fig. 11 Beams sample load-displacement curves at various temperatures

3.5 Flexural Behavior

3.5.1 Curves of Load–Displacement (Prism)

Figure 10 illustrates the load-displacement curves at varying temperatures. With the increase in the EG replacement in the geopolymer mortar, the load-bearing capacity and displacement decreased. The 10% EG sample exhibited the highest load of 3002 N with a displacement of 1.49 mm. Whereas, the sample consisting of 20% EG exhibited the highest load and displacement of 1816 N and 1.22 mm, respectively. The decrease in performance was due to the high brittleness and low toughness of the lightweight aggregate particles. On the other hand, the mixtures incorporating PVA fibers demonstrated ductile behavior, with a higher maximum displacement. The addition of PVA fibers had a direct positive impact on the flexural performance of lightweight geopolymer mortar. This improvement can be attributed to the high tensile strength of the fibers and their ability to bridge cracks, which is likely facilitated by their attachment to the matrix of geopolymer (Masi et al. 2015). The presence of fibers also shifted the failure from brittle to ductile behavior, as indicated by an increased area under the load-displacement curve. The ductility enhancement was evident in the change of failure mode, with samples without fibers splitting into two pieces after reaching peak load, while the PVA fiber sample exhibited ductile failure with only one fracture occurring. Exposure to a temperature of 250 °C caused in a decrease in load-carrying capacity for all samples. In comparison to room temperature, the ultimate flexural load of the 10% EG, 20% EG, and 20% EG – 1% PVA samples decreased by 51.53%, 53.36%, and 38.63% respectively. The ductility of the samples was also reduced at this temperature, except for the 20%-1% PVA sample, which displayed deflection softening and retained its ductility as a result of the presence of fibers. At temperatures exceeding 250 °C, thermal cracks formed between the geopolymer matrix and aggregates, leading to a significant loss in load-bearing capacity. Exposure to 500 °C resulted in a sudden decrease in the maximum load and reduced ductility. The PVA samples exhibited brittle behavior at higher temperatures, attributed to a loss in PVA fiber bridging capacity caused by decreased fiber modulus of elasticity and weakened chemical connection between the geopolymer matrix and PVA fibers (Pourfalah 2018).

3.5.2 Curves of Load–Displacement (Beams)

Figure 11 shows the load-displacement relationship of beam samples at various temperatures. The behavior of these curves varied depending on the temperature. At room temperature, the PVA geopolymer samples demonstrated enhanced displacement capacity. The stress-strain curve exhibited noticeable first and second peak loads, indicating distinct points of significant resistance. The initial peak in the stress-strain curve signifies the point where cracking stress onsets, while the second peak demonstrates the capacity of PVA fibers to endure higher loads even after the initial fracture. The diagram indicated that the fiber-reinforced beam exhibited a displacement measurement of 1.4 mm at peak load, while the non-fiber-reinforced beam had a displacement of 1.27 mm. The load-displacement curves after subjected to high temperatures revealed that the displacement values increased with rising temperatures. Additionally, the influence of specimen size on flexural behavior became more pronounced with the increase in temperature (Abdulhaleem et al. 2018). Exposure to 250 °C generally led to a decrease in the load-carrying capacity of the samples, as observed in prisms. All samples experienced a drop in maximum load when exposed to this temperature, with the ultimate flexural load of the 20% EG sample and 20% EG – 1% PVA sample reduced by 44.54% and 22.05% respectively compared to ambient temperature. The samples

also exhibited decreased ductility at this temperature, except for the 20% PVA sample, which displayed deflection softening and retained its ductility due to the presence of PVA fibers. Exposure to 500 °C caused a significant decrease in the maximum load of the specimens. Moreover, the samples became less ductile at this temperature, with the PVA samples showing signs of brittleness. This indicates that the ductile characteristic of the fibers mortars transitions to a brittle state when subjected to elevated temperatures.

3.6 Uniaxial Tensile Strength

The tensile behavior of the lightweight geopolymer mixture incorporating PVA fiber was examined using dog-bone-shaped samples. It is important to mention that samples without fibers were brittle and fractured during the demolding process. Figure 12 shows the relationship between the stress and strain for all samples at various levels of temperatures. The samples underwent uniaxial tensile testing, utilizing load, displacement, and sample dimensions to construct a stress-strain curve. The shift in curves with temperature exhibited a clear pattern. At room temperature, the 20% EG with PVA fiber demonstrated an ultimate tensile strength of 2.62 MPa and a tensile strain capacity of 1.13%. However, heating the sample resulted in a decrease in these properties. When the temperature was increased to 250 °C, the tensile strength decreased by 69.84% compared to room temperature, and the tensile strain capacity also significantly dropped by 46.9%. Additionally, with increasing temperature, the tensile strength further decreased. At 500 °C, the tensile strength was reduced by 72.9% compared to room temperature. These changes in mechanical properties followed a predictable pattern in the stress-strain curves. At room temperature, the 20% EG with PVA fiber exhibited an ultimate tensile strength of 1.82 MPa and a tensile strain capacity of 2.13%. Nevertheless, the heated sample showed a lower tensile strength than the unheated sample. This reduction was due to structural changes of fibers at

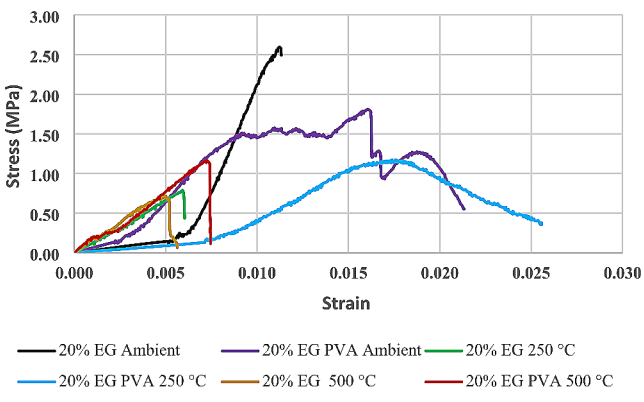

Fig. 12 Dog-bone specimens at varied temperature stress-straining tensile curves

elevated temperatures of around 225 °C, as indicated by Liu and Tan (Liu and Tan 2017). At 250 °C, the tensile strength was 35.71% less than at room temperature, while the tensile strain capacity notably increased by 16.8%. The general trend of decreasing tensile strength with increasing temperature followed the findings of Bhat et al. (Bhat et al. 2014). Heated samples at 500 °C resulted in a similar reduction in tensile strength compared to room temperature by about of 16.8% as a results of fibers melting, which led to void formation and shrinkage-induced fractures (Zhang et al. 2021). It should be noted that the tensile strain capacity of the material slightly decreased after exposure to 500 °C due to a decrease in tension stiffness caused by different degrees of heat breakdown in the 20% EG with PVA fiber mixture (Liu and Tan 2017).

4 Conclusions

The main findings from this experimental study are as follows:

1. Increasing the EG replacement amount reduces the workability of LWGM, as revealed by recent LWGM test findings. The addition of PVA fibers also decreases LWGM's workability.
2. Geopolymer mortar's fresh and dry density decreases with rising EG concentration due to its low density. However, adding PVA fibers increases LWGM's density, classifying all mixes as lightweight according to ACI committee 213R.
3. Replacing river sand with EG reduces the compressive strength of geopolymer mortar at 1, 7, and 28 days due to the porous nature of EG particles. However, adding fibers significantly increases the compressive strength, and the mix with 10% EG achieves a maximum strength of 17.9 MPa after 28 days.
4. Mechanical behavior of LWGM (with and without fibers) changes at high temperatures. The 10% EG samples outperform others at 250 °C and 500 °C in terms of compressive strength, but 20% EG and 20% EG-PVA samples show increased strength at 250 °C due to additional geopolymerization. At 500 °C, strength starts to degrade as a result of the difference in thermal expansion between geopolymer matrix and aggregates.
5. The presence of fibers in geopolymer mortar allows it to deform and maintain a load after reaching maximum load, improving strain capacity. Flexural behavior improves significantly with PVA fibers.
6. At 250 °C, all samples show decreased load-carrying capacity and increased displacement compared to room

temperature, and the maximum load drops rapidly at 500 °C, reducing ductility.
7. Reinforced mixes with PVA fibers exhibit reduced tensile strength and strain capacity at 250 °C and 500 °C due to the low melting point of fibers.
8. EG proves suitable for lightweight geopolymer mortar, and the addition of PVA fibers enhances flexural and tensile behavior.

The utilization of EG and fibers in geopolymer mortars results in improved compressive strength and decreased degradation at room and moderate temperatures, which makes them appropriate for application in areas or sectors that are periodically exposed to moderately high temperatures. Nonetheless, the fact that spalling occurs beyond 300 °C even in samples containing EG aggregates emphasizes the limits of long-term high-temperature durability. Therefore, even though these materials are appropriate for construction that is fire-resistant or for businesses that produce a modest amount of heat, further safety precautions could be required for structural applications in settings that consistently experience high temperatures. However, geopolymer mortars with expanded glass aggregates fare better and last longer than traditional materials in areas subject to severe weather. It is advised to conduct more study to improve these materials' performance at high temperatures, either by creating more composite reinforcements or sophisticated formulations.

Author Contributions Ahmad Al Mohammad: Conceptualization, Methodology, Investigation. Abdulkadir ÇEVİK: Supervision, Methodology, Investigation. Zahraa Jwaida: Data curation, Writing- Original draft preparation. Ali Shubbar: Writing- Original draft preparation, Methodology. All authors reviewed the manuscript.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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