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The Role of Glass Powder in Strength and Durability Improvement of Concrete

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Abstract. The cement industry is one of the prime sources of carbon dioxide diffusion that causes global warming by releasing greenhouse gases into the atmosphere Therefore, many researchers tend to replace the proportions of cement in concrete with other materials such as waste glass powder. This study investigates the use of waste glass powder as a partial replacement for cement in concrete production. The glass powder, with a particle size range of 90–63 µm, was incorporated at three different substitution levels: 10%, 15%, and 20%. The workability, compressive strength, and split tensile strength of the concrete were evaluated. Additionally, durability was assessed by subjecting the concrete cubes to direct fire at 400°C for two hours. The results indicate that replacing cement with waste glass powder leads to a decrease in workability as the glass content increases. Both compressive and splitting tensile strengths showed a significant enhancement with higher glass content. the mix with 20% glass powder demonstrated the most promising performance, offering a good balance between mechanical strength and durability. Based on these findings, the study concludes that 20% glass powder can serve as a viable alternative to cement, providing an environmentally friendly concrete mix with satisfactory performance.

Keywords: Glass Powder, Fineness, Fire Exposure

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1 Introduction

Cement production is a significant contributor to greenhouse gas emissions, and utilizing supplementary cementitious materials (SCMs) to partially replace cement in concrete is a promising strategy to mitigate the environmental impact of the industry. One such material is finely ground glass powder, which has shown positive results as a cement substitute in concrete mixtures. Glass, being amorphous material rich in silica, becomes an effective pozzolanic material when ground to a particle size finer than 75 µm [1]. A key concern with using glass powder in concrete is the potential for alkali silica reaction (ASR), which occurs between the silica rich glass particles and the alkali in the concrete's pore solution. This reaction can compromise the stability of the concrete unless appropriate measures are taken to mitigate its effects [2]. Despite this challenge, ground glass powder can improve concrete workability and reduce permeability, offering potential benefits for durability, especially when considering the high alkali-silica reactivity (ASR) between cement and waste glass [3]. Khmiri [4] explored the use of waste glass powder (both clear and green) as a cement replacement in mortar bars, varying the particle size of the glass powder in three ranges: 100-80 µm, 80-40 µm, and less than 40 µm, with a 20% cement replacement. The study found that green waste glass powder with a particle size finer than 40 µm had a strength activity index of 82%, while the clear waste glass powder with the same fineness achieved only 75%. Similarly, Dhanaraj [5] investigated cement replacement with glass powder in two particle sizes (150-90 µm and smaller than 90 µm) at replacement levels of 10%, 20%, and 30%. The results indicated that as the particle size decreased, concrete strength improved, with the finest particles (less than 90 µm) yielding higher strength than those in the 90-150 µm range. The optimum cement replacement level for maximum strength was found to be 20%. Damian [6] also examined the effect of particle size on the performance of glass powder in cement replacement, testing sizes from 150 µm to 75 µm, 75 µm to 38 µm, and below 38 µm for 30% cement replacement. His findings suggested that smaller particle sizes promoted greater reactivity with lime, resulting in higher strength. Ali [7] studied the workability, compressive strength, and split tensile strength of concrete with glass powder (finer than 75 µm) replacing up to 25% of the cement. The study showed that higher replace-ment levels enhanced concrete slump, and for concrete mixes with grades of 33 MPa and 45 MPa, compressive strength improved with glass powder substitution. The optimal levels for split tensile strength were 10% for 33 MPa and 15% for 45 MPa concrete. Gunalaan [8] investigated the compressive strength of concrete with 10%, 15%, and 20% glass powder as a cement replacement, finding that 20% replacement achieved a compressive strength similar to that of the control mix after 28 days. Bhagyasri [9] studied the workability and compressive strength of concrete with glass powder (finer than 90 µm) replacing up to 40% of the cement in 10% increments. The study concluded that maximum compressive strength occurred at a 20% replacement level after 28 days, although workability decreased as the glass powder content increased. For split tensile strength, Rahman [10] observed that the highest strength occurred with 30% glass powder replacement at 28 days. Hongjian Du [11] examined concrete with up to 60% glass powder as a cement replacement and up to 15% as an additive. The study showed that the maximum compressive strength was achieved with 15% glass powder as an additive, while 15% and 30% replacement levels for cement performed similarly to the control mix after 90 days. Shivacharan [12] tested glass powder (passing through a 150 µm sieve) as a cement replacement up to 25%, finding that 15% replacement provided the best results for compressive strength. Amol [13] reported that 16% glass powder replacement resulted in the highest values for compressive strength, split tensile strength, and flexural strength after 28 days, although the particle size of the glass powder was not specified. Shilpa [14] studied the effect of glass powder replacement in the range of 5% to 40%, in 5% increments, and found that 20% cement replacement with glass powder achieved the highest strength. This study tested waste glass powder as a cement substitute in proportions of 0%, 10%, 15%, 17.5%, and 20%, with curing times of 7, 14, and 28 days. Results showed that 17.5% replacement increased compressive strength by 6.07% and flexural strength by 6.85% on the 28th day. The 15% replacement outperformed 10%, which was stronger than the control. However, 20% replacement resulted in a decrease in compressive strength

(-2.42%) and flexural strength (-1.42%) on the 28th day, indicating it is unsuitable for concrete. The best results were achieved with a 17.5% replacement [15]. The research was conducted in two phases: First Campaign: Glass powder was added in increments up to 15% of cement weight, showing modest improvements in slump and compressive strength, Second Campaign: Glass powder was added at 7.5% with a super-plasticizer, leading to more significant improvements, indicating its potential for high-performance applications, especially in self-compacting concrete. The findings suggest that combining glass powder with a plasticizer enhances concrete performance [16]. This study investigates the use of recycled glass (CG and GP) in concrete, focusing on performance at high temperatures. Concrete mixes with 0-30% replacement of CG and GP were tested for compressive strength, tensile strength, UPV, weight loss, and volume changes after heating to 600°C. Results show compressive strength increased by 3-6% up to 150°C, then declined by 30-40% at 600°C. Split tensile strength decreased by 60-70% after 600°C. Concrete with 10% GP and 10-20% CG showed the best performance. All mixes experienced higher water absorption, mass loss, and reduced UPV at high temperatures [17]. Another study found that recycled glass concrete (RGC) performs similarly to control concrete up to 450°C, with GPC offering better heat resistance than CGC. The inclusion of waste glass reduces temperature-related damage, and equations were developed for practical applications [18]. Replacing up to 21% river sand with waste glass improved performance, particularly under fire exposure, with better resistance to freeze-thaw damage and reduced drying shrinkage [19]. Another study showed that up to 15% GP and 10% SF increased compressive strength and elastic modulus. Glass also improved thermal insulation, showing better heat performance and reduced mass loss at high temperatures [20].

These studies collectively demonstrate the potential of glass powder as a sustainable alternative to traditional cement, particularly when finely ground. However, careful attention must be paid to particle size and replacement levels to optimize concrete performance and minimize risks such as alkali-silica reaction. This research aims to investigate the impact of waste glass powder (WGP) on the properties of concrete, specifically focusing on compressive strength and split tensile strength, with partial cement replacement. The use of waste glass serves a dual purpose: to promote a more environmentally sustainable, pollution-free approach, as glass is non-biodegradable, and to reduce the consumption of cement in construction, thereby mitigating the environmental pollution associated with cement production emissions.

2 Materials

The used commercial cement used was CEM I (42.5) N. Several tests were conducted to test the quality of cement. The cement had a specific surface area of 345 m^2/kg, a soundness of 1.0 mm, and an initial/final setting time of 135/180 minutes, respectively. The compressive strength at 28 days was 52 MPa. The waste glass used in this study was primarily sourced from discarded glass materials commonly found in construction, such as old windows and doors. The glass was first broken into smaller pieces and then ground using a ball milling machine to achieve the required fineness. After grinding, the glass powder was sieved to obtain the desired particle size distribution. The study focused on a specific particle size range of 90–63 μm to assess the effect of fineness on the properties of the concrete. Clean river sand was used as the fine aggregate, with particle sizes not exceeding 4.75 mm. The fine aggregate had a bulk specific gravity of 2.54 and a bulk density of 1.69 g/cm^3. The coarse aggregates used in the study had particle sizes ranging from 20 mm to 4.75 mm, with a bulk specific gravity of 2.58, bulk density of 1.36 g/cm^3, and a crushing value of 25%. Tap water was used throughout this research for both the mixing and curing processes. A 1% superplasticizer by weight of the binder (Sika R 2004) was added to all concrete mixes to enhance workability. The superplasticizer is a liquid with a brown color.

3 Experimental Procedure

3.1 Mix Procedure

A 1.2 m³ capacity mixer was used to prepare the concrete mixtures. The sand and coarse aggregate were initially dry-mixed for 2 minutes. The cement and waste glass powder (WGP) were pre blended in a separate container before being added to the aggregate mixture. The total dry mixing time for all martials was 5 minutes. The superplasticizer was dissolved in half of the required water and gradually incorporated into the mix, with continued mixing for another 5 minutes. The remaining water was then added in portions while mixing. Concrete was poured into 150 mm cubic molds and cylindrical molds with a 150 mm diameter and 300 mm height. After casting, the specimens were kept at room temperature for 24 hours, then demolded and submerged in curing water until the testing date.

3.2 Mix Design

This study considered a total of 4 concrete mixes: one control mix without any waste glass powder and the others with cement substituted by waste glass powder at 10%, 15%, and 20% for particle size: (Size 90 µm–63 µm. The replacement percentage was limited to a maximum of 20%, as most research has reported optimal results with up to 20% cement substitution. The mixtures were prepared with a constant water-to-binder (cement + GP) ratio of 0.48 across all mixes. with 1% superplasticizer by weight of binder. The proportions of aggregates, water, and superplasticizer were kept the same for all mixes.

Table 1. Mix proportions.

MIX	GP Rep. %	Glass powder Kg/m³	Cement Kg/m³	Sand Kg/m³	Coarse Kg/m³	Water Kg/m³
Control	0%	0	375	704	1057	181.8
Mix10	10%	37.5	337.5	704	1057	181.8
Mix15	15%	56.3	318.8	704	1057	181.8
Mix20	20%	75	300	704	1057	181.8

3.3 Test Specimens

24 Cubes (150×150×150 mm) were cast to determine the compressive strength at 28 days for tests without fire exposure and tests with fire exposure. 12 Cylinders (150×300 mm) were cast for testing split tensile strength at 28 days. All specimens were prepared in steel molds, compacted, and finished with a smooth steel trowel. After 24 hours, the samples were demolded and placed in a curing tank with tap water until the time of testing. Tests conducted included slump, compressive strength and split tensile strength. 3 samples for each mix were conducted for each test and the average results of 3 samples calculated. (**Fig.1**) is a picture for a cube and cylinder sample during the tests.

Fig. 1. Pictures for Cube and Cylinder

4 Results and discussions

4.1 Workability

Workability refers to the ease with which freshly mixed concrete can be handled, mixed, set, and finished without segregation. As noted, the water content and superplasticizer were kept constant across all percentages. Workability was assessed using the slump test prior to casting the concrete into molds. Slump tests were performed on all concrete mixes, and (**Fig.2**) illustrates the results for different glass powder replacements as follows: The control mix, without any glass powder (GP) addition, has a slump of 16 cm. This slump value indicates a moderate workability, meaning the mix was relatively easy to handle and place but may require some effort to avoid segregation and ensure uniform compaction Adding 10% glass powder (GP) increases the slump slightly to 17 cm. This suggests that the inclusion of GP has improved the workability slightly. Glass powder may be acting as a fine particle filler, which could increase the fluidity of the mix, possibly due to the smooth nature of the glass particles helping to lubricate the mix. However, the change in slump was not dramatic, indicating that the glass powder's influence on the workability is modest at this percentage. With a 15% replacement of cement by GP, the slump decreases to 14 cm, indicating a reduction in workability. This reduction could be attributed to the increased volume of glass powder, which, despite its fine nature, may absorb more water compared to the control mix. The higher percentage of GP could lead to a stiffer mix, making it harder to achieve the same flow or ease of placement as the control mix. This result suggests that beyond a certain level of GP, the water demand increases, potentially reducing workability. For the mix with 20% glass powder, the slump further decreases to 13 cm. This further reduction in workability is expected, as the glass powder likely has a higher surface area that requires more water to achieve the same consistency as the control mix. The increase in glass powder content at this level may significantly alter the rheological properties of the mix, making it more difficult to achieve adequate workability. The results demonstrate a trend where the addition of glass powder (GP) initially improves workability at lower percentages (10%), but as the replacement level increases (15% and 20%), workability decreases. This suggests that while a small amount of GP may enhance the flow ability of the mix, larger amounts of GP may absorb more water, leading to a stiffer, less workable mix. Therefore, to optimize workability while using glass powder, careful consideration of the replacement percentage is important, as higher levels can negatively affect the ease of handling and placement of the concrete. Further testing with varying water-to-cement ratios or admixtures might be needed to counteract the decrease in workability at higher GP contents.

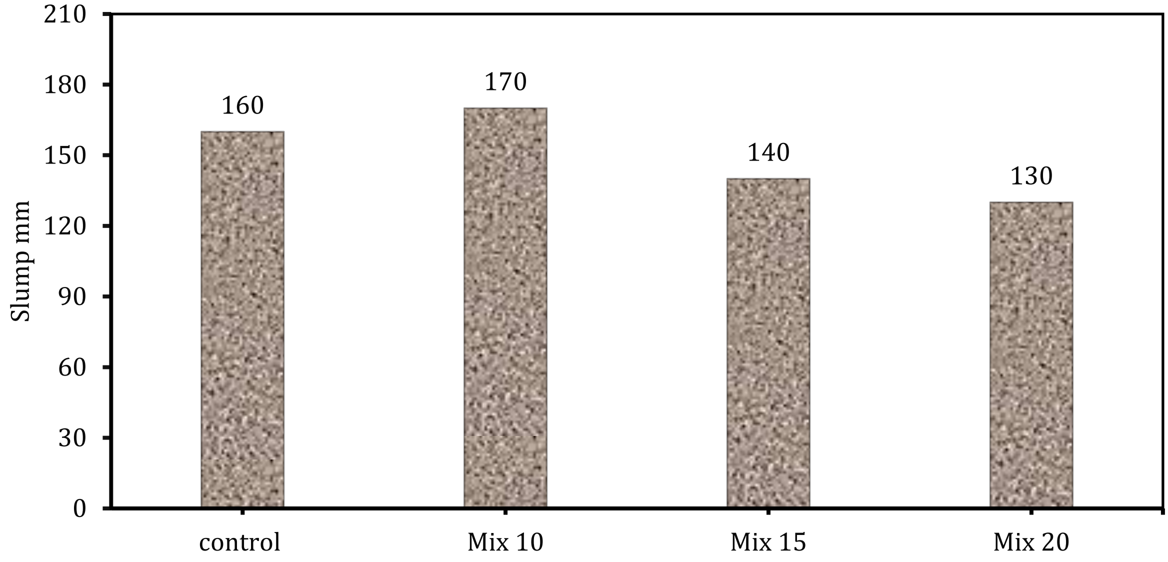

Fig. 2. Values of The Slump [mm].

4.2 Compressive Strength

The compressive strength of concrete samples incorporating varying amounts of glass powder (GP) as a partial replacement for cement was evaluated at 28 days of curing. The compressive strength results for the control mix and the mixes with varying levels of cement replacement by glass powder (GP) are shown in **Fig. 3**. The compressive strength of the control mix was recorded as 38.5 MPa, serving as the baseline for comparison with the experimental mixes. This represents the typical strength achieved by conventional concrete at 28 days of curing. The mix with 10% glass powder exhibited a slight reduction in compressive strength (37.0 MPa) compared to the control mix. This decrease may be attributed to the potential dilution effect of glass powder on the overall cementitious content or the incomplete pozzolanic reaction between the glass powder and the calcium hydroxide (CH) in the concrete. The compressive strength of the concrete with 15% glass powder was similar to the control mix (38.0 MPa), showing that up to 15% replacement did not significantly compromise the concrete's compressive strength. This result suggests that the 15% glass powder mix could maintain or even slightly enhance the concrete's mechanical performance, possibly due to a more optimal pozzolanic reaction at this replacement level. The 20% glass powder mix showed a compressive strength equal to that of the control mix (38.5 MPa), indicating that higher levels of glass powder (up to 20%) may not negatively impact the compressive strength. This could be attributed to a balance between the pozzolanic effects of the glass powder and its role as a filler material, providing enhanced packing density or other beneficial microstructural effects that offset the decrease in cement content.

The results suggest that the addition of glass powder in concrete mixes up to 20% by weight of cement does not substantially reduce the compressive strength at 28 days of curing. In fact, the concrete with 15% and 20% glass powder maintained or achieved a compressive strength comparable to the control mix. These findings imply that glass powder can be used as a sustainable alternative material in concrete mixes without significantly compromising the mechanical performance at typical curing periods. However, further studies on long-term durability, shrinkage, and other mechanical properties should be conducted to fully assess the impact of higher glass powder content in concrete.

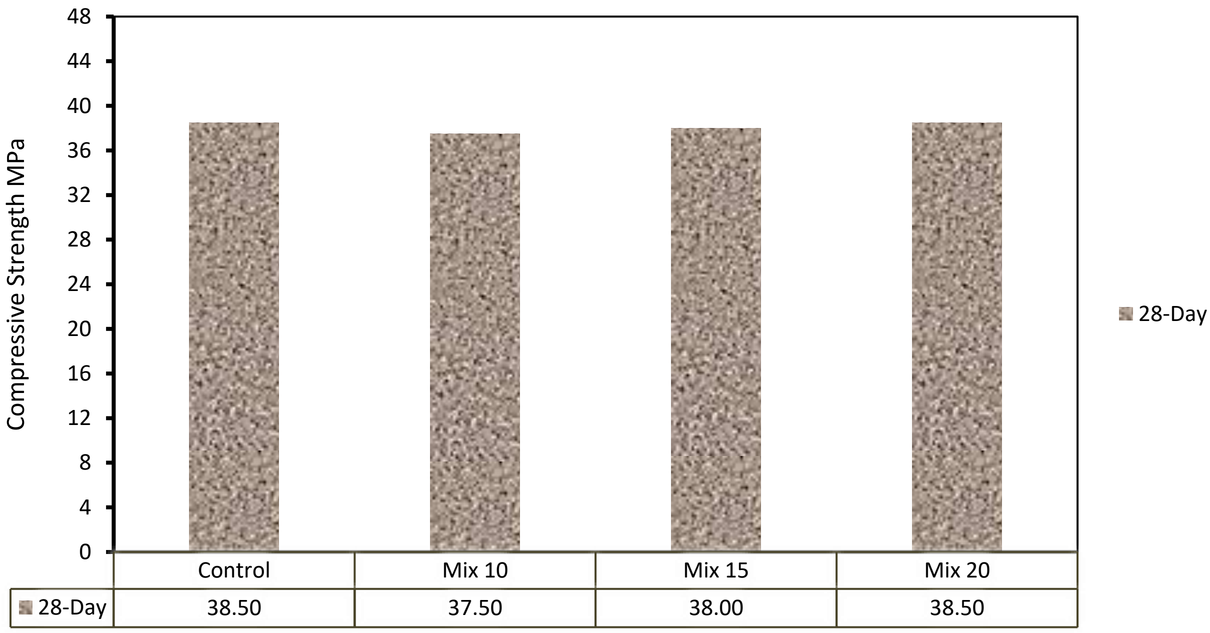

Fig. 3. Compressive Strength of the Concrete Cubes results

4.3 Split Tensile Strength

Cylindrical specimens with a diameter of 150 mm and a length of 300 mm were cast, cured, and tested for split tensile strength at 28 days. The tests were conducted using a 2000 kN capacity compression testing machine. The split tensile strength of concrete mixes incorporating glass powder as a partial replacement for cement was measured at 28 days of curing. The mixes were tested with 0%, 10%, 15%, and 20% glass powder by weight of cement. **Fig. 4** presents the split tensile strength results for different percentages levels of glass powder (GP) replacement at 28 days. The control mix, containing no glass powder, exhibited a split tensile strength of 2.66 MPa. This serves as the baseline tensile strength for comparison. The mix with 10% glass powder showed a slight reduction in split tensile strength (2.49 MPa), indicating a decrease in tensile resistance. This reduction could be due to the partial replacement of cement by glass powder, which may have altered the bonding properties or reduced the overall cementitious content, impacting the concrete's ability to resist tensile forces. The concrete mix with 15% glass powder exhibited a slight increase in split tensile strength (2.55 MPa) compared to the control mix. This indicates that, at this level of replacement, the glass powder may have contributed positively to the microstructure, possibly enhancing the bond between the cement matrix and aggregates, improving the tensile strength of the concrete. The mix with 20% glass powder showed the highest split tensile strength (2.79 MPa), which was higher than the control mix. This could be attributed to a combination of factors, such as improved packing density or enhanced pozzolanic reactions at this higher replacement level, which may have led to a more cohesive and stronger matrix in terms of tensile behavior. The split tensile strength results indicate that the incorporation of glass powder in concrete mixes can influence tensile properties depending on the percentage used. Specifically:

- A small reduction in tensile strength was observed with 10% glass powder (2.49 MPa), which could suggest that a low replacement level may not provide optimal results in terms of tensile performance.
- At 15% glass powder, there was a slight improvement (2.55 MPa), suggesting that this level might be an optimal point where the benefits of glass powder's pozzolanic properties start to outweigh any negative effects on the mix.

- The highest increase in split tensile strength was observed with the 20% glass powder mix (2.79 MPa), indicating that higher levels of glass powder can potentially improve the tensile strength of concrete. This improvement might be due to better particle packing and enhanced pozzolanic activity, leading to a more cohesive structure capable of withstanding tensile stresses.

The results suggest that glass powder can be used effectively in concrete mixes to enhance split tensile strength, particularly at higher replacement levels (e.g., 20%). However, further investigation into the underlying mechanisms, such as microstructural changes and long-term durability, is recommended to fully understand the potential benefits of glass powder in concrete mixes.

And it is noticeable that glass powder slightly reduces compressive strength at lower replacement levels (10% and 15%), it generally enhances tensile strength, particularly at higher replacement levels (20%). This indicates that glass powder can contribute to improving certain properties of concrete, especially in terms of tensile performance, without significantly compromising compressive strength.

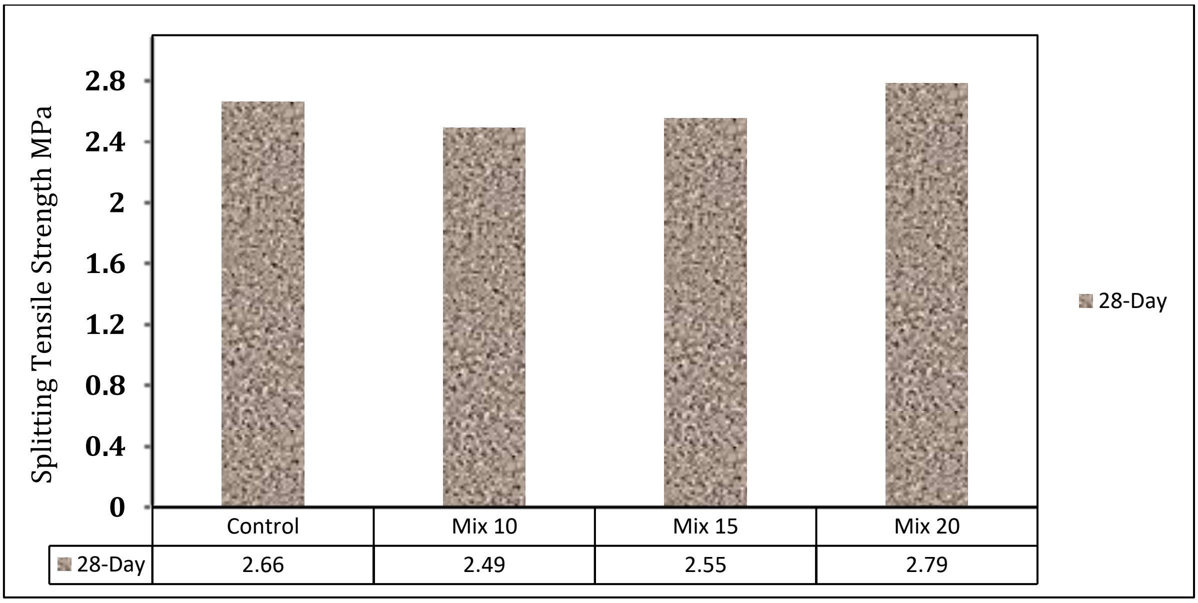

Fig. 4. Splitting Tensile Strength results

4.4 Durability of Concrete with Glass Powder: Fire Exposure Results

The durability of concrete incorporating glass powder as a partial replacement for cement was assessed by subjecting the concrete cubes to fire exposure in oven at 400°C for two hours. The compressive strength of the samples was measured post-heating to evaluate the impact of thermal stress on the material**. Fig. 5** shows the compressive strength results after the fire exposure process. the control mix, without glass powder, exhibited a compressive strength of 30.93 MPa after exposure to 400°C for two hours. And this was a moderate reduction from its initial 38.5 MPa at 28 days of curing, the relatively high value suggests that the control mix exhibited a strong resistance to thermal degradation, maintaining a significant portion of its original strength. The concrete mix with 10% glass powder showed a reduction in compressive strength to 25.93 MPa after heating. This decrease suggests that the incorporation of glass powder at this level might slightly reduce the thermal resistance of the concrete. The reduction could be due to the glass powder's influence on the microstructure, potentially altering the phase transitions of cement paste or affecting the overall density of the concrete, which could make it more susceptible to thermal cracking or degradation. The mix with 15% glass powder demonstrated a relatively better performance under fire exposure, retaining 28.43 MPa of compressive strength after fire exposure process. This suggests that the 15% replacement level of glass powder might provide a more stable microstructure, helping the concrete to resist thermal damage better than the 10% glass powder mix. The pozzolanic reactions between glass powder and calcium hydroxide could have contributed to a more thermally stable matrix. The mix with 20% glass powder exhibited a compressive strength of 30.01 MPa after fire exposure, which was very close to the control mix's performance (30.93 MPa). This result indicates that, at this higher replacement level, the concrete's durability under fire exposure was not significantly impacted, and the glass powder may have provided a beneficial effect. The higher glass powder content likely enhanced the overall packing density, possibly leading to reduced micro-cracking and better thermal resistance compared to lower replacement levels.

The results of the fire exposure (400°C for 2 hours) indicate that the durability of concrete with glass powder is largely influenced by the percentage of glass powder replacement. The key findings are as follows:

- **Control Mix** maintained the highest compressive strength after fire exposure (30.93 MPa), indicating good thermal stability.
- **10% Glass Powder** showed a noticeable reduction in compressive strength (25.93 MPa), suggesting that this level of replacement may slightly compromise the concrete's thermal durability.
- **15% Glass Powder** exhibited a moderate reduction in strength (28.43 MPa), demonstrating a relatively balanced performance with improved thermal stability compared to the 10% replacement.
- **20% Glass Powder** achieved the best thermal durability, with a compressive strength of 30.01 MPa, which was almost identical to the control mix. This suggests that higher replacement levels of glass powder can potentially enhance the concrete's resistance to Fire exposure, possibly due to the pozzolanic effects and the improved microstructural integrity.

Overall, the results indicate that concrete with up to 20% glass powder exhibits comparable or even improved durability under Fire conditions, making it a promising material for applications where thermal resistance is important. However, further research into the long-term effects of temperature cycling, as well as the specific mechanisms that contribute to this enhanced thermal stability, would provide more comprehensive insights into the material's performance.

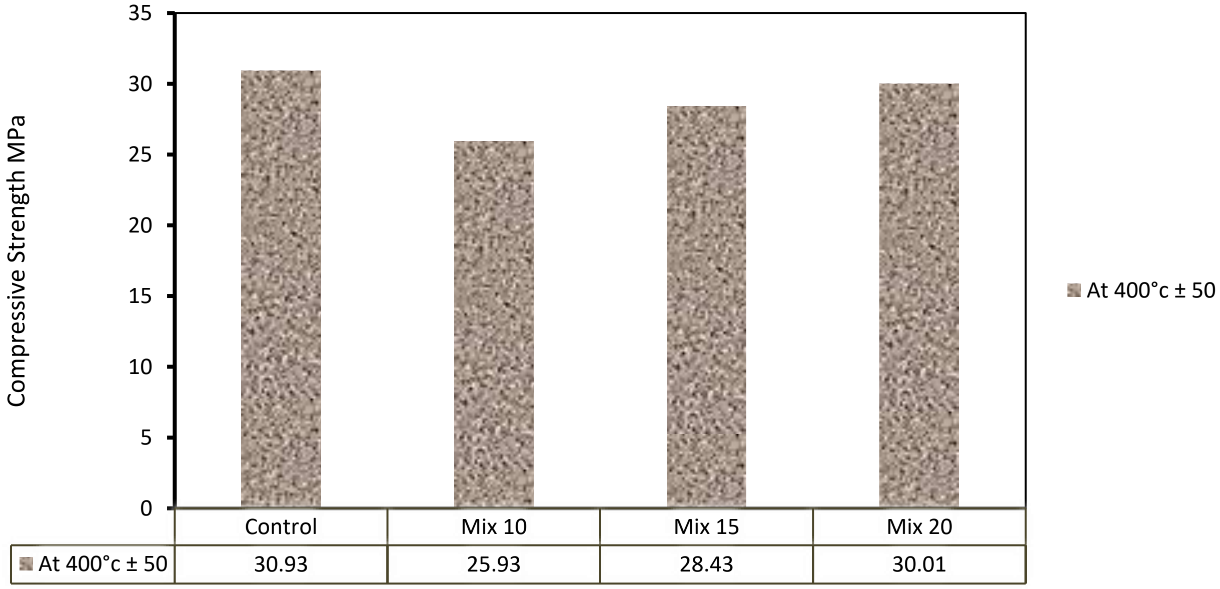

Fig. 5. Compressive Strength Results for burned cubes

4.5 Loss of Strength

The observed decrease in strength due to fire exposure in **Fig.6** showed the influence of glass powder (GP) as a partial cement replacement in concrete. The strength reduction for the control mix (without glass powder) was 20%, indicating the natural impact of fire exposures on the concrete's integrity. However, as glass powder replaced cement, the percentage decrease in strength increased at lower replacement levels but showed some improvement at higher levels of replacement. The trend observed in these results suggests that while replacing cement with glass powder can improve some properties of concrete, including its environmental sustainability, its performance under fire exposure needs to be considered carefully. The higher the replacement percentage, the more the mix can potentially mitigate some of the strength loss from fire exposure, although at the cost of reduced thermal resistance compared to traditional concrete.

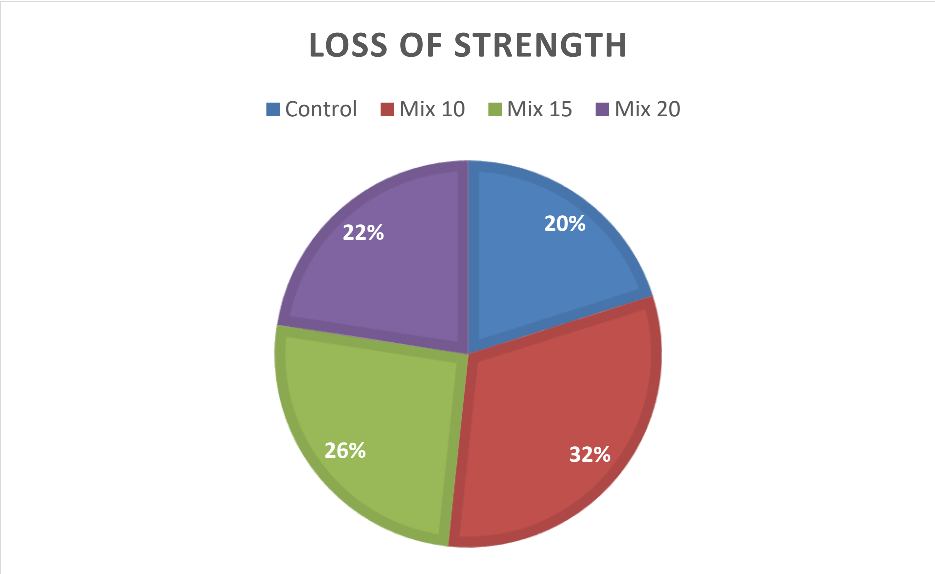

Fig. 6. Loss of strength

5 Conclusions and Future Study

5.1 Conclusions

The main findings of this research on the incorporation of waste glass powder (GP) in concrete are summarized as follows:

- Environmental Benefits: Replacing a portion of cement with glass powder helps lower carbon dioxide emissions, making the concrete mix more sustainable and environmentally friendly.
- Regarding workability, lower glass powder contents (10%) slightly improved flow ability, while higher contents (15% and 20%) reduced workability, likely due to increased water demand and changes in particle interactions.
- The addition of glass powder in concrete mixes up to 20% replacement did not significantly compromise compressive strength or split tensile strength, and in some cases, even enhanced these properties, particularly in terms of tensile strength.

- In terms of durability, the incorporation of glass powder showed promising results, especially at 20% replacement, where the concrete demonstrated the best performance under high-temperature exposure, comparable to the control mix.
- Overall, glass powder appears to be a viable alternative for partial cement replacement in concrete mixes, providing good mechanical performance and enhanced durability, particularly at higher replacement levels (15% and 20%). However, adjustments in the mix design, particularly in terms of water content or the use of plasticizers, may be necessary for maintaining optimal workability at higher glass powder contents.
- The cost analysis for replacing cement with waste glass powder (WGP) in 1 cubic meter of concrete is based on the current prices of cement and superplasticizer, with 1% superplasticizer included in the mix, and assuming no cost for the WGP. The cost savings are approximately 9%, 13.5%, and 18% for 10%, 15%, and 20% WGP replacement, respectively.

5.2 Recommendation for future study

- Study the long-term mechanical properties of concrete with glass powder after exposure to fire over multiple cycles (repeated heating and cooling). This could help understand how the concrete behaves over extended periods and under repeated thermal stresses.
- Extend the fire exposure to higher temperatures (1000°C, 1200°C, etc.) to evaluate whether the glass powder replacement continues to provide enhanced fire resistance or whether it reaches a limit. This would allow a better understanding of the temperature threshold at which the glass powder's effectiveness as a fire-resistant agent starts to decrease.

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