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# EFFECTS OF LECA CONTENT ON THE BEHAVIOR OF STEEL FIBER-REINFORCED GEOPOLYMER CONCRETE AT HIGH TEMPERATURE

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**Abstract**

This paper examines how steel fiber and the amount of lightweight expanded clay aggregate (LECA) affect the mechanical and microstructural properties of geopolymer concrete (GPC) made from fly ash after being heated. LECA has been used with different contents (0, 10, and 20%) as a partial replacement by weight of coarse aggregate. Steel fiber has been employed in GPC with volume fractions of 0 and 1%. A slump test was applied to examine the workability of fresh concrete. Compressive strength, splitting tensile strength, flexural strength, and elastic modulus tests also measured the mechanical properties. Furthermore, the microstructure characterization was also carried out by performing scanning electron microscopy (SEM). The findings suggest that including steel fiber and raising the LECA content in the mixture enhanced the strength's retention following high-temperature exposure. After being exposed to a constant temperature of 800°C, GPC containing steel fiber and 20% LECA achieved the best result compared to the plain GPC in terms of decrease in mass, residual compressive and tensile strengths, residual flexural strength, and residual amount of elastic modulus: 6.04 and 4.39%; 27.08 and 39.27%; 37.6 and 47.02%; 16.07 and 30.3, and 2.17 and 6.19%, respectively.

**Keywords:**

Geopolymer concrete;
Steel fiber;
LECA;
High temperature;
Residual strength.

## 1 Introduction

There has been a notable increase in building activities worldwide to meet the escalating demands for infrastructure. Ordinary Portland cement concrete (OPC) is often considered the primary material in many construction projects. The production of regular Portland cement involves using fuel and converting raw materials, resulting in the significant emission of carbon dioxide into the environment. Based on a study, the manufacture of one ton of cement results in the emission of one ton of carbon dioxide into the atmosphere. [1]. According to estimations, there is a projected growth of 50% in the yearly production of Portland cement (PC) from 2017 to 2050. The significant growth in the demand for PC as a critical component in concrete production is anticipated to significantly increase carbon dioxide ($CO_2$) emissions into the atmosphere. It is projected that the manufacture of PC may release around 85 to 105 gigatons of $CO_2$ emissions into the atmosphere during the next 33 years [2] and [3]. In addition to the high emission linked with PC production, about 2 to 3% of the worldwide energy demand is also consumed [2] and [4].

Researchers and environmentalists need help identifying a viable substitute for conventional OPC concrete and effectively handling or disposing of the resulting industrial waste. Hence, it is essential to identify optimal strategies for efficiently utilizing industrial outputs and wastes to mitigate the adverse impacts of land and air pollution. One potential option is using alkali-activated cement or geopolymer concrete (GPC). This type of concrete is created by alkali activation, which involves utilizing various byproducts and waste materials, such as fly ash, slag, rice husk ash (RHA), and waste ceramic materials. [5] and [6]. GP concrete is considered the upcoming generation of concrete due to its sustainability advantages. It presents a unique approach that eliminates using Portland cement (PC) as a binder in concrete production.

Consequently, this leads to a significant decrease in carbon dioxide ($CO_2$) emissions. [7] and [8]. In addition to the sustainability benefits of GP concrete [9] and [10], the use of GP concrete also opens a pathway to effectively manage wastes that could have an adverse effect on health, safety, and the environment. GPC, despite its environmental and technical benefits, has limitations in ductility, making it less suitable for extensive structural applications in the building sector [11 - 13].

As the investigation advanced, academics discovered that geopolymer concrete exhibits several drawbacks similar to conventional concrete, including elevated brittleness, inadequate toughness, and limited fracture resistance [14] and [15]. Cracks in geopolymer concrete are frequently observed due to prolonged exposure to the external environment [16].

Numerous research [17] and [18] have focused on investigating the impact of different fiber types on the mechanical characteristics of geopolymer concrete in recent times. As reported by [19] and [20], the findings of the study indicate that the incorporation of fibers in geopolymer concrete may significantly mitigate fracture formation and propagation while enhancing its brittleness, crack resistance, flexural strength, and toughness.

Concrete is frequently subjected to high temperatures in many conditions, such as exposure to fire, thermal processes, furnaces, and nuclear environments. It is crucial to know the performance of concrete and structural parts when subjected to high temperatures in situations like these [21]. While a considerable body of research exists on the performance of OPC concrete at ambient temperatures [22], there needs to be more knowledge on the behaviour of geopolymer concrete following exposure to extreme temperatures.

Moreover, the mechanical properties of steel fiber-reinforced geopolymer concrete (SFGPC) were investigated after high-temperature exposure (at 800 °C). The findings suggested that the addition of 1% steel fiber in SFGPC improved compressive strength, splitting tensile strength, peak strain, and toughness index. A constitutive model of SFGPC under uniaxial compression at high temperatures was developed [23].

LECA is a shortened form of the term lightweight expanded clay aggregate. The product is made of a porous ceramic material with a consistent pore structure composed of tiny, sealed cells and a strong, dense outer layer. The LECA grains possess a complex cellular structure with many air-filled spaces, offering thermal and acoustic properties. Expanded clay aggregates are utilized in many sectors because of their technical features and numerous advantages compared to other industrial raw materials. LECA was used to enhance the qualities of the concrete mixture due to its excellent insulating characteristics [24].

LECA has been enhanced to serve as a substantial substitute, either partially or entirely, for conventional aggregate in the building of various structural components. These components are exposed to different types of loads (static or dynamic) and various sorts of disasters, such as fire. This improvement has been documented in studies [25].

The objective of this study is to examine the impact of incorporating steel fibers and different proportions (0%, 10%, and 20%) of LECA on the performance of concrete subjected to varying levels of high-temperature exposure (200°C, 400°C, 600°C, and 800°C). The residual mechanical characteristics of the concrete—modulus of elasticity, compressive strength, tensile strength, flexural strength, and degree of mass reduction—are considered in evaluating the behaviour.

## 2 Materials used in the study

### 2.1 Fly ash

In the present study, fly ash has been used as a primary source of aluminosilicate material to produce geopolymer concrete. Fly ash was supplied from the local market. It was obtained in airtight plastic bags to avoid exposure to atmospheric conditions, with 25 kg in one sack. The provided fly ash was delivered in a single batch in order to mitigate variations in characteristics. The chemical analysis and physical properties of fly ash are presented in Table 1 and 2 respectively. The test results of the fly ash comply with the ASTM C618-19 [26] fly ash class F requirements.

Table 1: The chemical analysis of fly ash used.

| Oxides | Weight [%] | ASTM C618-19 class F requirements [26] |
|---|---|---|
| $SiO_2$ | 50.77 | $SiO_2$+ $Al_2O_3$+$Fe_2O_3$%= 85.58 >50 |
| $Al_2O_3$ | 30.79 | |
| $Fe_2O_3$ | 4.02 | |

| | | |
|---|---|---|
| CaO | 9.39 | ≤ 18% |
| MgO | 2.02 | – |
| $Na_2O$ | 1.3 | – |
| $K_2O$ | 1.7 | – |
| $SO_3$ | 1.18 | < 5% |
| L.O.I. | 1.82 | < 6% |

Table 2: Physical properties of fly ash used.

| Property | Value | ASTM C618-19 class F requirements [26] |
|---|---|---|
| SAI, 7 days, % of control | 99.1 | > 75 |
| Fineness-amount retained on 45 μm sieve % | 25.5 | < 34 |
| Form and color | Grey powder | |

## 2.2 Alkali activator solution

The hydroxide of sodium and silicate of sodium has been used as the activator to initiate the geopolymer source. The activator solution utilized in this study was procured from a commercially available source of hydroxide of sodium flakes with a purity level of 98%. Additionally, a water-based solution of sodium silicate was employed. (32.5% $SiO_2$, 13.4% $Na_2O$ and 51% $H_2O$) and distilled water. The ratio of sodium base to water glass was 1:2. The initial stage in the production of the alkali activator involves the preparation of the sodium hydroxide (NaOH) solution, which is achieved by dissolving NaOH flakes in distilled water according to the specified molarity concentration outlined in Table 3. The solution was adequately mixed and given sufficient time to reach a stable concentration and temperature before being combined with the solids of the combination, with a duration of 24 hours

Table 3: Amount of NaOH solid for 1 kg of solution at specified molarity [27].

| Molarity [mole/L] | NaOH weight concentration [gm] | Weight of water [gm] |
|---|---|---|
| 8 | 262 | 738 |
| 10 | 314 | 686 |
| 12 | 362 | 638 |
| 14 | 404 | 596 |
| 16 | 440 | 560 |

## 2.3 Fine aggregate

All samples were cast using natural sand with a maximum size of 4.75 mm. The test findings are shown in Tables 4 and 5 based on the requirements outlined in Iraqi Specification No. 45/1984 [28]. The sand used is classified as Zone 2 according to the outcomes of the sieve analysis.

Table 4: Sieve analysis of the fine aggregate.

| Sieve size [mm] | Passing by weight [%] | IQS No.45/1984 Limits Zone 2 [28] |
|---|---|---|
| **10** | **100** | **100** |
| 4.75 | 94.5 | 90-100 |
| 2.36 | 81.3 | 75-100 |
| 1.18 | 68.7 | 55-90 |
| 0.60 | 50.1 | 35-59 |
| 0.30 | 19.2 | 8-30 |
| 0.15 | 3.8 | 0-10 |

Table 5: Properties of the fine aggregate.

| Property | Result | IQS No.45/1984 Limits [28] |
|---|---|---|
| Finess modulus | 2.82 | – |
| Specific gravity | 2.58 | – |
| $SO_3$ [%] | 0.22 | Max,0.5 |
| Passing on sieve No. 200 [%] | 3.7 | Max,5 |
| Water absorption [%] | 0.91 | – |

## 2.4 Coarse aggregate

The present study used crushed gravel siliceous aggregate with a maximum size of 14 mm. The sieve analysis and the properties of coarse aggregate are presented in Table 6 and Table 7, respectively. The test results showed that the coarse aggregate met IQS No. 45/1984 requirements [28].

Table 6: Sieve analysis of coarse aggregate.

| Sieve size [mm] | Passing by weight [%] | IQS No.45/1984 Limits Zone 2 [28] |
|---|---|---|
| 20 | 100 | 100 |
| 14 | 98 | 90-100 |
| 10 | 81 | 50-85 |
| 5 | 5 | 0-10 |
| 2.36 | 0 | – |

Table 7: Properties of coarse aggregate.

| Property | Result | IQS No.45/1984 Limits [28] |
|---|---|---|
| Specific gravity | 2.64 | - |
| SO3 % | 0.083 | Max. 0.1 |
| Passing on sieve No. 200 % | 0.0 | Max.3 |
| Water absorption % | 1.1 | – |

## 2.5 Lightweight aggregate

In this study, locally available, structural lightweight expanded clay aggregate (LECA) with a maximum size of (9.5mm) has been used as a partial replacement by weight of coarse aggregate, as shown in Figure 1. LECA has a thermal isolation characteristic due to its low thermal conductivity coefficient. Therefore, it is expected to improve concrete performance when exposed to a high temperature. Table 8 demonstrates the sieve analysis of LECA; the test result indicates that LECA conformed to the limits of ASTM C330 [29]. The properties of LECA are presented in Table 9.

Fig. 1: Lightweight Expanded Clay Aggregate (LECA) used.

Table 8: Sieve analysis of LECA.

| Sieve size [mm] | Passing by weight [%] | ASTM C330 Limits Nominal Size 2.36-9.5 [mm] [29] |
|---|---|---|
| 100 | 100 | 12.5 |
| 80-100 | 100 | 9.5 |
| 5-40 | 38.1 | 4.75 |
| 0-20 | 15.3 | 2.36 |
| 0-10 | 2.3 | 1.18 |

Table 9: Properties of LECA*.

| Property | Performance | |
|---|---|---|
| Particle shape | Semi-round/cracked | |
| Loss bulk density, ASTM C29-97 | 600-700 [kg/m³] | |
| Dry specific gravity | 1±0.2 | |
| Water absorption, ASTM C128 | 30-60 [min] =5-6 [%] | 24[h] =8-12 [%] |
| Thermal coefficient [λ] | 0.09-0.11 [W/m.K] | |

*According to the supplier.

### 2.6 Steel fiber

Micro steel fiber, with a 1% volume fraction, has been used in some mixes throughout the present research (Figure 2). Table 10 illustrates the steel fiber properties according to the datasheet provided by the manufacturer, which indicates that the steel fiber used conforms to the requirements of the ASTM C1116/C1116M [30] and ASTM A820/A820M-04 [31].

Fig. 2: Steel fiber used.

Table 10: Properties of steel fiber.

| Description | Micro steel fiber |
|---|---|
| Length | 13 [mm] |
| Diameter | 0.2 [mm] |
| Aspect ratio | 65 |
| Appearance | Straight |
| Coating | Brass coating |
| Color | Golden |
| Density | 7850 [kg/m³] |
| Tensile strength | 2700 [MPa] |

### 2.7 Water

Distilled water was added to all geopolymer concrete mixes as extra water to enhance their workability.

### 2.8 Superplasticizer

In the present work, a commercially available water-reducing admixture (superplasticizer) were employed called MasterGlenium® 54, which conforms to the specifications outlined in EN BS 934-2 [32] and ASTM C494-10 [33], Type F and G. The superplasticizer is classified as Polycarboxylic Ether based High Range Water Reducing/ New Generation Super Plasticizer Admixtures, known for their exceptional qualities. The specifications of this admixtures are shown in Table 11, according to the manufacturer sheets.

Table 11: Typical properties of MasterGlenium® 54.

| Appearance | Whitish to straw colored liquid |
|---|---|
| Relative density | 1.07 |
| Ph value | 4.0-7.0 |
| Type according to EN BS 934-2 and ASTM C494 [32] and [33] | F and G |

## 3 Experimental Program
### 3.1 Mix Proportioning and Mixing Procedure

One of the challenges encountered in manufacturing geopolymer concrete is the need for an established technique or specification for its mix design. Many studies in this field rely on trial mixes or the experiences documented in prior literature. It is thought that geopolymer concrete gains most of its strength in the first few days of curing, and only slightly more strength is gained after seven days [34]. Therefore, based on the maximum compressive strength of trial mixes at seven days, the reference Fly Ash-based geopolymer concrete (FA-GPC) mix was obtained.

Depending on previous investigations., the molar content of the alkaline solution (NaOH) was set at 14 (mol/liter), while the weight ratio of NaOH to $Na_2SiO_3$ was consistently maintained at 1:2. The curing heat and duration have also been adjusted for optimum results. The higher compressive strength was achieved at a heating temperature of 75 °C and a curing time of 12 hours. The fine and coarse aggregates were combined in a pan mixer when dry. Next, binders were introduced, followed by alkaline solutions and superplasticizer with an additional 5% of water. Based on the quantities obtained by trial mixes, a total of four mixtures of geopolymer concrete have been made, as shown in Tabe 12.

Table 12: Details of geopolymer concrete mixes.

| Mix type | Fly ash [Kg/m³] | Alkaline activator* | | | Sand [Kg/m³] | Gravel [Kg/m³] | LECA** [Kg/m³] | Steel fiber [kg/m³] | Extra water [Kg/m³] | S.P. [L/m³] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $Na_2SO_3$ [Kg/m³] | NaOH [Kg/m³] | Water [Kg/m³] | | | | | | |
| M | 417 | 153 | 30.9 | 45.56 | 673 | 1088 | 0 | 0 | 20.8 | 0 |
| MS0 | 417 | 153 | 30.9 | 45.56 | 673 | 1088 | 0 | 78 | 20.8 | 3 |
| MS10 | 417 | 153 | 30.9 | 45.56 | 673 | 979 | 109 | 78 | 20.8 | 5 |
| MS20 | 417 | 153 | 30.9 | 45.56 | 673 | 871 | 218 | 78 | 20.8 | 5 |

* Alkaline activator=0.55 by weight of fly ash.
** Replacement by weight of coarse aggregate.

### 3.2 Exposure to elevated temperature

The specimens were heated to high temperatures using an electrically powered furnace, as shown in Figure 3. The furnace can heat up to 1200 degrees Celsius. Specimens were heated at a steady rate of 5 °C/minute to the targeted temperatures. The capacity of the electric furnace determined the heating rate. The samples were held at the predetermined temperature for 1 hour after attaining the target temperature to ensure consistent heating throughout the specimen. The temperature–time relation criteria were based on the ASTM E-119 Standard [35].

Fig. 3: Heating of specimens.

### 3.3 Testing procedures

This investigation included the casting and testing of 60 cubes, 60 prisms, and 80 cylinders. The compressive strength of mixtures at 28 days was measured using 100 × 100 × 100 mm cubes following BS-1881: Part 116 [36]. A cylindrical specimen of 100 mm in diameter and 200 mm in length was utilized to conduct a tensile strength test on the 28th day, following the guidelines of standard ASTM C496/C496M-11 [37]. The flexural strength test was conducted on 100 × 100 × 400 mm prism specimens on the 28th day, according to ASTM C78/C78M-18 [38]. An average was calculated for each testing age based on three specimens. The modulus of elasticity was evaluated on the 28th day using a cylinder specimen (150 × 300 mm) following the ASTM C469-10 standard [39].

## 4 Results and discussion

### 4.1 Mass loss

All the four GPC mixes showed an increase in the mass loss as temperature increased from 20 to 800 °C, as demonstrated in Table 13. Within the temperature range of 200 to 500 °C, the fly ash-based geopolymer concrete specimens showed a gradual increase in mass loss, then a sharp increase above 500 °C [40]. The study results indicate that the addition of steel fiber reduces mass loss. Furthermore, when the quantity of LECA content rises, there is a reduction in mass loss., as seen in Figure 4. The rise in spalling effects may diminish as the lightweight aggregate content increases, as indicated by references [41], [42], and [43]. Despite LECA helping minimize mass loss of specimens at high temperatures, adding steel fibers to FA-geopolymers decreases workability and porosity but enhances density, mechanical strength, toughness, ductility, and shrinkage [44].

Table 13: Mass loss percentage

| Temp. [°C] | Mix type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | MS0 | | MS10 | | MS20 | |
| | Density [kg/$^3$] | Mass loss [%] | Density [kg/$^3$] | Mass loss [%] | Density [kg/$^3$] | Mass loss [%] | Density [kg/$^3$] | Mass loss [%] |
| 20 | 2166 | – | 2248 | – | 2123 | – | 2004 | – |
| 200 | 2150 | 0.74 | 2238 | 0.44 | 2115 | 0.37 | 1997 | 0.35 |
| 400 | 2091 | 3.46 | 2174 | 3.29 | 2064 | 2.78 | 1959 | 2.24 |
| 600 | 2057 | 4.93 | 2149 | 4.4 | 2031 | 4.33 | 1940 | 3.19 |
| 800 | 2035 | 6.04 | 2127 | 5.38 | 2017 | 4.99 | 1916 | 4.39 |

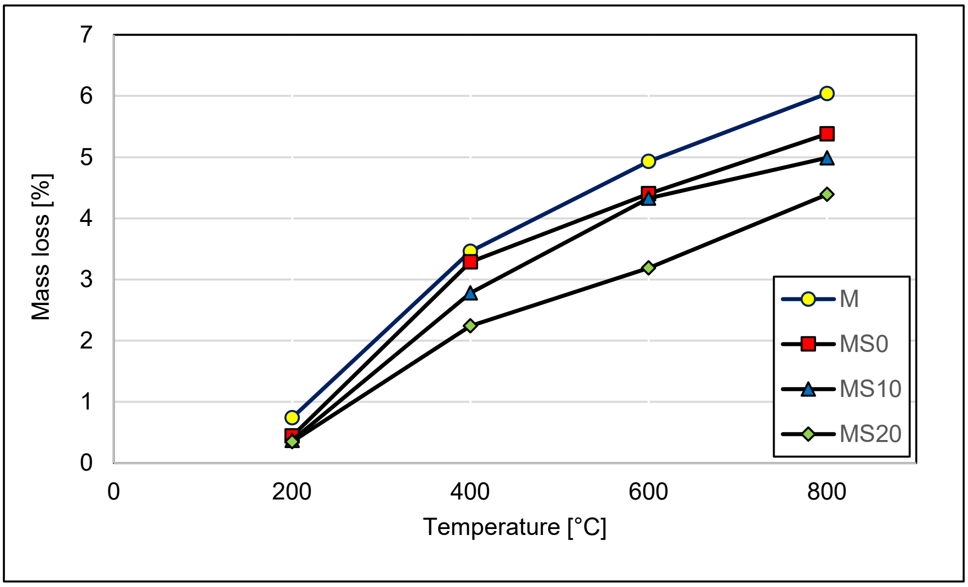


Fig. 4: Mass loss of specimens after high temperature exposure.

### 4.2 Compressive strength

The compressive strength of hardened concrete is a well-known mechanical parameter that demonstrates characteristics closely related to its strength. The test results were determined by calculating the average of three cubes for each concrete mix at 28 days. Table 14 displays the residual compressive strength of the specimens. The residual compressive strength significantly declines as the temperature rises from 20 to 800 °C, as seen in Figure 5.

The study's results demonstrated that using 1% steel fibers in GPC mixes significantly enhanced residual compressive strength across all temperatures. Incorporating fibers into the material serves as a bridge for the cracks, while the fibers' high melting point contributes to their excellent performance under high temperatures [45]. Nevertheless, as the quantity of LECA in the mixture increased, the retention factor experienced a rise. The retention factor is the fraction of the residual compressive strength of specimens following exposure to a high temperature, divided by the compressive strength of the specimens maintained at room temperature.

The compressive strength of geopolymer concrete significantly decreases when subjected to high temperatures. This reduction can be attributed to several factors. One factor is that heat induces the evaporation of water molecules in the concrete, and the reduction in water content impacts the overall structure and strength. A second factor, geopolymers, consists of chemical linkages between silicon, oxygen, and aluminum atoms, known as Si-O-Al bonds. Upon exposure to heat, the bonds undergo dihydroxylation, resulting in water liberation and the material's weakening [27]. Another factor is a mismatch in thermal expansion between the geopolymer matrix and the aggregates, causing a decrease in the strength of geopolymer concrete at high temperatures [46].

Table 14: Residual compressive strength.

| Temp. [°C] | Mix type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | MS0 | | MS10 | | MS20 | |
| | $f_{cu}$ [MPa] | Residual [%] | $f_{cu}$ [MPa] | Residual [%] | $f_{cu}$ [MPa] | Residual [%] | $f_{cu}$ [MPa] | Residual [%] |
| 20 | 60.14 | – | 69.63 | – | 60.06 | – | 50.47 | – |
| 200 | 51.41 | 83.82 | 59.12 | 84.9 | 52.23 | 86.96 | 44.82 | 88.8 |
| 400 | 38.72 | 64.38 | 45.95 | 65.47 | 40.48 | 67.39 | 41.44 | 82.1 |
| 600 | 26.4 | 43.89 | 30.67 | 44.04 | 30.73 | 51.65 | 35.36 | 70.06 |
| 800 | 16.29 | 27.08 | 23.06 | 33.11 | 22.21 | 36.97 | 19.82 | 39.27 |

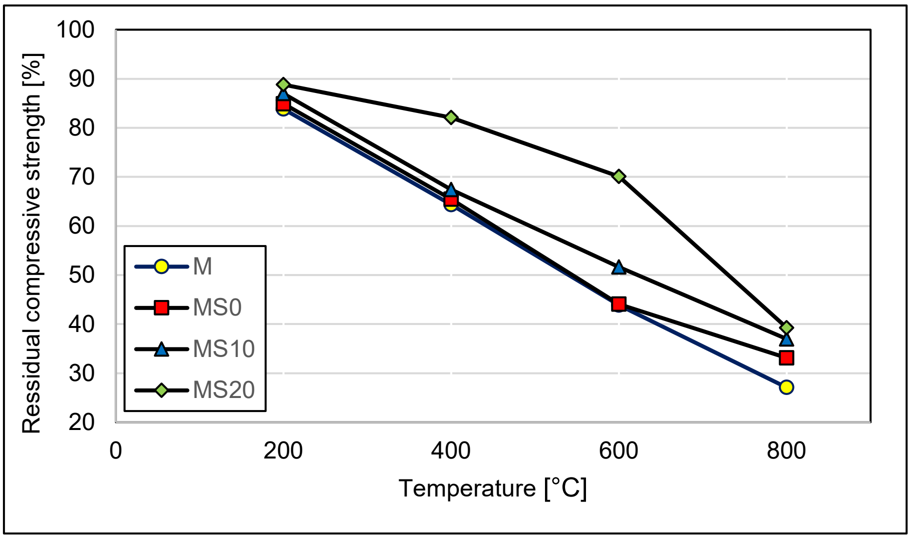


Fig. 5: Compressive strength retention after high temperature exposure.

### 4.3 Splitting tensile strength

Specimens with cylindrical shapes of 100 × 200 mm, as specified by ASTM C496/C496M-17 [38], were tested for splitting tensile strength both before and after exposure to high temperature. Table 15 illustrates the degree to which the tested specimens retain their tensile strength. Table 15 and Figure 6 clearly demonstrate a significant decrease in the tensile strength of the specimen as the temperatures rise from 20 to 800 C. Exposure to high temperatures can cause thermal stress-induced cracking, which is a significant consequence [47] and [48]. However, the incorporation of steel fiber and increasing the proportion of LECA in concrete result in improved strength preservation. The presence of LECA in mixes is known to increase porosity, hence reducing thermal stresses and minimizing the occurrence of fractures, leading to improved strength retention.

Table 15: Residual splitting tensile strength.

| Temp. [°C] | Mix type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | MS0 | | MS10 | | MS20 | |
| | $f_t$ [MPa] | Residual [%] | $f_t$ [MPa] | Residual [%] | $f_t$ [MPa] | Residual [%] | $f_t$ [MPa] | Residual [%] |
| 20 | 2.42 | – | 4.32 | – | 4.06 | – | 3.7 | – |
| 200 | 2.23 | 92.14 | 4.04 | 93.51 | 3.85 | 94.82 | 3.55 | 95.94 |
| 400 | 1.61 | 66.52 | 2.95 | 68.28 | 3.06 | 75.36 | 3.31 | 89.45 |
| 600 | 1.47 | 60.74 | 2.76 | 63.89 | 2.79 | 68.71 | 2.92 | 78.91 |
| 800 | 0.91 | 37.6 | 1.65 | 38.19 | 1.68 | 41.37 | 1.74 | 47.02 |

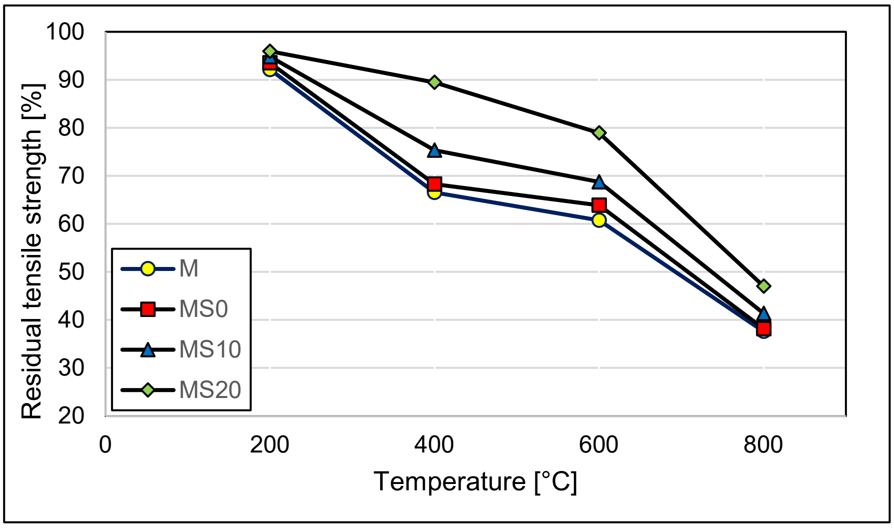

Fig. 6: Tensile strength retention after high temperature exposure.

### 4.4 Splitting flexural strength (MOR)

The impact of steel fiber and LECA content on the residual flexural strength of GP concretes at different operating temperatures is demonstrated in Figures 7. As presented in Table 16, the residual flexural strength of all types of GP concrete decreases as the temperature rises. This reduction can be attributed to the loss of strength with increasing temperature as mentioned previously. The relationship between the strength of concrete in compression and tension, including flexural tension and direct tension, is closely related [42].

Adding steel fiber resulted in a notable improvement in the overall strength and ductility of the GP concrete [13]. Furthermore, it significantly enhanced the bending strength compared to the plain matrix. Moreover, the inclusion of steel fiber along with LECA further enhanced strength retention. This enhancement was more pronounced with greater levels of LECA content. Numerous tiny, air-filled spaces in LECA contribute to its lightweight nature and provide thermal and acoustic insulation properties [49].

Table 16: Residual flexural strength.

| Temp. [°C] | Mix type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | MS0 | | MS10 | | MS20 | |
| | $f_b$ [MPa] | Residual [%] | $f_b$ [MPa] | Residual [%] | $f_b$ [MPa] | Residual [%] | $f_b$ [MPa] | Residual [%] |
| 20 | 5.66 | – | 5.87 | – | 5.46 | – | 5.18 | – |
| 200 | 5.1 | 90.1 | 5.48 | 93.35 | 5.17 | 94.68 | 4.96 | 95.75 |
| 400 | 2.85 | 55.88 | 3.35 | 57.06 | 3.43 | 62.82 | 3.46 | 66.79 |
| 600 | 1.59 | 28.09 | 2.04 | 34.75 | 1.98 | 36.26 | 2.1 | 40.54 |
| 800 | 0.91 | 16.07 | 1.38 | 23.5 | 1.52 | 27.83 | 1.57 | 30.3 |

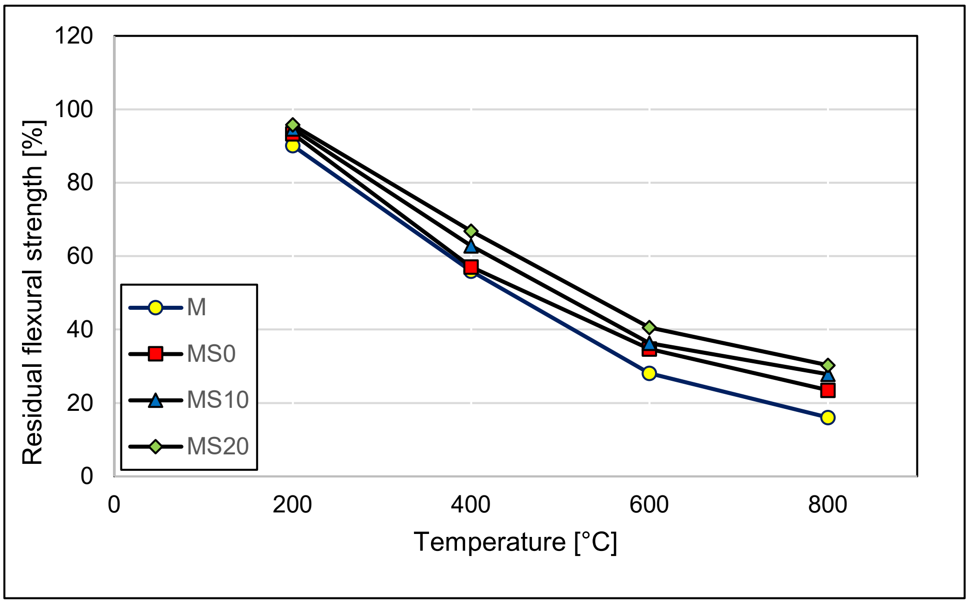


Fig. 7: Flexural strength retention after high temperature exposure.

### 4.5 Static modulus of elasticity

The static modulus of elasticity (Ec) is a significant characteristic among the major mechanical characteristics of concrete. As per the ASTM specification (C469/C469M-14) [39], the concrete's compressive strength may be determined by conducting a test on concrete cylinders. The stress-to-strain ratio of cemented concrete undergoes variations within the elastic range. The term used to refer to the line segment on the stress-strain curve corresponding to a location 40% away from the ultimate strength is called the secant [50]. The experimental findings demonstrate a significant drop in the Ec when subjected to elevated temperatures. Adding steel fibers to GPC mixes resulted in a considerable increase in residual static modulus, just like it did for compressive strength, particularly when steel fibers were added with LECA.

LECA comprises numerous tiny spaces inside the clay, creating a honeycomb arrangement that imparts LECA with its characteristics of low density, high porosity, and poor heat conductivity. LECA possesses features that enable it to provide insulation to concrete by preventing heat transmission. It also can avoid spalling and cracking caused by thermal stress. Furthermore, LECA retains its mechanical strength and thermal insulation capabilities more effectively than regular aggregate when exposed to high temperature [51]. Therefore, mixtures that contain LECA maintain their stiffness more effectively due to reduced heat degradation. The variances in the residual Ec of the specimens are shown in Table 17 and Figure 8**.**

Table 17: Residual Ec.

| Temp. [°C] | Mix type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | MS0 | | MS10 | | MS20 | |
| | Ec [GPa] | Residual [%] | Ec [GPa] | Residual [%] | Ec [GPa] | Residual [%] | Ec [GPa] | Residual [%] |
| 20 | 25.8 | – | 27.9 | – | 23.4 | – | 20.1 | – |
| 200 | 22.7 | 87.98 | 25.3 | 90.68 | 21.9 | 93.58 | 19.01 | 94.57 |
| 400 | 13.4 | 51.93 | 16.1 | 57.7 | 14.05 | 60.04 | 14.1 | 70.14 |
| 600 | 2.15 | 8.33 | 2.8 | 10.03 | 3.4 | 14.52 | 4.5 | 22.38 |
| 800 | 0.56 | 2.17 | 1.3 | 4.65 | 1.18 | 5.04 | 1.24 | 6.19 |

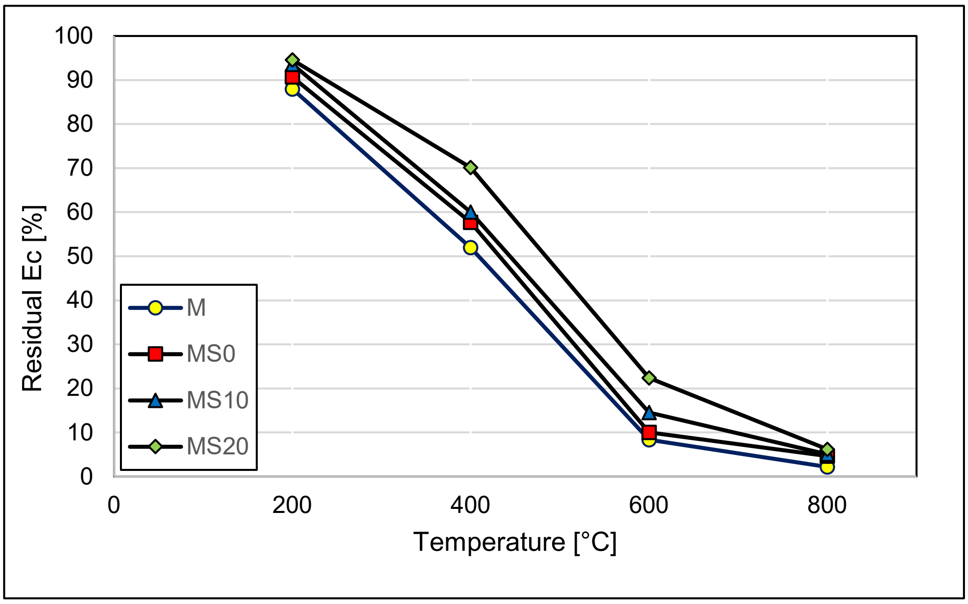


Fig. 8: Ec retention after high temperature exposure.

**4.6 Microstructure**

Scanning Electron Microscopy (SEM) examination allows for the visualization of the microstructure and facilitates the comprehension of the processes occurring in GP paste. Furthermore, it is beneficial to analyze and comprehend the response of GP paste when subjected to high temperatures. Abd Razak et al. [52].

Different types of GP concrete specimens have been analyzed using SEM technique at ambient temperature (20°C) and after exposure to a high temperature of 600 °C to understand what changes might have occurred in the microstructure of GP concrete. Figure 9a depicted SEM images at a temperature of 20°C for GP reference concrete, As shown in Figure 8, the microstructure of reference GPC paste is dense, homogenous and compacted due to the chemical reaction between alkali solution and alumina-silicate resource of fly ash. Geopolymer gel consists of alkali aluminosilicate hydrate (AASH) and alkali hydroxide (AH) [53]. AASH is a complex and changeable solid formed when water combines with the aluminum and silicon monomers that arrive from the source. AH is a byproduct of the dissolution of aluminosilicates with the alkaline activator [54]. On the other hand, Figure 9 shows the outcomes of the SEM test on GPC at 600 °C. As shown in Figure 9b, large cracks and holes in the matrix of GPC are formed due to high temperature.

The microstructure of GPC specimens containing steel fiber with 0%, 10%, and 20% LECA content at 20 and 600 °C is presented in Figure 10. Figure 10 demonstrated that, under typical circumstances, the microstructure of GPC is compact and uniform, matching the reference concrete. Additionally, there is a strong bond between the steel fiber and the matrix, independent of the presence or absence of LECA. However, when exposed to temperatures as high as 600 °C, the microstructure of GPC experiences the formation of fractures and holes. Consequently, the binding strength between the steel fibers and the concrete matrix weakens, as shown in Figure 10.

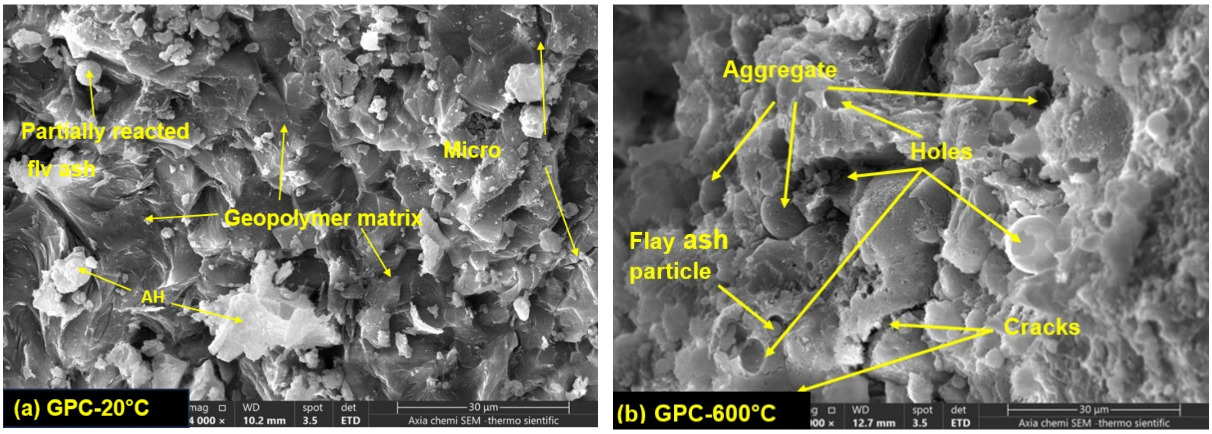


Figure 9: SEM images for the reference GPC mix at temperatures of 20 and 600°C.

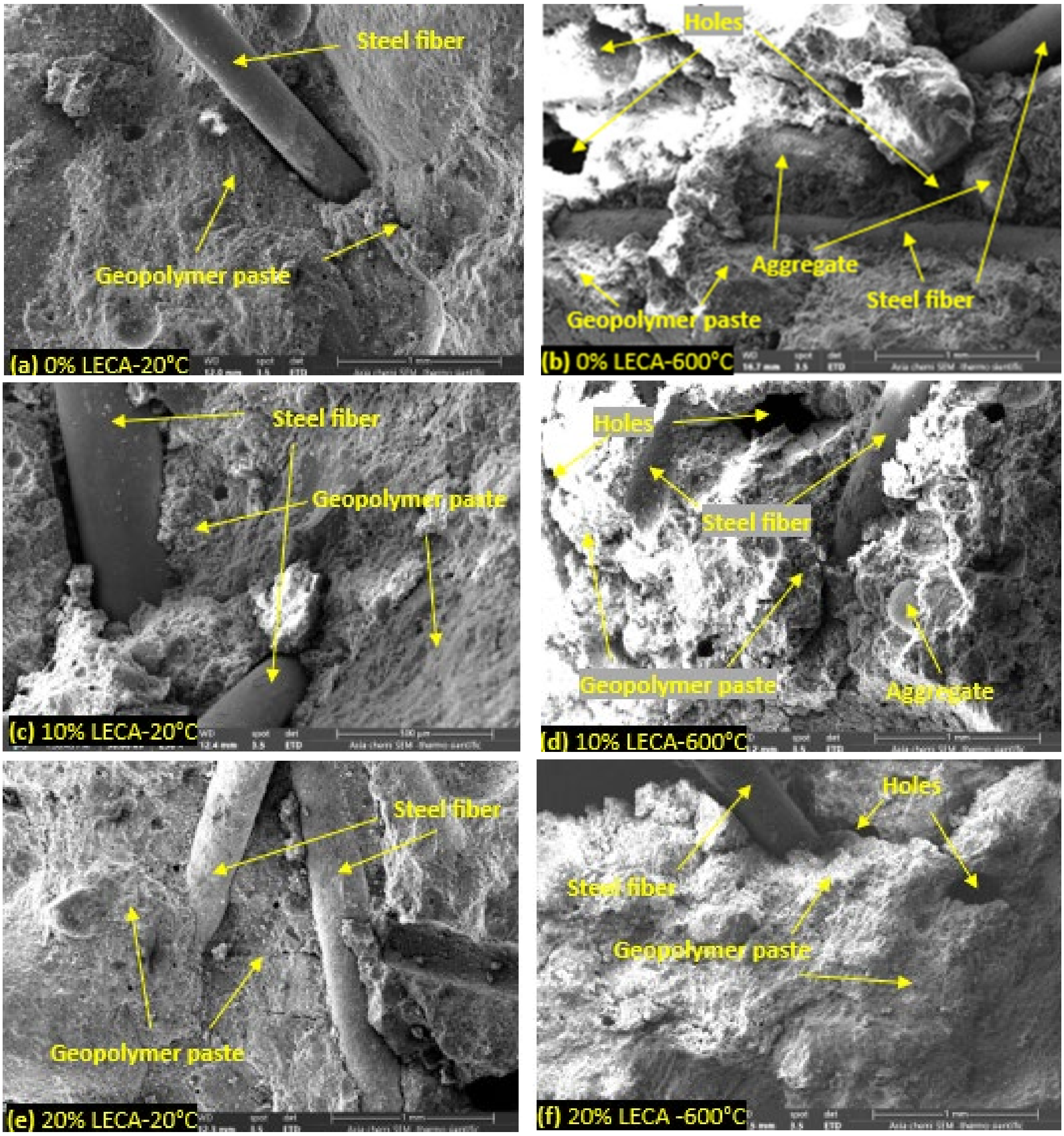

Figure 10: SEM images for steel fiber-reinforced GPC mixes with different LECA content at temperatures of 20 and 600°C.

## 5 Conclusion

1) Adding steel fiber to GPC increases density, compressive strength, tensile strength, flexural strength, and elasticity. In contrast, including LECA as a partial replacement by weight of coarse aggregate decreased these properties.

2) Using steel fiber along with LECA as a partial weight replacement for coarse aggregate lowers mass loss from the high-temperature effect at all steady-state temperatures.

3) The residual compressive strength of GPC reduces as the temperature rises from 20 to 800°C, whereas employing steel fiber and a higher content of LECA results in improved strength retention. The residual compressive strength at 800°C was 16.29% for plain GPC, 39.27% for a GPC with steel fiber, and 20% LECA.

4) As the temperature of the specimen increases, there is a considerable reduction in its tensile strength. Nevertheless, increasing the LECA proportion in steel fiber-reinforced GPC results in improved durability and retention of strength.

5) The flexural strength decreases at elevated temperatures. Incorporating LECA in steel fiber-reinforced GPC enhanced durability, and higher proportions of LECA in the GPC mixture improved performance.

6) At high temperatures, the elastic modulus decreases; by increasing the LECA content, the residual elastic modulus of the steel fiber-reinforced GPC increases.

7) The microstructural analysis revealed the formation of holes and fissures within the geopolymer matrix following exposure to elevated temperatures. The presence of steel fiber and the increasing LECA content can reduce the occurrence of these fractures.

8) There is a continued improvement in the residual properties of SFRGC exposed to elevated temperatures as the LECA content increases.


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### References


[1] TAMÀS, F. – BALÁZS, G. L.: Properties of Concrete, Cement and Concrete Research, vol. 8, no. 26, 1996, p. 1290.

[2] ARSHAD, S. – SHARIF, M. B. – IRFAN-UL-HASSAN, M. – KHAN, M. – ZHANG, J. L.: Efficiency of supplementary cementitious materials and natural fiber on mechanical performance of concrete, Arabian Journal for Science and Engineering, vol. 45, 2020, pp. 8577-8589.

[3] MILLER, S. A. – HORVATH, A. – MONTEIRO, P. J.: Readily implementable techniques can cut annual $CO_2$ emissions from the production of concrete by over 20%, Environmental Research Letters, vol. 11, no. 7, 2016, p. 074029.

[4] MILLER, S. A. – MOORE, F. C.: Climate and health damages from global concrete production, Nature Climate Change, vol. 10, no. 5, 2020, pp. 439-443.

[5] TURNER, L. K. – Collins, F. G.: Carbon dioxide equivalent ($CO_2$-e) emissions: A comparison between geopolymer and OPC cement concrete, Construction and Building Materials, vol. 43, 2013, pp. 125-130.

[6] MCLELLAN, B. C. – WILLIAMS, R. P. – LAY, J. – VAN RIESSEN, A. – CORDER, G. D.: Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement, Journal of Cleaner Production, vol. 19, no. 9-10, 2011, pp. 1080-1090.

[7] GOLLAKOTA, A. R. – VOLLI, V. – SHU, C. M.: Progressive utilisation prospects of coal fly ash: A review, Science of the Total Environment, vol. 672, 2019, pp. 951-989.

[8] XIAO, R. – POLACZYK, P. – ZHANG, M. – JIANG, X. – ZHANG, Y. – HUANG, B. – Hu, W.: Evaluation of glass powder-based geopolymer stabilized road bases containing recycled waste glass aggregate, Transportation Research Record, vol. 2674, no. 1, 2020, pp. 22-32.

[9] RAJ, M. K. A. – MUTHUSAMY, S. – PANCHAL, H. – IBRAHIM, A. M. M. – ALSOUFI, M. S. – ELSHEIKH, A. H.: Investigation of mechanical properties of dual-fiber reinforcement in polymer composite, Journal of Materials Research and Technology, vol. 18, 2022, pp. 3908-3915.

[10] ELSHEIKH, A. H. – PANCHAL, H. – SHANMUGAN, S. – MUTHURAMALINGAM, T. – El KASSAS, A. M. – RAMESH, B.: Recent progresses in wood-plastic composites: Pre-processing treatments, manufacturing techniques, recyclability and eco-friendly assessment, Cleaner Engineering and Technology, vol. 8, 2022, p. 100450.
[11] ASSI, L. – CARTER, K. – DEAVER, E. E. – ANAY, R. – ZIEHL, P.: Sustainable concrete: Building a greener future, Journal of Cleaner Production, vol. 198, 2018, pp. 1641-1651.
[12] SAYYAD, A. S. – PATANKAR, S. V.: Effect of steel fibres and low calcium fly ash on mechanical and elastic properties of geopolymer concrete composites, Indian Journal of Materials Science, 2013, p. 2013.
[13] GANESAN, N. – INDIRA, P. V.: Engineering properties of steel fibre reinforced geopolymer concrete, Advances in Concrete Construction, vol. 1, no. 4, 2013, p. 305.
[14] LAZORENKO, G. – KASPRZHITSKII, A. – KRUGLIKOV, A. – MISCHINENKO, V. – YAVNA, V.: Sustainable geopolymer composites reinforced with flax tows, Ceramics International, vol. 46, no. 8, 2020, pp. 12870-12875.
[15] GOMES, R. F. – DIAS, D. P. – DE ANDRADE SILVA, F.: Determination of the fracture parameters of steel fiber-reinforced geopolymer concrete, Theoretical and Applied Fracture Mechanics, vol. 107, 2020, p. 102568.
[16] ZHONG, H. – ZHANG, M.: Effect of recycled polymer fiber on dynamic compressive behavior of engineered geopolymer composites, Ceramics International, vol. 48, no. 16, 2022, pp. 23713-23730.
[17] ZHANG, P. – WANG, W. – LV, Y. – GAO, Z. – DAI, S.: Effect of polymer coatings on the permeability and chloride ion penetration resistances of nano-particles and fibers-modified cementitious composites, Polymers, vol. 14, no. 16, 2022, p. 3258.
[18] ALBIDAH, A. – ABADEL, A. – ALRSHOUDI, F. – ALTHEEB, A. – ABBAS, H. – AL-SALLOUM, Y.: Bond strength between concrete substrate and metakaolin geopolymer repair mortars at ambient and elevated temperatures, Journal of Materials Research and Technology, vol. 9, no. 5, 2020, pp. 10732-10745.
[19] WANG, Y. – ASLANI, F. – VALIZADEH, A.: An investigation into the mechanical behaviour of fibre-reinforced geopolymer concrete incorporating NiTi shape memory alloy, steel and polypropylene fibres, Construction and Building Materials, vol. 259, 2020, p. 119765.
[20] LARSEN, I. L. – THORSTENSEN, R. T.: The influence of steel fibres on compressive and tensile strength of ultra-high-performance concrete: A review, Construction and Building Materials, vol. 256, p. 119459, 2020.
[21] JOSEPH, B. – MATHEW, G.: Behavior of geopolymer concrete exposed to elevated temperatures, (Doctoral dissertation), Cochin University of Science and Technology, 2015.
[22] PART, W. K. – RAMLI, M. – CHEAH, C. B.: An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products, Construction and Building Materials, vol. 77, 2015, pp. 370-395.
[23] Zheng, Y., Zhang, W., Zheng, L., & Zheng, J. (2024). Mechanical properties of steel fiber-reinforced geopolymer concrete after high temperature exposure. Construction and Building Materials, 439, 137394.
[24] LECA AE. Catalog [Internet]. Available from: [https://leca.ae/ Catalog/]., 2017.
[25] ABDULLAH, A. H. – MOHAMMED, S. D.: Effect of lightweight expanded clay aggregate as partial replacement of coarse aggregate on the mechanical properties of fire-exposed concrete, Journal of the Mechanical Behavior of Materials, vol. 32, no. 1, 2023, p. 20220299.
[26] ASTM C 618: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete.: Barr Harbor Drive, West Conshohocken: Annual Book of ASTM Standards, 2019.
[27] HARDJITO, D. – RANGAN, B. V.: Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete, Curtin University of Technology., 2005.
[28] Iraqi Specifications, No. 45/1984: Aggregate from Natural Sources for concrete and construction.
[29] ASTM C 330: Standard Specification for Lightweight Aggregates for Structural Concrete, ASTM International, West Conshohocken, Pa, USA, 2005.
[30] ASTM C1116/C1116M: Standard Specification for Fiber-Reinforced Concrete, ASTM International, West Conshohcken, PA, , 2015.
[31] ASTM: Standard Specification for Steel Fibers for Fiber-Reinforced Concrete, A820/A820M-04, 2004.

[32] EN–BS 934: Admixtures for Concrete, Mortar and Grout-Part 2: Concrete Admixtures; Definitions, Requirements, Conformity, Marking and Labelling. British Standards Institution, 2002.
[33] ASTM C494/C494M: Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA, 2010, 10 p.
[34] JOSEPH, B. – MATHEW, G.: Influence of aggregate content on the behavior of fly ash based geopolymer concrete, Scientia Iranica, vol. 19, no. 5, 2012, pp. 1188-1194.
[35] ASTM E 119: Standard Methods of Fire Tests of Building Construction and Materials. West Conshohocken (PA), USA: ASTM International, 1983.
[36] BS 1881 Part 116: Method for Determination for Compressive strength for Concrete Cubes, 1983.
[37] ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, American Society for Testing and Materials, 2011.
[38] ASTM C78/C78M: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), American Society for Testing and Materials, 2018.
[39] ASTM C469: Standard test method for static modulus of elasticity and poisson's ratio of concrete in compression, American Society for Testing and Materials, 2010.
[40] NEMATOLLAHI, B. – SANJAYAN, J. – CHAI, J. X. H. – LU, T. M.: Properties of fresh and hardened glass fiber reinforced fly ash based geopolymer concrete, key engineering materials, vol. 594, 2014, pp. 629-633.
[41] IQBAL, S. – ALI, A. – HOLSCHEMACHER, K. – BIER, T. A.: Effect of change in micro steel fiber content on properties of High strength Steel fiber reinforced Lightweight Self-Compacting Concrete (HSLSCC), Procedia Engineering, vol. 122, 2015, pp. 88-94.
[42] M. S. SHETTY: Concrete Technology (theory and practice), New Delhi, S. Chand and Company LTD, 2000, pp. 321-323.
[43] ZHAO, J. – WANG, K. – WANG, S. – WANG, Z. – YANG, Z. – SHUMUYE, E. D. – GONG, X.: Effect of elevated temperature on mechanical properties of high-volume fly ash-based geopolymer concrete, mortar and paste cured at room temperature, Polymers, vol. 13, no. 9, 2021, p. 1473.
[44] M. RASHAD: Effect of steel fibers on geopolymer properties–the best synopsis for civil engineer, Construction and Building Materials, vol. 246, 2020, p. 118534.
[45] ZHANG, P. – KANG, L. – WANG, J. – GUO, J. – HU, S. – LING, Y.: Mechanical properties and explosive spalling behavior of steel-fibre reinforced concrete exposed to high temperature-A review, Appl. Sci., vol. 10, 2020, p. 2324.
[46] KONG, D. L. – SANJAYAN, J. G.: Effect of elevated temperatures on geopolymer paste, mortar and concrete, Cement and concrete research, vol. 40, no. 2, 2010, pp. 334-339.
[47] DABBAGHI, F. – DEHESTANI, M. – YOUSEFPOUR, H.: Residual mechanical properties of concrete containing lightweight expanded clay aggregate (LECA) after exposure to elevated temperatures, Struct Concr., vol. 23, no. 4, 2022, p. 2162–84.
[48] KRISHNA, DA – PRIYADARSINI, R. – NARAYANAN, S.: Effect of elevated temperatures on the mechanical properties of concrete, Procedia Struct Integr., vol. 14, 2019, p. 384–94.
[49] M. RASHAD: Lightweight expanded clay aggregate as a building material–An overview.," Construction and Building Materials, vol. 170, 2018, pp. 757-775.
[50] MESBAH, HA. – LACHEMI, M. – AITCIN, PC.: Determination of elastic properties of high-performance concrete at early ages, Mater. J., vol. 99, no. 1, 2002, pp. 37-41.
[51] KUMAR, R. – LAKHANI, R. – KUMAR A.: Physico-mechanical and thermal properties of lightweight structural concrete with light expanded clay aggregate for energy-efficient buildings, Advanced in Construction materials and Sustainable Environment, Singapore, Springer, 2021, pp. 175-85.
[52] ABD RAZAK, S. N. – SHAFIQ, N. – NIKBAKHT, E. H. – MOHAMMED, B. S. – GUILLAUMAT, L. – FARHAN, S. A.: Fire performance of fly-ash-based geopolymer concrete: Effect of burning temperature on mechanical and microstructural properties, Materials Today, vol. 66, 2022, pp. 2665-2669.
[53] JWAIDA, Z. – DULAIMI, A. – MASHAAN, N. – OTHUMAN MYDIN, M. A.: Geopolymers: The Green Alternative to Traditional Materials for Engineering Applications, Infrastructures, vol. 8, no. 6, 2023, p. 98.
[54] CASTILLO, H. – COLLADO, H. – DROGUETT, T. – VESELY, M. – GARRIDO, P. – PALMA, S.: State of the art of geopolymers: A review, e-Polymers, vol. 22, no. 1, 2022, pp. 108-124.