Compressive Strength of Ambient- and Heat-Cured Fly Ash Geopolymer Concrete after High-Temperature Exposure

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ABSTRACT
This paper investigates the behavior of low-calcium fly ash geopolymer concrete subjected to high temperatures in both ambient-cured and heat-cured situations. The temperature at which concrete samples were gradually heated to 100, 200, 400, 600, 800, and 1000°C was maintained at 5°C per minute. The impact of elevated temperatures on geopolymer concrete was evaluated by the use of microstructural analysis, visual inspection, mass loss measurement, fracture evaluation, and residual strength determination. Interestingly, the cross-sectional and surface fractures peaked at 800°C and decreased around 1000°C. Based on the findings, all of the concrete samples remained strong after two hours at 600°C.

Keywords: low-calcium fly ash, geopolymer concrete, high temperatures, ambient-cured, heat-cured, temperature gradient

1. INTRODUCTION

Fly ash geopolymer concrete that was heat- and ambient-cured and exposed to high temperatures was studied by (Singh et al., 2015) for residual compressive strength and deterioration. (Rajmohan et al., 2022)found that a crushing index of 7.7% is the threshold for maintaining original compressive strength up to 600 °C; above this temperature, the main causes of strength losses are dehydration, lower aggregate strength, and microstructural deterioration(Almutairi et al., 2021). The early age properties of low-calcium fly ash geopolymer concrete suitable for ambient curing were emphasized by (Van Chanh et al., 2008), who also demonstrated the material's potential as a low-emission Portland cement alternative(Hardjito et al., 2004). The effects of heat curing temperatures on fly ash-based geopolymer concrete were investigated by (Lloyd &Rangan, 2010).

In 2013, (Lloyd &Rangan, 2010)conducted an investigation on the durability properties of geopolymer concrete that was combined with fly ash and slag and allowed to cure at room temperature(Farooq et al., 2021). In addition, (Deb et al., 2014)talked about the fracture properties of ambient-cured geopolymer concrete and emphasized the material's importance as a sustainable alternative to traditional concrete(Neupane et al., 2018). (Amran et al., 2020) Heat curing and the transport properties of low-calcium fly ash-based geopolymer concrete were investigated(Ding et al., 2018). Curing at 75 °C for 18–24 hours was shown to enhance compressive strength and minimize permeability voids. Using Class F fly ash activated by sodium hydroxide and silicon dioxide solutions, (Rangan, 2014)aimed to produce geopolymer concrete that could be left outside to cure.

Further research on the effects of GGBFS on the setting, workability, and early strength of fly ash geopolymer concrete after it was cured in ambient conditions yielded results that were comparable to those of ordinary Portland cement (Rajmohan et al., 2022). By using manufactured sand rather than river sand, (Ma et al., 2018) focused on ecologically friendly techniques while examining the mechanical characteristics and durability of heat-cured low-calcium fly ash-based sustainable geopolymer concrete. (Raijiwala&Patil, 2011)compared fiber-reinforced geopolymer concrete to Portland cement-made concrete in terms of its higher technical features and reduced carbon footprint when used for in situ applications with ambient curing.

Experiments

In this investigation, low-calcium fly ash was used to create the geopolymer, with its chemical composition analyzed via X-ray fluorescence (XRF). The results, including chemical composition, loss on ignition (LOI), bulk density, particle density, and moisture content, are presented in Figures 1 and 2. Crushed basalt aggregate (4.75–22 mm) and natural siliceous sand (less than 4 mm, mainly composed of SiO2) were used as coarse and fine aggregates, respectively. The water content, bulk density, and particle density of the aggregates are also provided.

In this experiment, an alkali-activator solution was created by combining sodium hydroxide (NaOH) and liquid sodium silicate (Na2SiO3) with a modulus ratio of 3.23. The NaOH solution was prepared by dissolving 98% pure NaOH particles in distilled water, with concentrations varying between 8 M (density: 1.275 g/cm^3) and 14 M (density: 1.425 g/cm^3). The alkali-activator was mixed 24 hours before use. Four geopolymer concrete mixtures were tested: Mix-1 (normal strength, room temperature cure), Mix-2 (normal strength, heat-cured), Mix-3 (high strength, room temperature cure), and Mix-4 (high strength, heat-cured). No additional water was added during casting.

Table 1. Revised Proportions and Curing Conditions for Geopolymer Concrete Mixes

Mix ID	Coarse Aggregate (kg/m^3)	Sand (kg/m^3)	Fly Ash (kg/m^3)	Na_2SiO_3 Solution (kg/m^3)	NaOH Solution (kg/m^3)	Na_2SiO_3 / NaOH Ratio	Molarity of NaOH Solution	Curing Temperature	Water Content
Mix-1	1250	530	480	150	60	2.5	10 M	30°C	5.60%
Mix-2	1250	530	480	150	60	2.5	10 M	85°C	5.60%
Mix-3	1250	530	480	160	55	2.9	12 M	30°C	5.30%
Mix-4	1250	530	480	160	55	2.9	12 M	85°C	5.30%
Mortar	0	1400	480	160	55	2.9	12 M	45°C	-

This table presents the proportions and curing conditions for various geopolymer concrete mixes. Four concrete mixes (Mix-1 to Mix-4) and one mortar mix are described. The coarse aggregate and sand quantities are consistent across the concrete mixes, while the mortar mix contains no coarse aggregate. The Na_2SiO_3 (sodium silicate) and NaOH (sodium hydroxide) solutions are used in different ratios, with Na_2SiO_3/NaOH ratios ranging from 2.5 to 2.9. The molarity of the NaOH solution varies between 10 M and 12 M. Curing temperatures range from 30°C to 85°C for the concrete mixes and 45°C for the mortar mix. Water content is slightly higher in Mix-1 and Mix-2, with a value of 5.60%, compared to 5.30% in Mix-3 and Mix-4. The table provides a clear overview of the mix compositions and curing conditions used in this experiment.

2. Casting, Curing, and Sample Preparation for Concrete Specimen Testing

In the study, concrete was mixed using a laboratory-grade mixer, combining dry components for three minutes before adding the alkali-activator solution and mixing for an additional four to six minutes until uniform. Fresh concrete was then poured into 100 x 100 x 100 mm steel molds, vibrated in two layers, and covered with plastic to prevent moisture loss. The specimens were cured either in an oven at 80°C for 24 hours or at room temperature for 72 hours, then demolded. For internal structure analysis, specimens were sliced into three sections before exposure to high temperatures to prevent spalling or strength loss. These slices were coated with a thin mortar layer to form an artificial concrete block (AICB) before being subjected to the desired temperatures.

3. Testing Procedures

Mass loss evaluation samples were analyzed to determine the mass loss ratio of fly ash-based geopolymer concrete (FAGC) at various target temperatures. The coarse aggregate crushing index, which assesses the strength of coarse particles in concrete, was tested using a YAW-2000 electro-hydraulic device. Three kilograms of coarse aggregate (9.5-19 mm) were subjected to a 200 kN load at 1 kN/s, held for five seconds, and then reduced. The remaining mass was measured. Compressive strength tests were also conducted using an electro-hydraulic device, applying a load at 0.5 MPa/s until failure, to evaluate the residual compressive strength of concrete after high-temperature exposure.

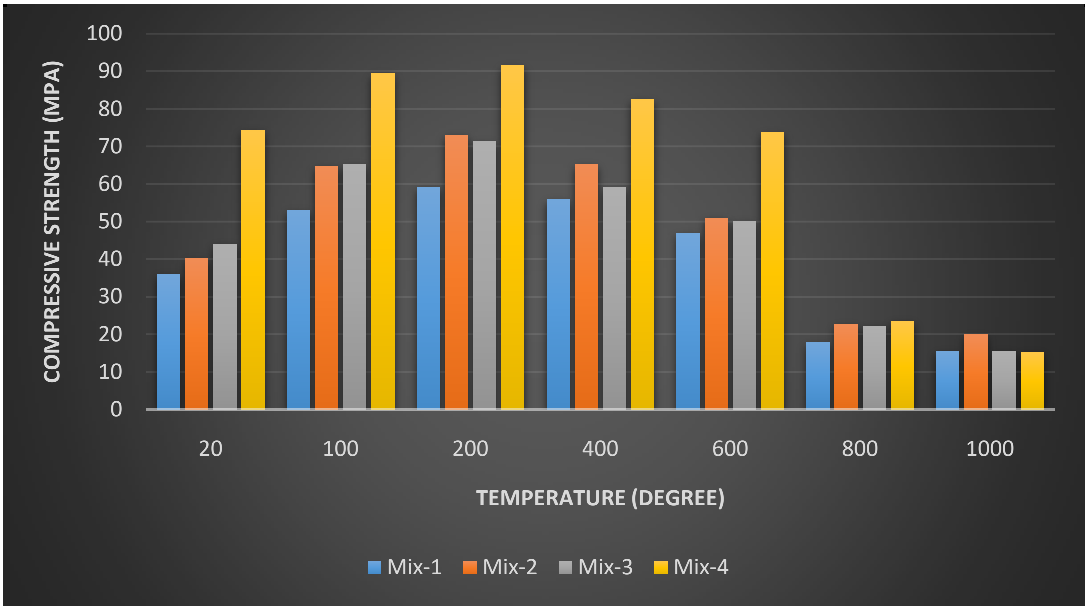

Figure 1. Compressive strength of concrete mix

4. RESULTS

The figure 1 provides data on the compressive strength (in MPa) of four different concrete mixes (Mix-1, Mix-2, Mix-3, Mix-4) subjected to various temperatures ranging from 20°C to 1000°C. At room temperature (20°C), Mix-4 exhibits the highest compressive strength (74.256 MPa), followed by Mix-3 (44.064 MPa), Mix-2 (40.188 MPa), and Mix-1 (35.904 MPa). As the temperature increases to 100°C, all mixes show an increase in strength, with Mix-4 reaching 89.352 MPa, indicating a positive response to initial heating. At 200°C, Mix-4 still leads in strength (91.494 MPa), while the other mixes also show strength gains, with Mix-3 peaking at 71.298 MPa.

However, at 400°C, the compressive strength starts to decline for all mixes. Mix-4 remains the strongest (82.518 MPa), but the reduction in strength is evident. This trend continues as the temperature rises to 600°C, with significant strength loss observed across all mixes, particularly in Mix-1 and Mix-2. At 800°C, the strength drops sharply, with Mix-4 and Mix-2 maintaining marginally higher strengths (23.562 MPa and 22.644 MPa, respectively). Finally, at 1000°C, all mixes experience severe degradation, with compressive strengths falling to nearly similar low levels, ranging from 15.3 MPa to 19.89 MPa. This indicates that prolonged exposure to extremely high temperatures results in a drastic reduction in the structural integrity of the concrete mixes.

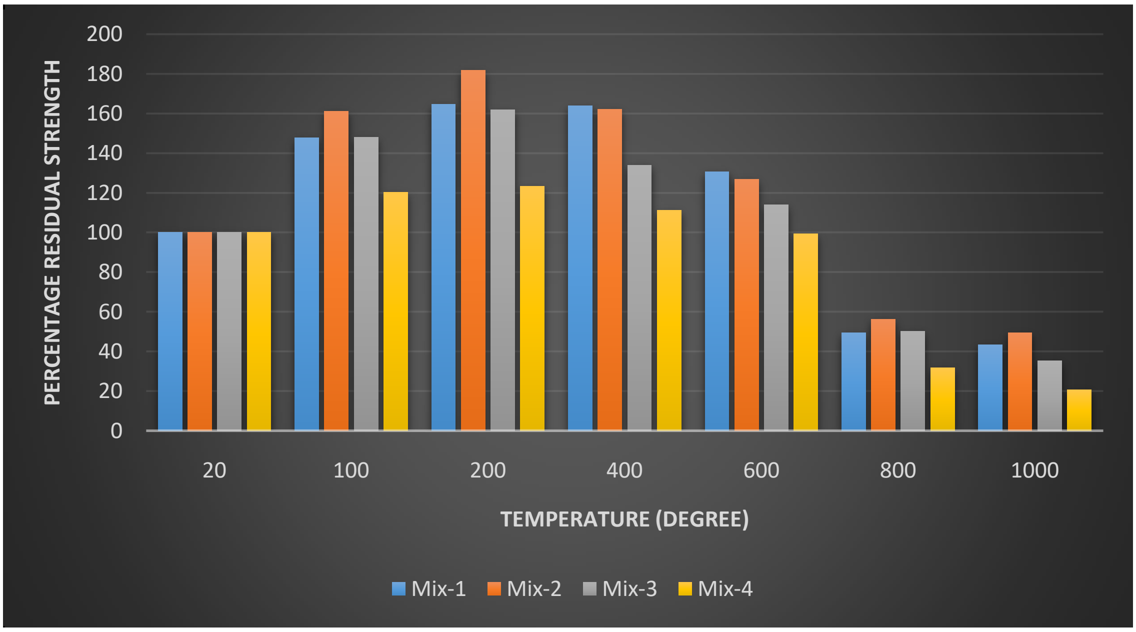

Figure 2. percentage residual strength

The data provided illustrates the behavior of four different mixes (Mix-1, Mix-2, Mix-3, and Mix-4) as they are subjected to varying temperatures, ranging from 20°C to 1000°C. At the lowest temperature of 20°C, all mixes display identical values of 100, indicating a uniform property or measurement at this baseline condition. As the temperature increases to 100°C, there is a noticeable rise in values across all mixes, with Mix-2 showing the highest increase to 161.2 and Mix-4 the lowest at 120.3.
At 200°C, Mix-2 continues to have the highest value at 181.7, while Mix-4 shows a slight drop to 123.2. When the temperature reaches 400°C, the values for Mix-1 and Mix-2 are relatively close, 163.9 and 162.2 respectively, while Mix-3 drops significantly to 134 and Mix-4 to 111.1, indicating a reduction in their respective properties.
By 600°C, there is a notable decrease in all mixes. Mix-1 drops to 130.7, Mix-2 to 126.9, Mix-3 to 113.9, and Mix-4 to 99.3. This trend continues at 800°C, where Mix-1 and Mix-3 show values of 49.4 and 50.2, respectively, while Mix-2 and Mix-4 show lower values of 56.3 and 31.7. Finally, at 1000°C, all mixes exhibit further significant decreases, with Mix-1 at 43.5, Mix-2 at 49.5, Mix-3 at 35.4, and Mix-4 at 20.6. This consistent decrease with increasing temperature suggests that the property being measured diminishes as the temperature rises, with Mix-4 consistently showing the lowest values at higher temperatures.

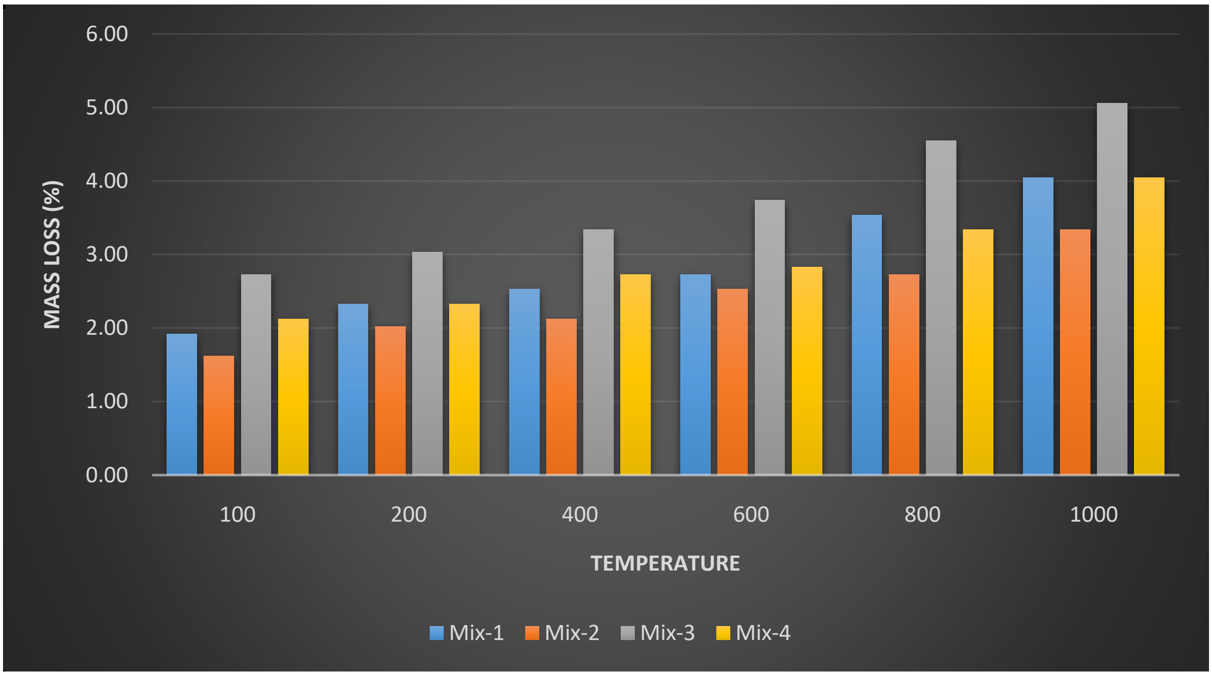

Figure 3. Mass loss v/s temperature

The data provided illustrates the mass loss percentages for four different mixes (Mix-1, Mix-2, Mix-3, and Mix-4) as they are subjected to increasing temperatures from 20°C to 1000°C. At the initial temperature of 20°C, all mixes exhibit no mass loss, recording a 0% loss. As the temperature rises to 100°C, each mix begins to show an increase in mass loss, with Mix-3 experiencing the highest at 2.73%, while Mix-2 shows the lowest at 1.62%. This trend continues at 200°C, where Mix-3 again demonstrates the highest mass loss of 3.03%, and Mix-2 remains the lowest at 2.02%.
At 400°C, the mass loss percentages increase further, with Mix-3 continuing to show the highest loss at 3.34% and Mix-2 the lowest at 2.12%. By 600°C, all mixes exhibit a noticeable rise in mass loss, with Mix-3 reaching 3.74% and Mix-4 showing 2.83%, while Mix-2 and Mix-1 record 2.53% and 2.73%, respectively. The trend persists at 800°C, where Mix-3 shows the highest mass loss of 4.55% and Mix-4 the second highest at 3.34%. Mix-2 and Mix-1 display lower mass losses of 2.73% and 3.54%, respectively. At the highest temperature of 1000°C, the mass loss percentages continue to increase for all mixes, with Mix-3 leading at 5.06% and Mix-4 at 4.04%, while Mix-2 and Mix-1 exhibit 3.34% and 4.04% respectively. This consistent rise in mass loss with temperature suggests that as the temperature increases, the mixes undergo greater degradation, with Mix-3 consistently showing the highest mass loss across all temperatures.

5. CONCLUSIONS

The following conclusions can be drawn:

1. **Mass Loss Trends**: All concrete mixes exhibit a consistent increase in mass loss with rising temperatures, from 20°C to 1000°C. Mix-3 consistently shows the highest mass loss at each temperature increment, indicating it is the most susceptible to thermal degradation. The mass loss percentages for Mix-4 are the second highest, while Mix-2 and Mix-1 generally display lower mass losses.
2. **Property Degradation with Temperature**: The property being measured (presumably related to a physical characteristic or performance metric) shows a marked decrease as temperatures increase. At 20°C, all mixes have uniform values, but this value drops significantly as temperatures rise. Mix-4 shows the lowest values at higher temperatures, suggesting it is the most affected by thermal exposure.
3. **Compressive Strength Analysis**: At ambient temperatures (20°C), Mix-4 demonstrates the highest compressive strength, followed by Mix-3, Mix-2, and Mix-1. All mixes exhibit an initial increase in compressive strength with moderate heating, with Mix-4 maintaining the highest strength at 200°C. However, as temperatures rise beyond 400°C, there is a noticeable decline in compressive strength for all mixes, with Mix-4 retaining the highest strength compared to others, though still showing significant reductions. By 800°C, the strengths drop sharply, with Mix-4 and Mix-2 showing relatively higher strengths compared to Mix-1 and Mix-3. At 1000°C, all mixes experience severe strength degradation, indicating that high temperatures result in substantial loss of structural integrity.
4. **Thermal Resistance**: The data suggests that while the concrete mixes exhibit some resilience to initial heating, prolonged exposure to high temperatures (particularly beyond 600°C) leads to significant degradation in both mass and compressive strength. Mix-3 shows the highest mass loss and the lowest compressive strength at extreme temperatures, indicating it is the least thermally resistant. Conversely, Mix-4, despite showing the highest initial strength and better performance at lower temperatures, also suffers considerable degradation at higher temperatures.

Overall, the concrete mixes demonstrate varying degrees of thermal performance, with increased temperatures leading to significant mass loss and reduced compressive strength, impacting the structural reliability of the mixes at high temperatures.

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