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Effect of Varying Glass Powder Size on Performance of Cement Mortar: Microstructural and Compressive Strength Assessment at High Temperatures

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ABSTRACT

This study employs fine glass powder as a partial replacement for ordinary Portland cement in order to better understand the complex effects of high temperature on the microstructure and compressive strength of cement mortar. The study aims to identify the optimal mix that maximizes the benefits of glass powder incorporation by experimenting with different glass powder sizes (38 µm, 53 µm, and 75 µm) and replacement rates (10%, 20%, and 30%). At 25ºC, 200ºC, 400ºC, 600ºC, and 800ºC, mortars containing glass powder were subjected to compressive strength tests. Mortar samples were examined using X-ray diffraction (XRD), scanning electron microscopy (SEM), and Thermo Gravimetric analysis (TGA) to gain insight into their behavior at high temperatures. Mortar mixes containing 10% glass powder (38 µm size) performed best at temperatures below 400ºC, with an average residual strength index value of 90.7% compared to 87.8% in the reference sample. The glass powder mortars with 10% and 20% replacement rates functioned better at higher temperatures of 800ºC, losing just 52-57% of their strength as opposed to 72% in the control sample. The increased pozzolanic activity attributable to the addition of glass powder is shown by XRD and SEM analyses to account for the increased strength of mortar by consuming more portlandite ($Ca(OH)_2$). TGA study has shown that at temperatures exceeding 400ºC, to bermorite and other hydrated products become dehydrated, which may account for the strength reduction.

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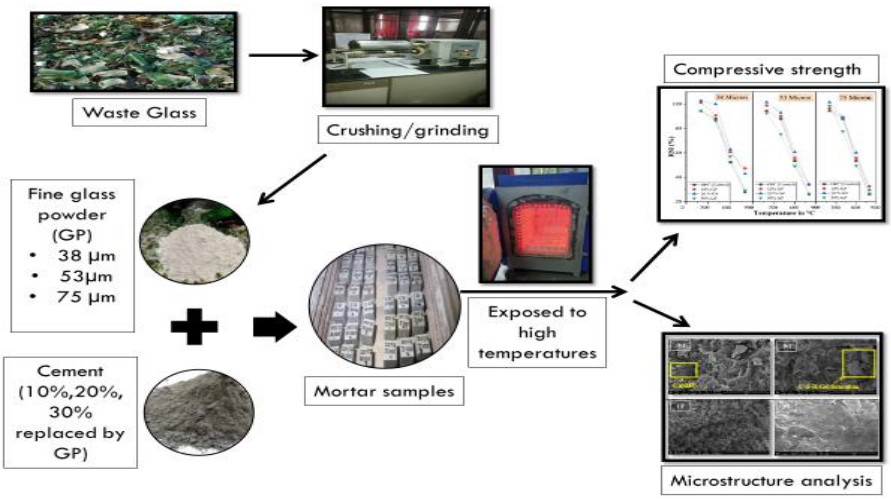
Graphical Abstract



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1. INTRODUCTION

The concrete industry, heavily reliant on non-renewable resources and CO_2-intensive processes, presents a significant opportunity for sustainability through the exploration of alternative materials (1). Concrete, a primary construction material, typically contains 10-15% Portland cement (OPC), with the remainder being aggregates, water, and other additives. However, OPC production is environmentally taxing due to its high CO_2 emissions—0.7 to 1 ton per ton of OPC—and its heavy reliance on natural resources like limestone (2). Additionally, Portland cement-based concretes have durability issues, leading to 40-50% of construction budgets being spent on repairs. This underscores the need for alternative cement materials that are more sustainable and address OPC's shortcomings (3). Such environmental awareness has heightened interest in converting industrial by-products into concrete ingredients. Using these wastes not only conserves materials and energy but can also enhance concrete performance. To this end, supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag, or glass powder are used to replace cement, reducing both consumption and environmental impact (4, 5).

One of the major issues faced by concrete is the elevated temperatures which can significantly compromise the structural integrity and durability of concrete. When exposed to high temperatures, concrete undergoes physicochemical transformations, leading to a loss of compressive strength, spalling, and changes in its microstructure (6). Supplementary cementitious materials (SCMs) play a pivotal role in mitigating these adverse effects. Incorporating SCMs enhances the thermal stability of concrete (7). They not only improve the concrete's resistance to high temperatures but also aid in preserving its mechanical properties, making it more resilient to temperature-induced degradation (8). However, with the increasing use of supplementary cementitious materials (SCMs) in concrete, its high temperature performance has become more complicated. Therefore, investigating the influence of concrete constituents such as SCMs at high temperatures is of great significance.

The use of fine glass powder, derived from waste glass, as a partial replacement for cement in concrete production, has recently gained attention due to its potential benefits in enhancing the mechanical and durability properties of concrete while promoting sustainability (9). Several studies have investigated the impact of fine glass powder on the compressive strength of concrete at ambient temperature conditions. Aliabdo et al. (10) found that the inclusion of glass powder at 10% as a cement replacement could enhance the compressive strength of mortar by 9%. Similarly, Nagrockienė and Barkauskas (11) found that adding 5% waste glass powder to cement-based mortar can improve its performance for civil engineering applications. Fine glass particles, when ground to less than 75 µm, can enhance concrete strength and durability due to their pozzolanic reactivity. This reactivity increases with the surface area of particles, improving the concrete microstructure (12). Moreover, finely ground glass powder (GP) with a particle size below 100 µm does not trigger alkali-silica reactions due to rapid pozzolanic reaction, a common issue with larger glass aggregates (13). However, the potential of glass powder as a supplementary cementitious material, especially its impact on cement hydration and microstructure at elevated temperatures, remains largely unexplored and warrants further investigation. Few studies have investigated the mechanical properties, durability, and thermal stability of concrete incorporating glass powder, showcasing potential avenues for sustainable and resilient construction materials. Yang et al. (14) found that cement mortar with glass powder showcased less degradation under high temperatures compared to traditional mortar. It is attributed to the vitreous nature of glass which tends to resist thermal degradation to a certain extent. The spalling behavior of concrete is a significant concern at high temperatures. Research conducted by Ali et al. (15) highlights that the use of glass powder can mitigate spalling, primarily due to its influence in modifying the pore structure of the concrete, thereby facilitating better thermal strain accommodation. While some research points to an initial decrease in strength with increased glass powder content (16), others suggest a possible enhancement in strength upon optimizing the particle size and blending proportions at high temperatures above 400°C (17). It is highly important to note that temperatures as high as 800°C can induce phase transformations in the concrete matrix. This often requires a thorough understanding of the formation of new phases and the decomposition of existing phases at high temperatures, which can affect the durability of the concrete. Scanning Electron Microscopy (SEM) analyses performed by Dyer and Dhir (18) showed that fine glass powder-blended concretes possessed denser microstructures, even after exposure to high temperatures. This is attributed to the pozzolanic reaction of the glass powder, which fills the micro voids in the matrix. However, existing literature insufficiently explores the microstructural alterations in glass powder concrete under high temperatures, particularly concerning the influence of glass powder fineness.

Therefore, this research aims to investigate the impact of high temperature on the microstructure properties and its subsequent effects on the compressive strength of glass powder-cement mortar. To achieve this, fine glass powder with varying granule sizes such as 38 µm, 53 µm, and 75 µm has been utilized as a substitute for cement at

replacement rates of 10%, 20%, and 30% to pinpoint the best substitution level for glass powder, emphasizing its role in enhancing cement mortar properties. The residual strength of glass powder-cement mortar after thermal exposure is also evaluated. The testing of residual compressive strength of cement mortar at temperatures up to 800°C is essential for safety assessments, material development, and a deeper understanding of the material's behavior under extreme conditions. The results of this study have the potential to improve building safety by contributing to the creation of fireproof concrete.

2. MATERIALS

2. 1. Cement and Aggregate In this study, OPC-53 grade Portland cement, conforming to IS 12269:2013 (19), was procured from a local market. Its basic properties and chemical composition determined through X-ray Fluorescence (XRF) analysis, are detailed in Tables 1 and 2, respectively. The chemical composition of cement highlights a predominant CaO content of around 60%. Locally sourced river sand, meeting IS 650:1991 (20) criteria, served as the fine aggregate with a specific gravity of 2.49. Potable water was utilized for both mixing and curing procedures.

2. 2. Glass Powder Greyish-white glass powder with a specific gravity of 2.61 was produced from mixed waste glass sourced locally, undergoing crushing, and grinding processes. The powder was then segregated into three distinct categories through a sieving process involving three different sieves: GP-A with an average size of less than 38 µm, GP-B with less than 53 µm, and GP-C with less than 75 µm. Sieve analysis data illustrates a uniform gradation in the particle size analysis, revealing that all glass powder types contain particles smaller than 75 µm (Figure 1). XRF analysis (Table 2) indicates a SiO_2 content increase in the sequence GP-A > GP-B > GP-C, attributed to decreasing particle size. As per ASTM-C618 requirements (25) outlined in Table 3, all three glass powder variants meet the chemical composition criteria for pozzolanic materials, presenting a viable option to substitute cement in mortar preparation.

TABLE 1. Physical properties of cement

Standard consistency	30.5	IS:4031 (Part-4) (21)
Initial setting time	155 minutes	IS:4031 (Part-5) (22)
Final setting time	234 minutes	
Soundness	1.00%	IS:4031 (Part-3) (23)
Fineness by Blaine surface	278 m^2/kg	IS:4031 (Part-2) (24)
Specific gravity	3.15	

TABLE 1. Chemical composition of raw materials (%)

Raw material	**OPC**	**GP-A**	**GP-B**	**GP-C**
SiO_2	15.7	70	68.7	67.6
CaO	71.8	7.46	7.85	7.46
Al_2O_3	2.01	1.6	2.03	1.45
Fe_2O_3	5.39	0.99	0.237	1.08
SO_3	2.65	0.59	0.124	0.69
K_2O	0.69	0.3	0.279	0.26
MgO	-	1.99	3.25	1.41
TiO_2	0.72	0.069	-	0.06
Na_2O	-	16.5	17.5	19.34
MnO	0.05	0.044	-	0.052

2. 3. Mixing and Casting Procedure Table 4 shows the mix proportion that was used for preparing 240 samples of mortar in which fine glass powder of varying sizes was substituted for OPC cement. In addition, 45 control samples were made using a ratio of 1 part Portland cement (100%) to 3-part sand by weight (26). The experimental work used a w/b ratio of 0.42 for the flow of mix 110 ± 5.0. Mortar samples were made by substituting 10%, 20%, and 30% of the cement with glass powder. Mortar sample composition, mixing, and casting were all carried out in accordance with IS 4031 (part 6):1988 (26) and IS 1727:1967 (27) standards. After thoroughly combining the dry ingredients, water was added in accordance with a predetermined w/b ratio. Later, using the steel trowel, the components were mixed by hand to ensure consistency. To test the compressive strength of mortar in accordance IS 4031 (part 6):1988 (26), a 70.6 mm cube mold was filled with a fresh mortar

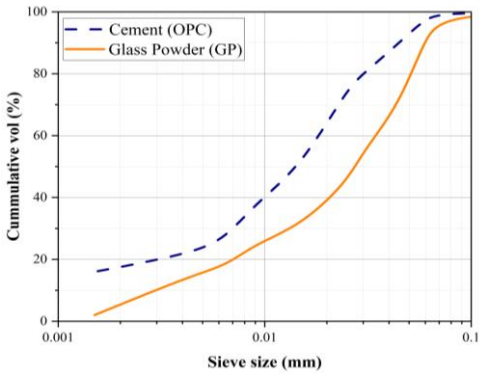

Figure 1. Grain size distribution

TABLE 3. ASTM C618 requirements for pozzolanic binders

ASTM C618	**Value**	**GP-A**	**GP-B**	**GP-C**
$SiO_2+Al_2O_3+Fe_2O_3$	≥ 70%	72.59	70.96	70.13
SO_3	≤ 4 %	0.59	0.12	0.69

TABLE 4. Mix proportion of mortars with different (%) of glass powder

Mix	Components (g)			
	Cement	Sand	GP	Water
OPC (Control)	600	1800	0	252
10%GP-A*	540	1800	60	252
20%GP-A*	480	1800	120	252
30%GP-A*	420	1800	180	252

(*same mix proportion used for GP-B and GP-C)

mix and vibrated on a vibration table to achieve compaction. Fresh samples were stored for 24 hours at room temperature before demolding and curing for 7 and 28 days in water, respectively.

To analyze the impact of high temperatures on the mortar samples, water-cured 28-day samples were first dried in an oven at 105°C for 24 hours to prevent unstable spalling. Subsequently, they underwent a high-temperature exposure process where they were subjected to temperatures of 200°C, 400°C, 600°C, and 800°C at a steady increase of 10°C/min in an electric furnace. Each sample was maintained at the target temperature for a 2-hour soaking period before the furnace was turned off. The samples were then removed and cooled naturally in open air. Additionally, all samples were tested under room temperature conditions at 25°C for comparison.

3. TEST PROCEDURES

The specimens for compressive strength were tested in the compression testing machine under a controlled loading rate of 35 N/mm^2/min before and after exposure to high temperatures. The results presented correspond to the average of a minimum of three specimens. XRD patterns were obtained using a high-resolution X-Ray diffractometer (Rigaku SmartLab, Japan). The samples were crushed and dried just before running the tests. Diffraction analyses were made from 10º to 80º 2θ using copper K radiation at a rate of 5° per min. The excitation voltage was 40 kV at 40 mA and the minerals and compounds in each specimen were determined using the "MATCH-3" software. The underlying internal changes in the microstructure were identified using 1-cm^3 specimens obtained from the compressive strength tested mortar samples by performing SEM analysis using a Carl Zeiss supra 55 FESEM model (Germany) with an energy dispersive X-ray spectroscopy (EDS) detector. A TG/DTG thermal analysis was performed on a simultaneous TA Instruments SDT-Q600 equipment. Samples were analyzed under an oxygen atmosphere (100 ml/min) at a heating rate of 10°C/min using alumina crucibles.

4. RESULTS AND DISCUSSION

4. 1. Effect of Glass Powder Size on the Strength Activity Index (SAI) According to ASTM C618 (25), the strength activity index (SAI) should be calculated using an 80:20 cement-to-additive mass ratio, with a minimum acceptable value of 75% for any pozzolan. This index is determined by comparing the compressive strength of pozzolan additive-inclusive samples to that of reference samples (10). Figure 2 illustrates the SAI for three different GP-inclusive mortar mixtures such as 80% OPC combined with 20% GP-A, GP-B, or GP-C at 7 and 28 days of period. Complying with the code, 20%GP-A exceeded the 75% threshold at both 7 and 28 days of curing. In contrast, 20%GP-B and 20%GP-C fell short of the criteria at 7 days but demonstrated significant improvement with SAI values of 89.2% and 88%, respectively at 28 days. The inconsistency in activity indices among the different glass powders can be attributed to variations as reported in literature (28). Specifically, GP-A, which contains a higher proportion of particles under 38 µm, offers a greater specific surface area (SSA), thereby resulting in better compressive strength compared to GP-B and GP-C.

4. 2. Effect of Glass Powder Size on Compressive Strength of Mortar Figure 3 shows the influence of curing age and glass powder size on the strength of GP-mortars with 10%, 20%, and 30% glass powder replacement levels at ambient temperature. Initially, at a 7-day curing age, all three variations of glass powder substitution resulted in decreased compressive strength compared to the control sample (C) with 40 MPa strength, likely due to a dilution effect (29). However, after a 28-day curing period, GP-mortars with 10% and 20% glass powder replacements demonstrate similar or superior strength levels to the control (58.12 MPa), owing to enhanced pozzolanic activity, promoting the

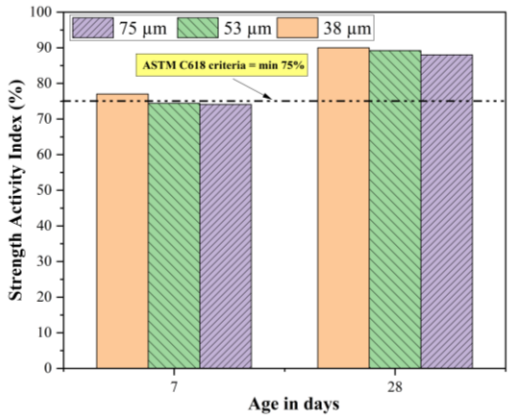

Figure 2. Effect of GP size on strength activity index

formation of more hydration and pozzolanic products (30). Notably, there is a decrement in strength with increasing glass powder size (38µm to 75µm) and replacement ratio (10% to 30%), irrespective of the curing duration. Particularly, the 10%GP-A mortar exhibits optimal performance, with its strength exceeding 10%GP-B and 10%GP-C strength values by 1.02 and 1.04 units respectively at 28 days, indicating it as the most efficient substitution ratio.

Figure 4 shows the behavior of compressive strength of the different mortars when exposed to an elevated temperature range between 200°C and 800°C. In general, all mortars lose strength as the temperature increases. The primary causes of this are the dissociation of hydration phases and thermal incompatibility at higher temperatures, both of which result from physical and chemical changes (31). If the cement mortar containing glass powder is exposed to temperatures near or above the transition temperature of the glass, the glass particles could soften. This could potentially lead to a reduction in the compressive strength of the mortar due to the softening of the glass particles, which would no longer contribute to the strength of the matrix as effectively. In the present study, the effect of temperature causes a significant loss in strength for all the mortars upto 800°C, but the residual compressive strength of GP-mortar for 10% and 20% replacement levels is found to be much higher with much less strength loss than 30% and control samples upto 400°C regardless of glass powder size. In particular, the decreased calcium hydroxide ($CaOH_2$) content due to the pozzolanic effect is responsible for the greater strength of the 10%GP and 20%GP replacement levels compared to the control. Higher temperatures accelerate the pozzolanic reaction, which results in the development of additional calcium silicate hydrate (C-S-H) phases in GP-mortars (16). This finding agrees with prior research that has found similar behavior of compressive strength as a result of elevated temperatures (14, 32). However, when the mortar samples are exposed to temperatures greater than 400°C, the compressive strength reduces dramatically in all samples mainly due to the microstructure changes in the material and glass transition temperature of glass.

In addition, it was determined that the residual compressive strength of the fine glass powder (GP-A) was more prominent than that of the relative coarse glass powders (GP-B and GP-C) because the pozzolanic activity increased with glass powder fineness (33). In comparison to GP-B, GP-C, and control samples, the residual compressive strength of 10%GP-A at 200°C was 4.68%, 9.17%, and 13.27% greater, respectively. Also, compared to GP-B, GP-C, and control samples, 10%GP-A at 800°C exhibited higher residual compressive strength by 42.4%, 51.3%, and 78.89%. The subsequent microstructure analysis further explains the possible mechanisms for the results obtained at elevated temperatures in this study.

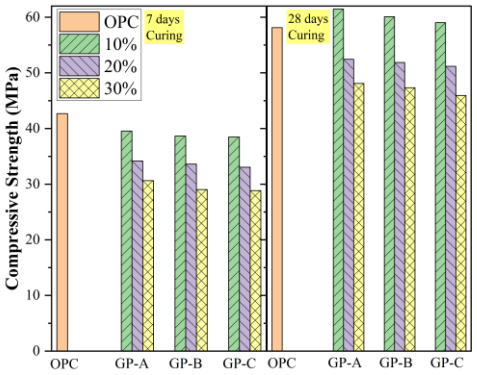

Figure 3. Effect of glass powder size on compressive strength at room temperature condition

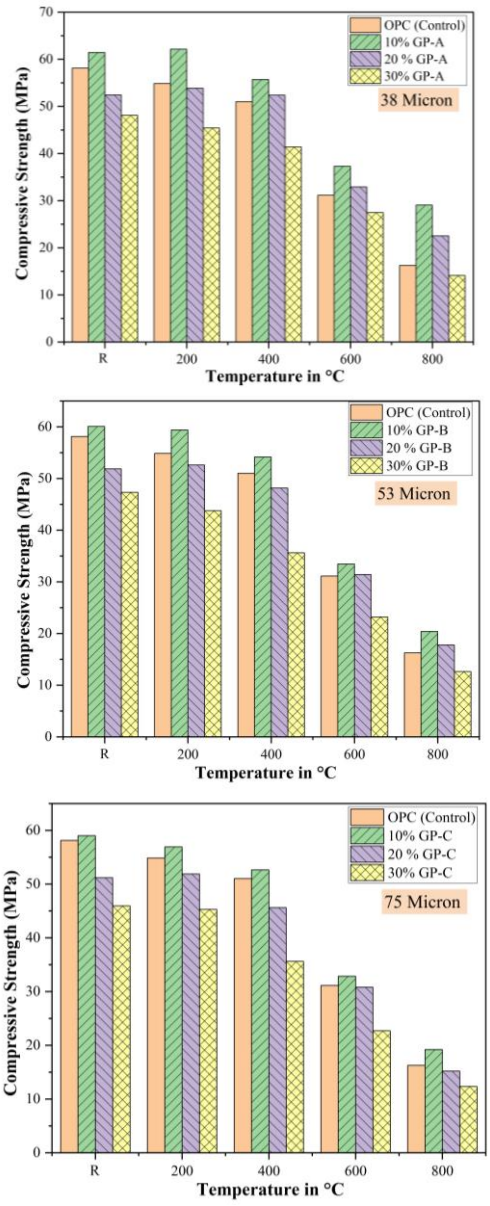

Figure 4. Effect of fine GP size on compressive strength of mortar at elevated temperatures

4. 3. Residual Strength Index (RSI) The residual strength index (RSI) for different GP-mortars as shown in Figure 5 was calculated as the percentage ratio of residual strength at elevated temperature to the initial strength at room temperature [7]. With an RSI of 101.1% and 102.7%, respectively, GP-A mortar with a 10% and 20% replacement rate exhibited excellent original strength at 200ºC temperature, in comparison to OPC mortar. Up to 400ºC, strength loss was minimal for both GP-B and GP-C mortars as well. The RSI value of GP-mortars drops considerably as the temperature increases from 400ºC to 600ºC and 800ºC, but 10%GP-A and 20%GP-A continue to perform better than control mortar, losing only 37-39% and 52-57% of their strength, respectively, at 600ºC and 800ºC compared to 47.7% and 72% strength loss for the control sample. The lower thermal conductivity of glass powder provides better fire resistance and maintains its structure and strength properties, and the enhanced pozzolanic activity of glass powder leads to the formation of a denser matrix as well as additional pozzolanic/hydration gels (34, 35). These two are the possible reasons for the higher RSI values for GP- mortars compared to control. The 30% substitution of OPC with GP in mortar proved less efficient, leading to a greater decrease in compressive strength. This is primarily due to the dilution effect: the higher replacement rate and reduced cement content result in lower formation of hydration products compared to the control sample.

4. 4. XRD Analysis The XRD spectra of 28 days cured OPC mortars before and after exposure to 200ºC and 800ºC temperatures are demonstrated in Figure 6. These mortar samples were chosen to analyze the strength behavior across a range of thermal exposures. The diffractograms reveal that the intensity variations in the peaks corresponding to portlandite, alite, and belite across all samples are a result of the thermal effects on the hydrated OPC mortar, with a notable decrease in peak height as temperatures escalate from 25°C to 800°C (36). This alteration is attributed to the transformation of portlandite into carbonate or lime. Furthermore, the XRD analysis confirms the formation of hydration products such as ettringite and dense C-S-H gel at room temperature, evidenced by their distinct peaks at 2θ-29.6º, 32.5º and 47.4º (37). However, these peaks diminish at 800°C, indicating the dehydration of crystalline structures at lower temperatures of 200°C-400°C and the disappearance of amorphous hydrated products from the XRD pattern. Notably, at the extreme temperature of 800°C, the C-S-H undergoes a transition to thermally stable forms of alite and belite (31).

Figure 6 also shows the XRD spectra of GP-A, GP-B, and GP-C mortars at 10% optimum replacement level for temperature exposure to 25ºC, 200ºC, and 800ºC. The temperature-induced alterations in crystalline phases appear consistent between cement paste and GP-mortars Notably, the glass powder particle size significantly influences the peak heights of crystalline products, with the intensity of portlandite, alite, and belite in the order of GP-C>GP-B>GP-A (8). Glass powder, a pozzolanic substance, interacts with the portlandite produced in the cement system, promoting C-S-H formation. This reaction not only creates a denser structure, as evidenced by the XRD patterns but also enhances the fire resistance of GP-mortar, indicated by the diminished portlandite peaks (38). At 800°C, portlandite peaks are nearly eliminated. Furthermore, the data reveals an increase in C-S-H peaks for GP-mortars at 200°C, particularly for GP-A mortar, suggesting enhanced compressive strength compared to the control. However, at 800°C, these peaks display reduced intensity, indicating a decrease in the C-S-H concentration.

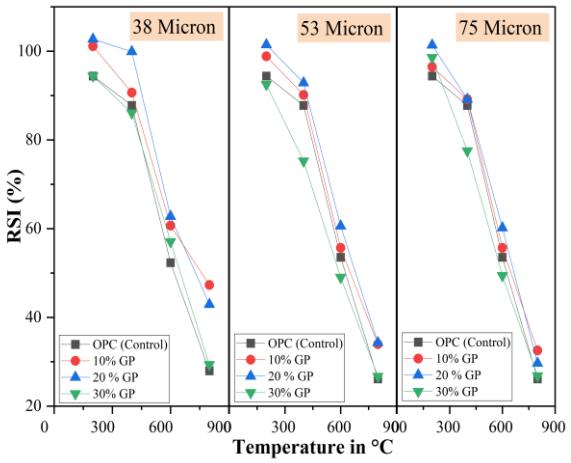

Figure 5. Effect of glass powder and varying temperature on RSI of mortar

4. 5. SEM Analysis Figure 7 illustrates the morphological changes in 28-day cured samples of OPC mortar and 10%GP mortars at various temperatures. Figures 6(a) and 6(b) depict the room temperature and 200°C exposure states of control sample, characterized by hexagonal portlandite plates that signify the microstructure of the samples (39). However, at 800°C, these plates are absent, indicating portlandite decomposition as shown in Figure 6(c). This thermal exposure also induces micro-cracks surrounding unhydrated particles and leads to the loss of distinct crystal structures in hydrated phases, resulting in the prevalence of irregular and amorphous agglomerates throughout the sample. Figures 6(d), 6(g), and 6(j) reveal that GP mortars at room temperature maintain a crystalline phase, evidenced by large plates similar to those in cement paste, with visible micrometer-sized

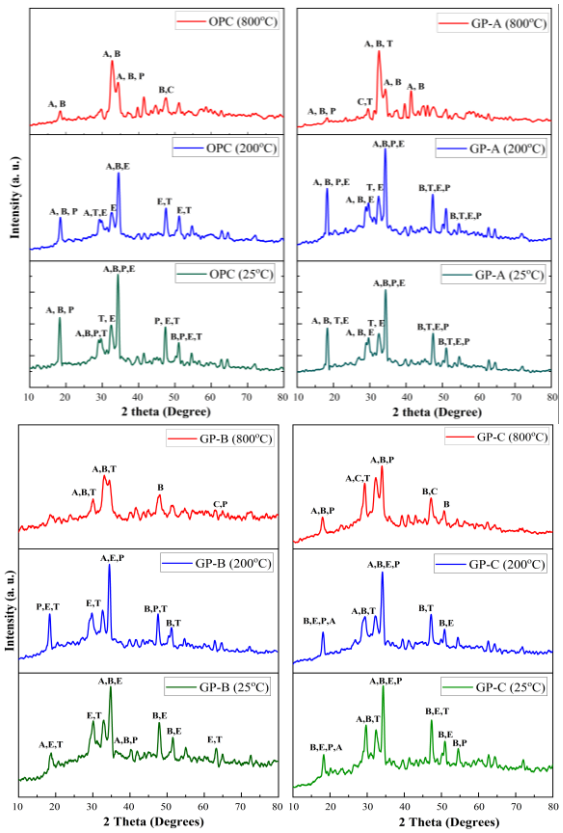

Figure 6. XRD analysis of OPC mortar and GP-mortars (A=Alite, B=Belite, C=Calcite, E=Ettringite, P=Portlandite and T=Tobermorite)

spherical glass powders dispersed uniformly across the sample. Additionally, all three GP-mortar variants exhibited the presence of C-S-H gel. Notably, higher temperature exposures caused the disappearance of platelike crystals, although some intact GP particles were occasionally observed within the sample.

4. 6. TGA Analysis The TG analysis curves of OPC mortar and GP-A mortar specimens after hydration of 28 days are shown in Figure 8. The weight loss of mortar samples was found by heating them continuously from 20°C to 900°C. Water evaporation and the dehydration of C-S-H hydrates accounted for the mass loss observed across all samples between 50°C and 200°C (40). Within this temperature range, OPC lost 3.59% of its weight while GP-A lost 4.31% for samples exposed to 200°C.

The greater percentage of weight loss seen with GP-A mortar indicates the highest level of gel formation. As gypsum and other gel products decomposed at 350°C–500°C in mortar samples, mass loss was significant in this range (36). In addition, portlandite $Ca(OH)_2$ melts at 500°C–600°C. Thus, all samples lost mass because of deformation at high temperature. Lastly, albite and $CaCO_3$ decomposed at 600°C –800°C, causing mass loss. The maximum GP-A mix weight-loss percentage during these peaks was 2.31%. Greater weight loss showed the highest carbonate content in the GP-A sample, which explains its (10) higher mechanical properties.

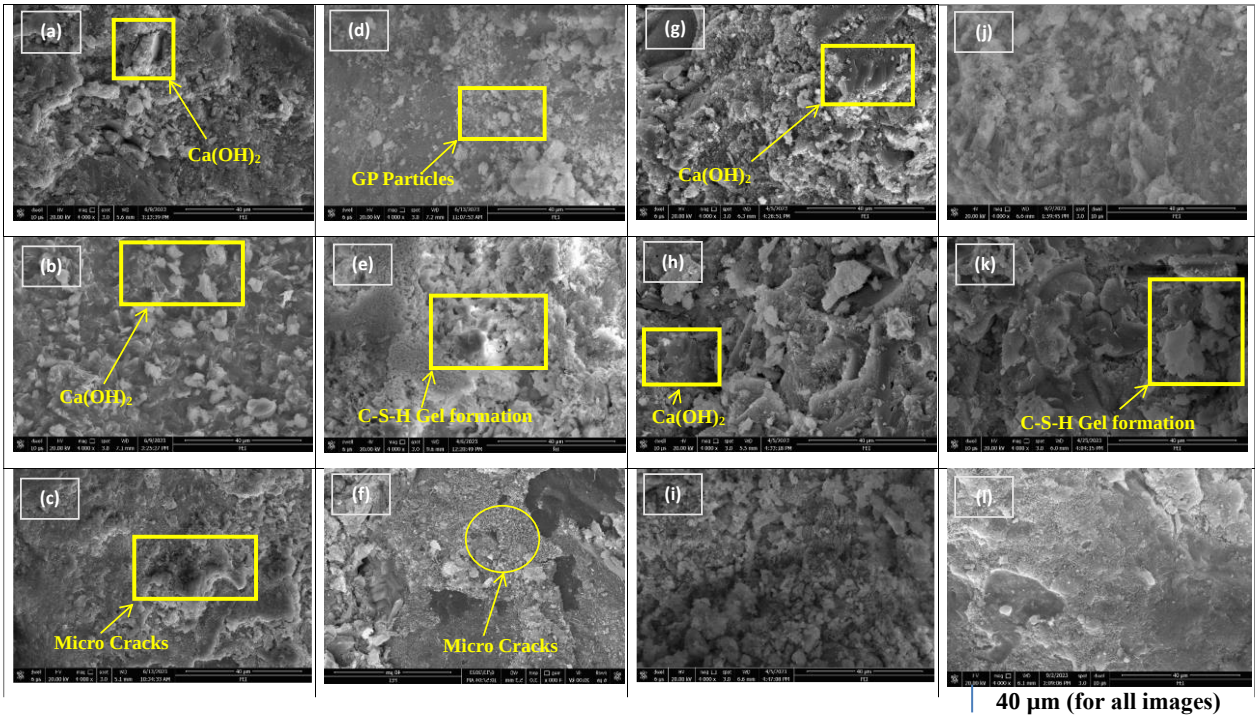

Figure 7. SEM analysis of OPC mortar and GP-mortars [(a),(b),(c)-OPCmortar;(d),(e),(f)-GP-A;(g),(h),(i)-GP-B; (j),(k),(l)-GP-C]

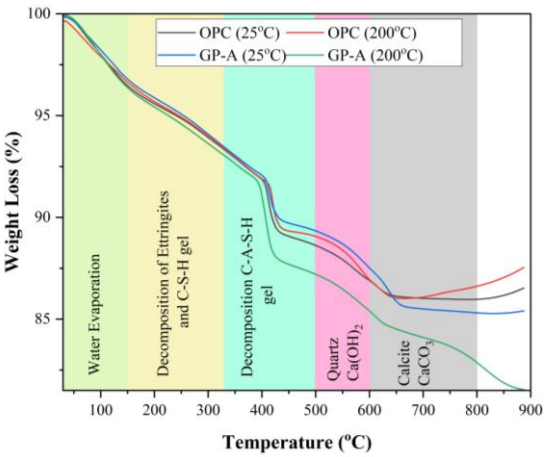

Figure 8. TG analysis of OPC mortar and GP-A mortar

5. CONCLUSION

Using cementitious mortars with 10%, 20%, and 30% replacement rates of glass powder of varying fine particle sizes, this study illustrates the influence of increased temperatures on the properties of the mortars. The following conclusions are drawn:

- Compressive strength testing indicated that 38µm particle size GP substitution in cement mortar was the most effective. At 200°C, 10% replacement increases the residual compressive strength by 13.27% compared to the control mortar.
- When exposed to temperatures above 400°C, mortar samples, including GP, show a decline in compressive strength. However, 10%GP-A and 20%GP-A performed better by achieving a higher RSI value than the others.
- XRD and SEM analysis demonstrate that the inclusion of GP increases the pozzolanic activity, which causes more portlandite to be consumed in GP mortars, resulting in greater strength. Dehydration of main hydration products and portlandite, as verified by TGA analysis, may account for the strength loss at temperatures above 400°C.

With its low thermal conductivity and pozzolanic character, GP is a great cement alternative because it helps cement mortar withstand high temperatures and maintain its strength. More study on the fire resistance of structural members built from concrete incorporating glass powder and its behavior at high temperatures is needed.

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Persian Abstract

چکیده

این مطالعه از پودر شیشه ریز به عنوان جایگزینی جزئی برای سیمان پرتلند معمولی به منظور درک بهتر اثرات پیچیده دمای بالا بر ریزساختار و مقاومت فشاری ملات سیمان استفاده می‌کند. هدف این مطالعه شناسایی ترکیب بهینه ای است که مزایای ترکیب پودر شیشه را با آزمایش با اندازه های مختلف پودر شیشه (۳۸ میکرومتر، ۵۳ میکرومتر و ۷۵ میکرومتر) و نرخ جایگزینی (۱۰٪، ۲۰٪ و ۳۰٪) به حداکثر می رساند. در دماهای ۲۵، ۲۰۰، ۴۰۰، ۶۰۰ و ۸۰۰ درجه سانتی گراد، ملات های حاوی پودر شیشه تحت آزمایش مقاومت فشاری قرار گرفتند. نمونه های ملات با استفاده از پراش اشعه ایکس (XRD)، میکروسکوپ الکترونی روبشی (SEM)و تجزیه و تحلیل ترموگراویمتری (TGA) برای به دست آوردن بینشی در مورد رفتار آنها در دماهای بالا مورد بررسی قرار گرفتند. مخلوط ملات حاوی ۱۰ درصد پودر شیشه (اندازه ۳۸ میکرومتر) در دمای کمتر از ۴۰۰ درجه سانتیگراد با میانگین مقدار شاخص مقاومت باقیمانده ۹۰.۷ درصد در مقایسه با ۸۷.۸ درصد در نمونه مرجع بهترین عملکرد را داشتند. ملات پودر شیشه با نرخ جایگزینی ۱۰٪ و ۲۰٪ در دماهای بالاتر ۸۰۰ درجه سانتیگراد عملکرد بهتری داشتند و تنها ۵۲-۵۷٪ از مقاومت خود را در مقایسه با ۷۲٪ در نمونه شاهد از دست دادند. افزایش فعالیت پوزولانی که به افزودن پودر شیشه نسبت داده می شود، توسط تجزیه و تحلیل های XRD و SEM نشان داده شده است که افزایش استحکام ملات را با مصرف بیشتر پرتلندیت ($Ca(OH)_2$)نشان می دهد. مطالعه TGA نشان داده است که در دماهای بیش از ۴۰۰ درجه سانتیگراد، برموریت و سایر محصولات هیدراته دچار خشکی می شوند که ممکن است دلیل کاهش مقاومت باشد.