Effect of elevated temperature on the mechanical strength of glass mortar

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Abstract. This experimental study aimed to investigate the elevated temperature behavior of glass powder (GP) as a partial replacement of Portland cement. The residual compressive strength is an essential consideration for the sustainability of newly introduced supplementary cementitious material at elevated temperatures. For this study, the powder of waste glass was used to replace portland cement in the proportion of 0%, 10%, 20%, and 30%. For fundamental understanding, the compressive strength test was carried out on samples after exposure to high temperature with two different cooling regimes. The experimental result reveals that the mortar mix with cement replaced by 20% GP for both cooling conditions retained more relative residual strength and showed sound behavior compare to the reference sample. The mortar sample with 20% glass powder replacement shows better performance with lower strength loss for both cooling regimes. For air cooling samples, the average strength loss was 27.0% compared to 31.2% of the reference sample. In water cooling samples, the average strength loss was 25.4% compared to the 30.7% reference sample. The two distinct temperature ranges were observed regarding the effect of glass powder replacement on mortar strength under elevated temperature. For temperature above 400 °C average strength loss was 38.62% in the mortar with glass powder and 35.60% in reference sample for water cooling condition. Similarly, for air-cooling samples, the average strength loss was 51.8% compared to 48.90% of the reference sample. Therefore, the lesser strength loss of mortars containing glass powder may be related with their low calcium hydroxide content.

Keywords: Glass mortar, Residual Strength, Compressive Strength, Elevated temperature, Waste glass powder

1. Introduction

Concrete is the largest consumed material after water on the earth's surface and plays a significant role in the construction field because of its adaptability in use [1]. It is a composite construction material consists of aggregate, cement, and water. Cement and water together form the binding paste that binds the aggregates and fills the voids within. Cement is the primary manufactured, most utilized important ingredients and massive contributor of the CO$_2$ emission of the construction industry, contributing to Global Warming, climate change, and ozone layer depletion. The production of every tonne of ordinary Portland cement (OPC) emits on average a similar amount of CO$_2$, i.e.0.7 to 1 ton per ton or roughly 6% of all human-made CO$_2$ emissions [2]. Due to heavy CO$_2$ emission and an immense contribution to the construction industry's global warming, there has been a growing emphasis on utilizing waste materials and by-products in construction materials. The safety and protection of the
building from fire largely depend on the stability and behavior of concrete ingredients at elevated temperature\[3\].

Therefore, great efforts have been made to reduce the consumption of cement in concrete production and to control greenhouse gas emission by partial replacement of ordinary cement with supplementary cementitious materials (SCMs), like ground granulated blast furnace slag (GGBS)\[4–6\] fly ash (PFA)\[6\], \[2\]and meta-kaolin (MK). To observe the feasibility and to use as a partial substitute for cement in concrete production, various types of unwanted material were examined as supplementary cementitious material, including waste glass\[7–10\]. This consumption permits reduction in cement production and utilization, with enhanced concrete strength and durability due to secondary calcium silicates' development through their pozzolanic reaction.

Worldwide, waste glass in broken forms constitutes a significant part of waste by-products from both the industry and domestic. Presently glass is one of the upcoming new waste materials in most of the countries requiring urgent concentration, which involves consuming large amounts of energy to process the raw constituents. Theoretically, glass can be recycled many times without altering its chemical properties, but colour glass has a relatively low recycling rate due to high impurity levels \[11\]. The existing condition of leaving waste glass in landfills is also not contributing to an environmentally friendly solution for the waste glass due to the non-biodegradable nature of glass. Waste glass represents an urgent environmental challenge worldwide due to the non-biodegradable nature of the glass materials resulting in severe environmental pollutions\[12\].

Therefore, numerous attempts have been made to consume waste glass (WG) in building materials, exclusively cement-based composites. Also, the chemical composition and the pozzolanic properties of waste glass encourages to use in the cement concrete industries and ultimately provide an environment-friendly solution for the glass and cement concrete industries \[13\]. This implies that waste broken glass can be used to produce cement concrete to conserves natural resources, save energy, and reduce greenhouse gases to the environment. Various studies have investigated the effect of elevated temperature on the properties and behavior of concrete containing crushed waste glass aggregates as a replacement for natural aggregates. It was observed that the particle size of the crushed glass aggregate is vital in restraining the effect of harmful alkali-silica reaction.

The alkali-silica reaction between the hydroxyl ion present in cement reacts with silica in aggregates in the presence of moisture produces a gel that swells with age and responsible for developing cracks in concrete\[14\]. Generally, 9–21\% of Na2O reported in different glasses, and a higher amount of alkali contain in glass could be the main restriction in its use in concrete due to possible ASR reaction risk. The reaction between alkali and silica is glass particle size dependant; it facilitates the reaction when particle size is more than 1.2–1.5 mm \[15\]. However, glass particle size less than 300 µm will not initiate ASR, and the particle size less than 100 µm was observed to mitigate ASR due to speedy pozzolanic reaction \[16,17\]. The microstructural study shows that the powdered glass utilization alters the engineering properties and affects the hydration process by the pozzolanic reaction. The X-ray diffraction and thermogravimetric analysis techniques showed decent mach regarding reduction in portlandite due to the addition of glass powder in cement. The portlandite consumes about 15–20\% of the cement past volume; when it reaches a temperature between 450-550°C decomposes rapidly and transforms into CaO. This alteration is responsible for developing cracks in the concrete surface, which is believed to be a key reason for a major loss of strength after 400°C in the Portland concrete specimen. \[18,19\]. In high-temperature applications, the CH dehydration is attributed to the Weakness of cement concrete. The partial replacement of cement by glass powder should reduce the portlandite content by the pozzolanic reaction. As an outcome, cement base material containing glass powder usually retains higher mechanical properties than ordinary cement in high-temperature exposure\[20,21\].
Significant research efforts are required to study high-temperature performance on cement concrete containing glass powder as SCM to make concrete versatile and sustainable in hazards like fire, which is the prime interest of this study.

2. Material and methods of experiment

2.1. Characterization of materials used

The Portland cement with properties given in Table 1 was used in the current study to produce mortar. The glass powder of greyish white color was used to replace cement at the rate of 10%, 20%, and 30% in samples. Table 2 shows the chemical composition of fine ground glass powder determined by using XRF (X-ray fluorescence analysis). The physical properties of glass powder used are shown in Table 4. The present glass powder was prepared by crushing the different waste glass bottles to less than 75 µm in this study. The glass powder was manufactured by two other local suppliers and selected as per the requirement of ASTM C618 (Table 3) as pozzolanic material to replace cement. The natural river sand was used as fine aggregates for the preparation of mortar according to ASTM C778 specification [22]. The potable tap water was utilized in mortar production and curing during the investigation.

### Table 1. Characteristics of used cement

| Description                        | Result  |
|------------------------------------|---------|
| Initial setting                    | 115min. |
| Final setting                      | 228min. |
| Finess using Blaine surface        | 280 m²/kg |
| Standard consistency               | 29 %    |
| Soundness                          | 1 %     |
| The specific gravity of cement     | 3.15    |
| The specific gravity of fine aggregate | 2.49   |

### Table 2. Chemical composition of used glass

| Parameters | SiO₂ | CaO | Al₂O₃ | Fe₂O₃ | K₂O | MgO | Na₂O | SO₃ | LOI |
|------------|------|-----|-------|-------|-----|-----|------|-----|-----|
| GP         | 68.70| 7.85| 2.03  | 0.24  | 0.28| 3.25| 17.50| 0.12| 1.45|

### Table 3. ASTM C618 requirements for pozzolanic additives

| Parameters                                | Specified Values | GP   |
|-------------------------------------------|------------------|------|
| SiO₂ + Al₂O₃ + Fe₂O₃ (Min.)               | 70               | 70.97|
| SO₃ (Max.)                                | 04               | 0.12 |

### Table 4. Physical properties of Glass powder

| Parameters                | Value  |
|---------------------------|--------|
| Specific gravity          | 2.61   |
| Finess passing 75 µm      | 100%   |
2.2. Mix Formulation

The mix formulation of cement and glass mortar is given in table 5. The control samples were prepared with ordinary Portland cement with a fixed water binder ratio of 0.42. For glass mortar preparation, glass powder was used to replace Portland cement by the proportion of 10%, 20%, 30%.

| Details     | Cement (g) | GP (g) |
|-------------|------------|--------|
| Replacement | 0%         | 10%    |
|             | 500        | 450    |
| Sand (g)    | 1375       | 1375   |
| Water (g)   | 210        | 210    |

2.3. Sample preparation

The composition of mortar, casting, and mixing was done according to the specification of ASTM C109/109M [23]. The ordinary Portland cement was replaced by GP in proportion levels of 10%, 20%, and 30%. The proportions of the standard mortar materials shall be one part of cement to 2.75 parts of standard sand by weight. The amount of mixing water was fixed using a flow test for a flow of 110 ± 5 as per ASTM 1437 [24]. Dry mix was first mixed uniformly and followed by adding water, then remixing done manually using steel trowel with ensured uniformity. The cube samples with a standard size of 50x50x50 mm were prepared to determine compressive strength as per ASTM C109/109M. All fresh casted cube mould were covered by a thin plastic sheet and kept at room temperature for 24h before demoulding. After that, demoulded mortar specimens were cured in a water tank until the testing period. The preparation of samples and testing as shown in figure 1.

![Figure 1](image1.jpg) **Figure 1.** Preparation of samples and heating in the furnace a) Casting of specimens b) Curing c) Specimen before heating d) Heating in furnace e) Specimen was taken out, f) Testing in compression testing machine.
2.4. Heating pattern
Before exposed to high temperatures, all mortar samples were first cured in water for seven days and 28 days. The water cured samples were kept in an oven at 105 °C for a drying period of 24 hours to avoid unstable spalling. In the high-temperature exposure procedure, the samples were exposed to 200, 400, 600, and 800 °C at a constant rate of 10 °C/min and then kept at targeted temperature for a soaking period 2 hours in an electric furnace. Figure 1(d) shows the elevated temperature testing setup. After that electric furnace was switched off, and the heated samples taken out from the furnace were allowed to cool down for two different cooling regimes. The two types of the cooling regime, air cooling and water cooling, were investigated for this study.

Firstly, for air cooling, samples were removed and allowed to cool down in open air; for water cooling, the hot samples were immediately removed from the furnace and cool down by using water for 10 minutes.

2.5. Compressive strength test
The compressive strength test of the sample was performed and measured as per ASTM-C109. Three 50mm cubic samples were tested in the compression testing machine under a controlled loading rate of 0.6 MPa before and after exposure to high temperature, as shown in figure 1(f)

2.6. Mass loss of mortar samples
The mass loss of the heated sample is an important parameter that can measure the expulsion of chemically and physically bound water due to heating. Before and after each heating sample mass was recorded using an electronic digital balance with an accuracy of ± 0.1g. The mass loss was calculated using \( \frac{M_{\text{Normal}} - M_{\text{Heated}}}{M_{\text{Normal}}} \), where \( M_{\text{Normal}} \) and \( M_{\text{Heated}} \) are the average mass before heating and mass after heating weighted, respectively.

3. Result and discussion
3.1. Compressive strength at ambient and high temperature
The strength activity index was determined as the ratio of compressive strength of a sample with a pozzolanic additive to the compressive strength of the reference sample [25]. The test sample is consists of 80% Portland cement plus 20% pozzolanic additive by mass as recommended by ASTM-C618-17. Figure 2 shows SAI for 20% glass Powder at different ages up to 28days. As per ASTM-C618-17, the pozzolana may have minimum SAI of 75%. AS a result, SAI of 20% GP at 28d was 85% and at 7d was 80%, which is higher than ASTM standard. The increase in the value of activity index from 7day to 28days indicates as the age increase, the index of glass mortar tends to increase

Figure 2. Strength activity index

Figure 3 shows the effect of age on the compressive strength of mortars prepared with 0%, 10 %, 20 %, and 30% glass powder. In all mortar sample the compressive strength increase with the increase in age. The controlled mortar sample compressive strength was greater than the mortar samples containing glass powder at an earlt age. This variation tended to decline with age. For instance, the
7 days compressive strength of mortar containing 10% GP was 90% of that of the controlled mortar, which increased up 118% at 28 days, indicating good pozzolanic reactivity. The compressive strength observed in the 20% replacement is 80% at 7d and 102% at 28d. In 30% GP, the strength was 76% and 86% at 7d and 28d respectively of a reference sample, which indicates an increase in glass powder reduces the reactivity.

Figure 4 and figure 5 show seven days compressive strength of 10%, 20%, and 30% replacement by GP mortar after exposure to elevated temperature is observed less than the normal mortar in both cooling regimes, which may be due to a slow pozzolanic reaction at an early age.

Figures 8 and 9 show that for 28d, the compressive strength of 10% replacement by GP mortar after exposure to elevated temperature is observed almost more than the normal mortar by 6 to 7% in both cooling regimes, which may indicate that progress in pozzolanic reaction at later age.
Figure 6. 7d Residual compressive strength of water cooling regime samples

Figure 7. 7d Residual compressive strength of air cooling regime samples

Figure 8. 28d Compressive strength of water cooling regime samples
Figure 9. 28d Compressive strength of air cooling regime samples

Figure 10. 28d Residual compressive strength of water cooling regime samples

Figure 11. 28d Residual compressive strength of air cooling regime samples
3.2. Mass loss of mortar samples

Figure 12 shows the mass loss of mortar sample after exposure to elevated temperatures. The mass loss of mortar samples was observed to increase as temperature increases, mainly due to the dehydration of calcium silicate hydrates and calcium hydroxide (CH) upon heating. In comparison, the control mortar sample shows a higher mass loss (6.8%) than glass mortar samples (6.3%). Furthermore, the maximum mass loss of cement mortar sample was observed at a temperature of 800 °C, mainly due to the rapid decomposition of hydration products in the cement pastes.

3.3. Residual Compressive strength

The residual compressive strength is a chief parameter to measure the effect of elevated temperature on cement when replacing with supplementary cementitious material. At the early curing age and for both cooling regimes, the residual compressive strength of glass mortar for all replacement levels was found less than the control sample shown in figures 6 and 7. Figure 10 and figure 11 show that mortar containing 10% and 20% replacement maintained a higher value of residual compressive strength than the normal reference sample at all temperature range. At 400 °C, the retained residual strength values are 72% and 80% in the water cooling regime. In the air cooling regime, the retained values are 80 and 82%; the maximum difference was maintained up to 800 °C was only 6%.

The Compressive residual strength retained of 10% GP mortar observes more at all temperatures than the normal mortar and all replacements levels with both cooling conditions that are maximum 99.3% in air cooling and 93.3% in water cooling 200°C. The comparative investigation of Figures 10 and 11 shows the differential performance between normal reference samples and glass mortar when exposed to temperature 200 to 800 °C. On a performance basis, the exposure could be divided into two parts as 0-400°C and 400°C -800°C. In the range 400 °C to 800 °C in water cooling regime, the strength loss is 38.75% & 38.62% for 10% and 20% replacements respectively as compared to the reference sample loss of 35.60%; it indicates that the loss is more by 3.15% and 3.02% for same replacement level. Similarly, for air cooling, the loss is 53.6% & 50.6% for 10% and 20% replacement, respectively, compared to the reference sample loss of 48.9%. It indicates that the loss is more by 2.9% and 1.7% for the same replacement level and less than the water cooling sample. Therefore air cooling retains more strength than water cooling, the more loss of strength due to thermal shock in water cooling.

The strength loss below 400 °C was observed indicates dehydration of portlandite[20]. The glass powder addition reduces the portlandite content.[26] The Compressive residual strength for 10% GP retained also seen higher and compatible with normal mortar samples in case of air cooling and water cooling.

The residual compressive strength of 20% replacement of GP mortar observes more than the normal mortar, and 10% Replacement level GP is sufficiently more than normal in both cooling regimes.
4. Conclusion

Based on the current experimental study, the effects of elevated temperatures on the compressive strength of glass mortar have been explored, and the following conclusions are drawn.

1. The pozzolanic activity index increase with the increase in the age of samples shows portlandite consumption by the pozzolanic reaction.

2. The residual compressive strength retained of 10% and 20% GP mortar observes more at all temperatures than the normal mortar and all replacements levels with both cooling conditions. The mortar sample containing 10% glass powder at 28 days curing found an ideal mix regarding compressive strength.

3. The residual strength at 800 °C was almost the same 10 to12% in all replacement levels, and the cooling regime compare to the normal sample shows similar thermal behavior and changes.

4. In the range 400 °C to 800 °C in the water cooling regime, the strength loss is 38.75% & 38.62% for 10% and 20% replacements, respectively, compared to the reference sample loss of 35.60 %. It indicates that the loss is more by 3.15% and 3.02% for the same replacement level. Similarly, for air cooling, the loss is 51.8% & 50.6% for 10% and 20% replacement compared to the reference sample loss of 48.9%. It indicates that the loss is more by 2.9% and 1.7% for the same replacement level and less than the water cooling sample. Therefore air cooling retains more strength than water cooling, the more loss of strength due to thermal shock in water cooling.

5. The experimental result shows that the mortar sample with 20% glass powder had a greater SAI than the value for the pozzolanic additive mentioned in ASTM C618. Thus, the glass powder is suggested as a pozzolanic material to replace Portland cement in the production of concrete partially. The experimental investigation reveals that GP contributed to the pozzolanic activity and enhanced the high-temperature performance of cement-based material. The study would inspire industrial practitioners to use glass as cement-based material to produce sustainable construction and building materials.

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