



ENHANCING SUSTAINABILITY IN PAVEMENT CONCRETE: UTILIZATION OF WASTE GLASS POWDER IN TWO DISTINCT SIZES AS A CEMENT REPLACEMENT MATERIAL

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ABSTRACT

This study investigates the influence of waste glass powder (WGP) with two particle sizes (75 μm and 300 μm) used as partial cement replacement (5–20%) in pavement concrete. The use of glass powder in two different particle sizes and the application of glass in concrete pavements represent the original and distinctive aspects of this research. A systematic experimental program including slump, density, water absorption, and compressive strength tests was conducted. Results showed that increasing WGP content improved slump values, reduced density, and significantly decreased water absorption. While the control mix exhibited the highest 7 days strength, the mix with 15% WGP achieved the highest 28 days compressive strength (2.5% higher than control). The findings demonstrate that WGP is an effective and sustainable cement replacement, offering environmental benefits through reduced cement use while maintaining or enhancing concrete performance. These results suggest practical potential for using WGP-modified concrete in pavement construction and other large-scale infrastructure works where cost efficiency and sustainability are priorities.

1. INTRODUCTION

The term "sustainability" has gained increasing importance over time, with significant economic and ecological implications. The aggressive development of human civilization, marked by innovations in industrial science and engineering, has caused considerable strain on the environment. The unchecked release of toxic gases into the atmosphere, improper disposal of waste materials, and the resulting destruction of biodiversity have escalated climate change and ecological degradation, making sustainability an urgent concern in all aspects of human life.

In the context of construction, sustainability has become even more critical in recent years, with a growing body of academic research emphasizing its importance and benefits. Victor (2022), in a review of waste material utilization in pavement construction, highlights that waste material recycling is increasingly seen as an environmental necessity, drawing global attention. Recycling waste materials in pavement construction and rehabilitation is a key initiative for achieving a sustainable environment in the near future [1]. Broadly speaking, sustainability refers to a system's ability to function within a larger context without causing harm, while addressing human and environmental needs. The U.S. Federal Highway Administration (FHWA) defines sustainable pavements as those that meet engineering goals, preserve and restore surrounding ecosystems, optimize the use of financial, environmental, and human resources, and fulfill human needs such as safety, health, equity, and comfort.

Pavement systems are crucial components of global transportation infrastructure, significantly impacting both the economy and the environment [2]. Concrete and asphalt, the most commonly used pavement materials, pose substantial environmental challenges, highlighting the need for sustainability in their construction and use. The integration of waste materials in pavement construction and rehabilitation is becoming increasingly common, with numerous waste products being tested to improve pavement durability while meeting sustainability goals.

Reclaimed Asphalt Pavement (RAP), one of the most recycled materials globally, is widely used in pavement construction. Other materials such as crumb rubber, plastic waste, steel pieces, glass fiber, Low-Density Polyethylene (LDPE) and crushed concrete also play a crucial role in sustainable pavement construction by improving performance and offering eco-friendly alternatives [1]. Research has shown that incorporating waste materials in concrete pavements enhances their performance, reduces damage, deformation, and failure, and helps repurposed to make pavement construction more sustainable and durable. Several studies have explored ways to reuse waste glass in construction.

Fly ash, most commonly Class F for pavement applications, functions as a pozzolanic material that reacts gradually with the calcium hydroxide liberated during cement hydration. This reaction forms additional C–S–H gel and progressively refines the internal pore structure of the concrete. Because the pozzolanic reaction proceeds slowly, concrete incorporating fly ash typically develops strength more gradually at early ages, which can influence early traffic opening requirements. However, once adequate curing is provided, fly ash mixtures often achieve equal or greater long-term strength compared to ordinary Portland cement mixtures. In fresh concrete, fly ash tends to improve workability because its particles are smooth and spherical, reducing water demand and enhancing placing and finishing characteristics. As the concrete hardens, the long-term benefits become more apparent: permeability decreases, chloride resistance increases, and long-term durability improves, though sensitivity to freeze–thaw conditions and deicer scaling remains highly dependent on proper curing practices. In pavement construction, fly ash is usually incorporated at 15–30% cement replacement, a range that balances durability gains with the need for predictable early-age performance. The material is widely available in regions where coal-fired power generation exists and is generally the most economical supplementary cementitious material. From a sustainability perspective, replacing cement with fly ash significantly reduces embodied carbon, making it a popular choice for routine highway pavements where long-term durability is required and early-opening schedules are manageable. Compressive strength ranges of 45–50 MPa were obtained and 20–35% water absorption values [3–4]. However, fly ash does not exist all around the world and transportation for it to islands is not cost effective.

Nano-silica (nS) is an ultrafine, highly reactive form of amorphous silica that actively participates in cement hydration by providing abundant nucleation sites for C–S–H formation and by filling extremely small voids within the cement matrix. This dual action leads to a highly refined microstructure and results in substantial improvements in both early-age and later-age strength. Unlike fly ash and GGBS, nano-silica tends to accelerate early hydration, making it particularly useful in situations where rapid strength gain is needed. However, its extremely high surface area reduces workability, so mixtures containing nano-silica generally require enhanced dispersion and increased superplasticizer dosage to maintain the desired consistency. When properly dispersed, nano-silica significantly reduces permeability, enhances bond within the interfacial transition zone, and provides excellent resistance to chloride penetration—critical for pavements containing dowel bars or exposed to deicing salts. It also improves abrasion resistance due to the formation of a denser, harder paste matrix. In practice, nano-silica is used in very small quantities, typically between 0.5% and 4% of binder mass, and is often combined with slower-reacting supplementary cementitious materials to counteract their reduced early-age strength. Although relatively expensive, its small dosage means that it can be applied strategically in high-performance pavement areas such as bridge decks, coastal pavements, industrial slabs, and other zones requiring superior durability. As availability increases and dispersion technology improves, nano-silica is becoming an important ingredient for designing high-performance and long-life concrete pavements. There is risk of poor dispersion of nS which cause agglomeration and reduces benefits and worsens workability. Quality control of nS product (colloidal vs powder) is essential. [5–7]. It shows even 120 MPa compressive strength at 28 days and 4.41% water absorption [8]. Slump values range between 174–192 mm. [9]

Ground-granulated blast-furnace slag (GGBS) is a latent hydraulic material derived from iron production. When finely ground and blended with cement, it reacts with water and calcium hydroxide to form additional C–S–H, thereby densifying the concrete matrix and improving long-term properties. In fresh concrete, GGBS behaves similarly to cement, though its hydration is slower, which generally leads to reduced early-age strength—an important consideration for pavement projects that demand early opening. However, as curing progresses, mixtures containing GGBS frequently surpass the

strength of conventional concrete, especially at 56 to 90 days. The slower hydration also results in reduced heat generation, which minimizes thermal cracking risks in large pavement slabs. One of the most notable advantages of GGBS in pavement applications is its contribution to durability. Concrete containing GGBS exhibits significantly improved resistance to chloride ingress, making it highly suitable for coastal environments, marine-exposed pavements, and areas subject to deicing chemicals. It also offers excellent sulfate resistance and effectively reduces long-term permeability. Abrasion resistance, vital for heavy-traffic pavements, is generally enhanced because of the denser microstructure produced during slag hydration. Typical dosages in pavements range from 20% to 50% cement replacement, although higher levels may be used when early strength is not a concern. GGBS provides substantial environmental benefits, reducing the overall carbon footprint of concrete and offering a resource-efficient use of industrial byproducts. These characteristics make GGBS a strong choice for long-life, durable pavements such as industrial yards, coastal highways, port pavements, and airport runways. Those studies resulted in around 220 mm slump values, with 2.42 kN/m³ dry unit weight, 2.41% water absorption and 57 MPa compressive strength. Early-age strength uncertainty with high fly ash or GGBS mixes creates pavements needing early opening to be tested under project curing & temperature conditions [4,10]. The information contained in the header will be completed by the journal, and therefore authors are not required to make any additional adjustments.

2. MATERIALS AND METHODS

To achieve the objectives of this study, distinct concrete mix compositions were prepared by incorporating varying percentages of waste glass powder with 75 and 300 μm in different ratios (0%, 5%, 10%, 15% and 20%), ensuring a consistent water-to-cement (w/c) ratio of 0.55. The primary aim was to investigate the impact of waste glass powder on the mechanical and durability properties of concrete. To evaluate these effects, several experiments were conducted, including compressive strength testing, water absorption measurement, density determination and slump testing. These experiments aimed to provide a comprehensive understanding of how the addition of waste glass powder influences concrete's performance. A limitation of this work is that SEM and XRD analyses SEM and XRD analyses were not performed, as these tests were not available within the scope of the current experimental facilities.

2.1. Materials

2.1.1. Cement

Typically, Portland cement (CEM I 42.5), obtained from the Cement Plant BEM in Iskele, TRNC, and Cement meeting ASTM C150/C150M-21 specifications, served as the primary binder in the concrete compositions utilized in this study. In order to comply with the ASTM standard specification, concrete mixes were prepared using 42.5-grade cement, guaranteeing a minimal compressive strength of 42.5 MPa after 28 days. Table 1 shows the chemical composition of cement and waste glass.

Table 1. Chemical composition of cement and glass.

Chemical Compound	Cement	Glass
CaO	54	10.24
SiO ₂	16	73.50
Al ₂ O ₃	4.2	-
Fe ₂ O ₃	2.2	0.34
SO ₃	2.0	-
K ₂ O	0.6	0.64
Na ₂ O	0.2	13.12
MgO	2.1	1.57

2.1.2. Water

The mixing water used in this study was ordinary tap water, with a pH range of 6.7. For both the curing process and the concrete mixes, a material free from oils, acids, and organic compounds was utilized [11]. This material, obtained from the research laboratory, complied with the standards outlined in ASTM C1602/C1602M-18 [12].

2.1.3. Fine Aggregate

Particles passing through a 4.75-millimeter sieve are classified as "fine aggregate." For this study, crushed limestone was used as fine aggregate, following the specifications outlined in ASTM C33/C33M-18 [13]. To reduce water absorption during mixing, the sand was utilized in a saturated surface-dry condition, in accordance with ASTM C128-17a [14]. Additional details on the properties of the sand are provided in Table 2, while Figure 1 illustrates the particle size distribution of the fine aggregate.

Table 2. Fine aggregate properties.

Properties	Values	ASTM
Water Absorption (%)	1.32	C128-15
Specific Gravity	2.630	C128-15
Fineness Modulus	2.79	C33/C33M-18
Moisture Content (%)	0.1	C566-19
Loss Bulk Density (kg/m ³)	1445	C29/C29M-17a
Compact Bulk Density (kg/m ³)	1728	C29/C29M-17a

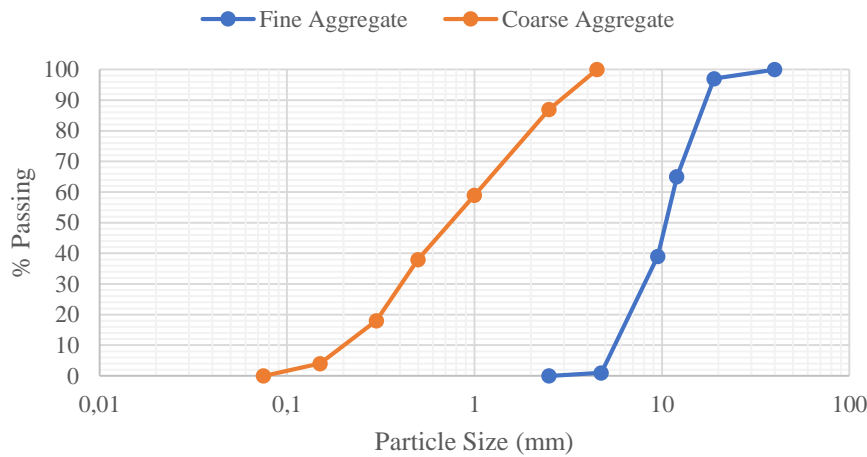


Figure 1. Grading curve for the coarse and fine aggregate.

2.1.4. Coarse Aggregate

The coarse aggregate size selection can have an impact on the characteristics of concrete, such as workability and strength. It is important to carry out a sieve analysis and closely monitor the gradation of the coarse aggregates in order to get the required properties. Guidelines for determining and controlling the gradation of coarse particles in concrete mixes are provided by ASTM C136M-14 and C33M-16 standards. Particle size distribution of coarse aggregate is given in Figure 1. Crushed granite stones were used as coarse aggregate.

2.1.5. Waste Glass Powder

Glass is a commonly used material found in items such as jars, bottles, louvers, and fluorescent lights, among other forms. For this study, glass was obtained from the surrounding area, particularly bottles of various colors, including brown, white, and green, collected from Nicosia, North Cyprus. Glass powder with particle sizes of 75 and 300 μm s was used in this research. To remove dust, labels, and other impurities, the bottles were cleaned by soaking in water, thorough washing, and rinsing. After drying, the bottles were processed using a crushing machine known as the Los Angeles Machine, which effectively ground and crushed them into powder. Waste glass powder production process is given in Figure 2. The chemical composition of the glass is given in Table 1.

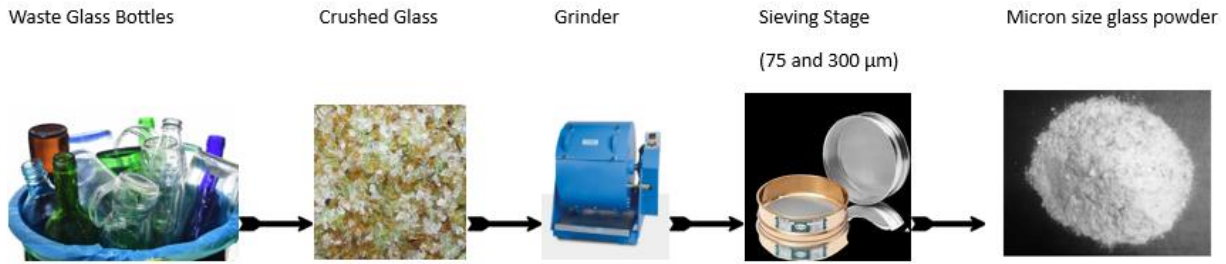


Figure 2. Waste glass powder production process.

2.2. Mix Design

To evaluate how waste glass powder (WGP) affects both the fresh and hardened properties of concrete pavement, Table 3 outlines five distinct mix designs. Each mix varies in the percentage of WGP used as a replacement material, while maintaining a constant water-to-cement ratio of 0.55.

Table 3. Mix proportions.

Mix Id	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	WGP (kg/m ³)
CM	382.0	890	895	210	0
WGP 5	362.9	890	895	210	19.1
WGP 10	343.8	890	895	210	38.2
WGP 15	324.7	890	895	210	57.3
WGP 20	305.6	890	895	210	76.4

2.3. Sampling and Curing

Each mix was prepared following the ASTM C305-20 specifications. The mixing process began by combining the coarse aggregate, 50% of the water, and 50% of the cement/WGP for 1 minute. Next, the remaining 50% of the cement, 25% of the water, and the fine aggregate were added and mixed for 3 minutes. The final 25% of the water was then introduced, and the mixture was blended for an additional 3 minutes. After mixing, the concrete was poured into cube molds measuring 100 mm on each side (100 mm x 100 mm). Sample preparation process is given in Figure 3. Molds were oiled to prevent damage during specimen removal and to facilitate easier extraction. The specimens were kept in a curing room at 25°C for 24 hours to allow them to harden before removing from molds.

The specimens, after setting in the moulds for 24 hours, were removed and subjected to curing to achieve the desired compressive strength. They were taken out of the water bath and then prepared for testing according to the specific requirements of each test. The curing period ranged from 7 to 28 days. For each test conducted in this study, a minimum of three samples were prepared and evaluated to ensure the reliability and reproducibility of the results. This approach allows for the identification of any anomalies and provides an average value that accurately represents the material behaviour. By testing multiple specimens under identical conditions, the influence of experimental variability is minimized, and the results can be considered statistically significant. This method was consistently applied across all tests, including workability, compressive strength and durability assessments, ensuring that the data obtained are robust and dependable for analysis and comparison.

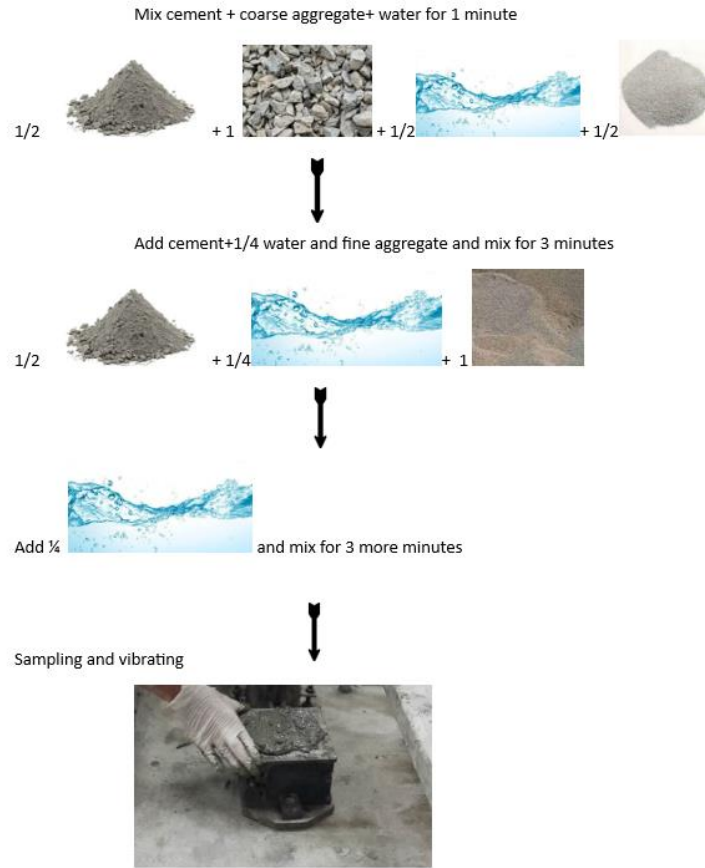


Figure 3. Sample preparation.

2.4. Test Methodologies

2.4.1. Slump Test

To determine the workability of each concrete mix, a slump test was conducted in accordance with ASTM C143. Figure 4 shows the slump test for one of the concrete mixtures. Samples have been placed in 3 layers and each layer has been tamped for 25 times.



Figure 4. Slump test.

Figure 5a. and 5b. gives how % WGP with 75 μm and 300 μm sizes replacement with cement change workability of mixes.

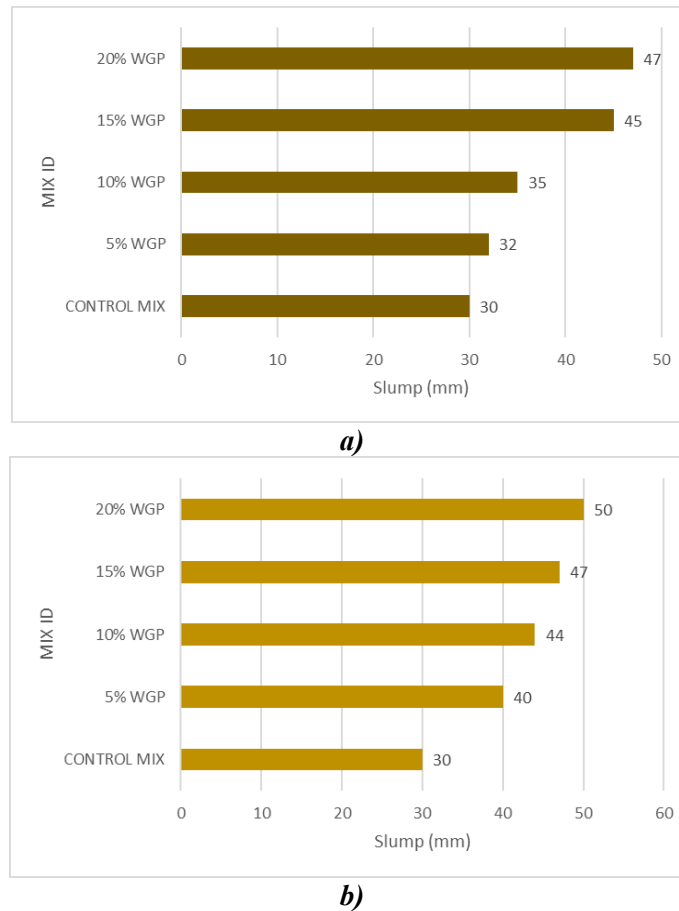


Figure 5. Slump test results a) 75 μm and b) 300 μm .

Waste glass affects the concrete's workability by changing the amount of free water in the mixture. The glass material's intrinsic cleanliness may be the cause of the enhanced concrete slump seen upon the addition of glass powder. The reduced cohesiveness between the cement paste and the smooth, impermeable surface of glass is the reason for its beneficial impact on concrete workability. This improves workability by allowing for better mobility and flow within the mixture since the glass particles do not bind as tightly to the cement paste.

In addition, the main causes of the improved workability include glass smoother surface and reduced absorption capacity. Additionally, the graph shows a clear correlation between the slump and the percentage of glass content. The percentage of glass content is directly proportional to the slump. The enhanced workability with the inclusion of glass is a significant advantage of utilizing this recycled material. In their respective studies, Malik et al. (2013) came to the conclusion that glass powder improves the workability of concrete [15]. This indicates that the concrete mix is simpler to work with, when glass powder is added. Through independent research, they were able to show that glass powder enhances the concrete's fluidity and consistency, making it easier to mix and apply.

The slump values for concrete containing 300 μm glass powder range from 30-50 mm, with 20% glass powder showing the highest slump, representing a 66.6% increase compared to the control mix. This enhanced workability might be attributed to the anti-adhesive properties of glass powders. The greater slump flow at higher glass replacement ratios may also be due to the increased compactness of the concrete's granular structure. Since the glass grains are finer than sand, they fill the pores between the coarse aggregates more effectively, have low water absorption, and possess a smooth surface. Wang et al., 2018, arrived at similar conclusion in their research [16]. Thus, the concrete became more workable with the addition of glass particles, negating the need for further superplasticizers.

2.4.2. Hardened Density Test

Density, is a unit of measurement for how compact a material is in relation to its weight per unit volume. The type of infrastructure determines the type of concrete and how dense it should be. The buoyancy technique for dry samples, which incorporates specifications from ASTM C642-13, was followed in conducting the test, as stated in ASTM C567-14. Figure 6a. and 6b. give how % WGP with 75 μm and 300 μm sizes replacement with cement change density of mixes.

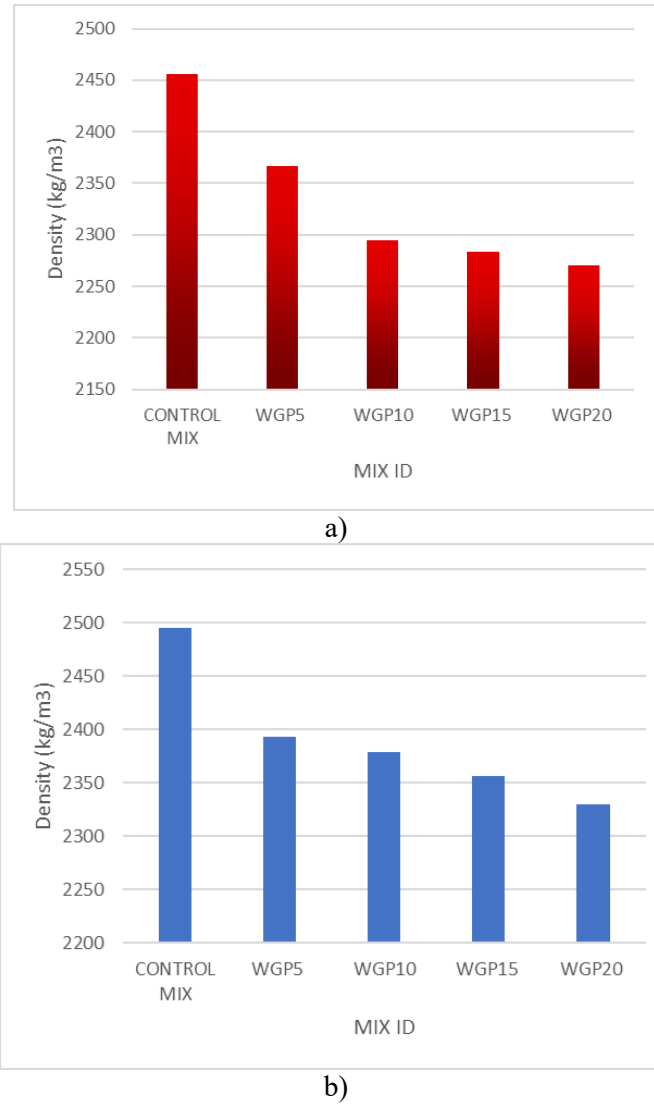


Figure 6. Density test results a) 75 μm and b) 300 μm .

Using substitute materials for cement in concrete allows for the refinement of pore sizes and shapes, creating a more uniform and compact structure. Figures 6a and 6b illustrate the saturated surface dry density of various combinations at 28 days. For mixtures incorporating WGP, densities range from 2409 to 2454 kg/m^3 for particle sizes of both 300 μm s and 75 μm s. Similarly, WGP exhibits densities ranging from 2384 to 2454 kg/m^3 and for 75 μm s ranges from 2270 to 2456 kg/m^3 .

The incorporation of waste glass powder in concrete leads to a reduction in its density, primarily because WGP in concrete are relatively lightweight materials. This decrease in density occurs despite WGP's inclusion due to its finer particle size, which enhances the packing concrete matrix [17-18].

When WGP is added to concrete, its smaller particles fill the voids and pores more effectively than traditional coarse aggregates. This improved packing density contributes to a more compact and homogeneous concrete mixture. As a result, the overall density of the concrete decreases, demonstrating the lightweight nature of WGP and its ability to optimize the use of space within the concrete matrix.

Furthermore, the incorporation of WGP does not compromise the structural integrity or mechanical properties of concrete most especially when used in pavement of road. Instead, it often enhances certain characteristics such as durability and resistance to environmental factors, making it a valuable sustainable alternative in construction materials.

2.4.3. Water Absorption Test

Water absorption is a non-destructive test of cement composites' durability qualities that assesses the material's ability to absorb water and shows how many pores are there. Each mix's water absorption was calculated using ASTM C642-13. Figure 7a. and 7b. give how % WGP with 75 μm and 300 μm sizes replacement with cement change water absorption of mixes. This test is the only one which is the concept of durability.

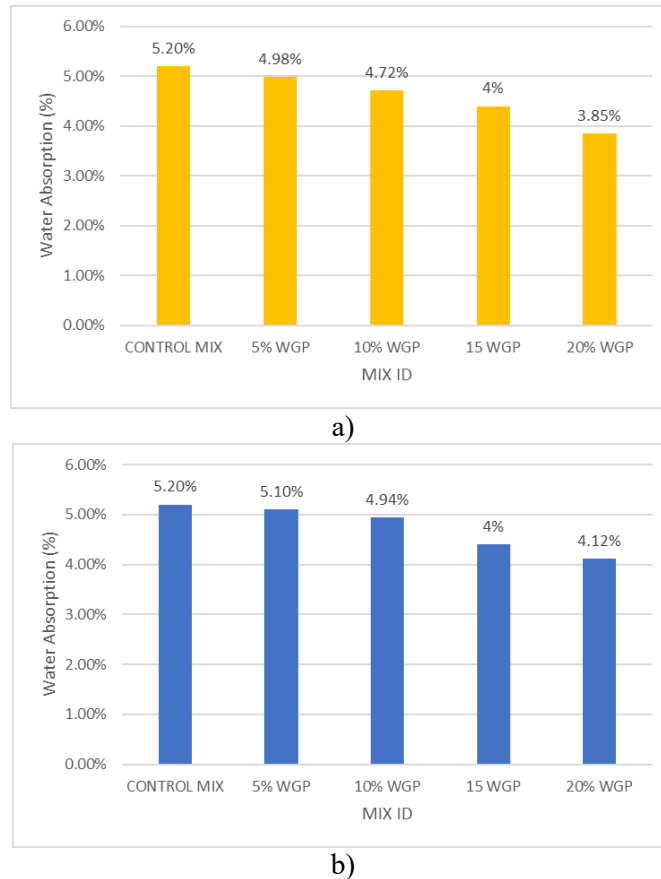


Figure 7. Water absorption test results a) 75 μm and b) 300 μm .

Figures 7a and 7b show the variance in water absorption as a function of glass powder used in place of cement. The percentage of water absorption decreases as the amount of glass powder increases. The water absorption test showed minor changes when two different glass powder particle sizes (75 and 300 μm) were used. Water absorption was reduced by the following percentages for concrete containing 75- μm glass powder: 4.2%, 9.2%, 19%, and 25.9% for concrete containing 5%, 10%, 15%, and 20% GP integration, respectively. In contrast, under same circumstances, the reduction for concrete with 300 μm GP was 1.9%, 5%, 15.4%, and 20.7%.

This is explained by the compact and porous microstructure of glass powder containing concretes, which are produced when glass powder undergoes a pozzolanic reaction. Glass's silica oxide and cement's calcium hydroxide combine to create a stronger C-S-H gel, which fills in the gaps and densifies the matrix, increasing the material's resistance to water penetration. This process is caused by WGP's pozzolanic activity, which transforms CH into C-S-H gel. Additionally, the filler role of the microscopic particles in WGP helps to fill the micropores in the structure [19].

The pozzolanic reaction, reduced voids, and improved hydration all contributed to the microstructural refinement of GP mixes. In their study, Patel et al. (2018) came to similar conclusions [20]. The normal allowed range for water absorption in concrete is between 3% and 8%, per ASTM standards. The results of this study fell within this range.

2.4.4. Compressive Strength Test

Compressive strength is a crucial property of cement-based materials that influences their ability to bear loads. The behaviour of cement mortar replaced with WGP under compressive pressure was examined using the compression testing apparatus shown in Figure 8 according to ASTM C109/C109M-20a. Figure 9a. and 9b. give how % WGP with 75 μm and 300 μm sizes replacement with cement change 7- and 28-days compressive strength of mixes.



Figure 8. Compressive strength testing.

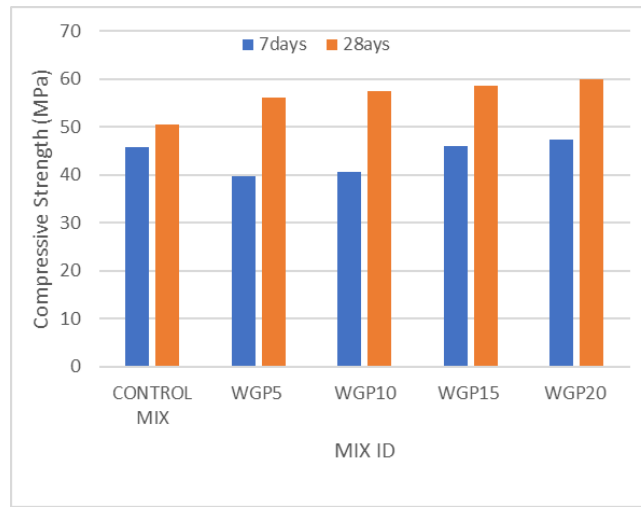
The average results of compressive strength tests on 3 specimens for each mixture of waste glass powder at varying proportions, taking into account particle sizes of 300 μm s and 75 μm s, are shown in Figures 9a and 9b. Following 7 and 28 days of cure, these tests were performed. The study sheds light on how different WGP ratios affect the way concrete mixes for rigid pavement build compressive strength over predetermined time periods.

The control mix recorded the highest 7 days compressive strength at 47.19 MPa. Relative to the lowest value observed in the 5% WGP mix, this represents a substantial increase of about 20.3%. Its continuous hydration process, unhindered by any possible interference from other ingredients, is responsible for the control mix's noticeable strength improvement. The long-term advantages of additives must be acknowledged, even though mixtures containing them may initially show slower strength increase because of possible delays in the pozzolanic process. The results after 7 days show that the pozzolanic reaction, which is slow in the early stages of hydration, contributes significantly to the material's increasing strength over time.

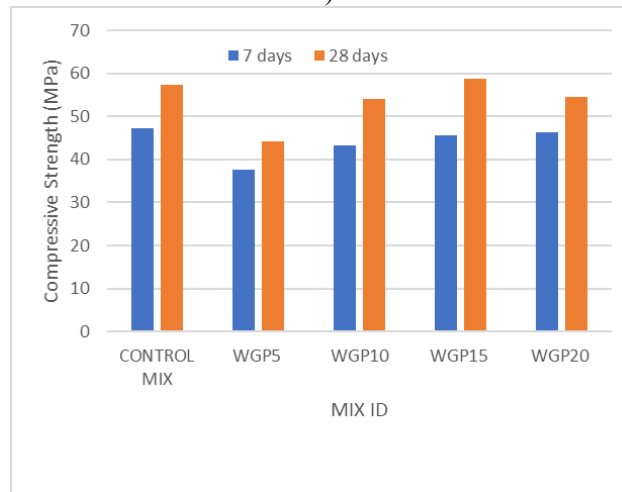
Notably, the control mix shows a notable improvement in compressive strength after 7 days, indicating the effectiveness of its hydration process and the lack of additive-induced delays. A similar discovery regarding the control strength's early strength was also made by Figueiredo et al. in 2019 [21]. This demonstrates how crucial it is to take into account both short-term and long-term effects when evaluating how well different mixes function for particular purposes. There are a number of reasons for the large increase in compressive strength that was shown in 20%WGP, but the main one is the presence of the pozzolanic reaction in the combination. Its fineness and pozzolanic reactivity may be the cause of the 20 WGP% to have risen in strength.

At 28 days, there was a noticeable 2.5% improvement in compressive strength for 15% WGP as compared to the control mix. As a result, there is a tiny drop in 20% WGP, which may be explained by the fact that strength tends to decrease when the amount of glass powder increases beyond 15%. In

contrast, Omran and Tagnit-Hamou explained that the 20% WGP increase could be ascribed to its pozzolanic reactivity and fineness, noting that its strength increases with the number of curing days [22].



a)



b)

Figure 9. Compressive strength test results a) 75 μm and b) 300 μm .

In general, concrete mixtures tend to have an optimal range for incorporating supplementary materials. The benefits from pozzolanic reactions and filler qualities may diminish after this threshold is exceeded, in this case at 15% WGP. additional elements include the concrete matrix's chemical interactions, hydration dynamics, enhanced porosity, and particle distribution. The research demonstrates how longer curing times (28 days) are associated with increased strength, which is mostly explained by the development of calcium silicate hydrate gel (C-S-H) during hydration. More C-S-H gel is created when the pozzolanic components in the mixture react with calcium hydroxide, a result of cement hydration. By filling the pore structure inside the concrete matrix, this gel formation raises density and enhances mechanical qualities like compressive strength. This improvement is further aided by the addition of glass powder as a cementitious ingredient. By interacting with calcium hydroxide to create more C-S-H gel, it functions as a pozzolan, strengthening the interfacial transition zone and lowering the concrete's porosity. This trend becomes more pronounced at higher replacement levels, such as 15% WGP, where the beneficial effects on compressive strength are more evident.

4. RESULTS AND DISCUSSION

The study includes a thorough analysis, assessment, and evaluation of glass powder samples in light of their unique characteristics. A set water-to-cement ratio of 0.55 was used to design five alternative ratios.

The experiment's main goal was to assess the modified concrete's workability, durability, and mechanical qualities. The following is a summary of the study's findings:

When compared to the control mix, the concrete with a glass powder percentage of 5–20% and a particle size of 75- μm showed the largest slump, with a 56% increase in workability. When compared to the control mix, the slump values for concrete containing 300- μm glass powder vary from 30 to 50 mm, with 20% glass powder exhibiting the maximum slump.

The control mix shows a notable rise in compressive strength after 7 days, indicating the effectiveness of its hydration process and the lack of additive-induced delays. At 28 days, there was a noticeable 2.5% improvement in compressive strength for 15% WGP as compared to the control mix. For both the 75- and 300- μm particle sizes, the highest compressive strength was found in 15% glass powder. When waste glass powder is added to concrete, the density of the concrete decreases, mainly because WGP is a relatively light material.

As the concentration of glass powder rises, the proportion of water absorption falls. When glass powder with particle sizes of 75 and 300 μm s was applied, the water absorption test revealed very little change. For both 75 and 300 μm particle sizes, the lowest percentages of water absorption were found in 20% WGP.

Compared with other supplementary materials commonly used in concrete pavements—such as fly ash, nano-silica, and GGBS—the results of this study indicate that the evaluated material provides comparable performance in terms of workability with lower slump values like 50 mm, durability like water absorption values very similar to GGBS and fly ash one around 4% and 55-60 MPa compressive strength on 28 days. Therefore, its selection can be considered appropriate and practical, particularly in regions where it is readily available.

The incorporation of waste glass as a supplementary material in concrete reduces CO₂ emissions and improves overall life-cycle performance. The primary source of these environmental gains is the partial replacement of Portland cement, since clinker production accounts for most of concrete's embodied carbon. Substituting a portion of the cement with finely ground waste glass lowers the clinker factor and, in turn, reduces both process-related and energy-related emissions. From a life-cycle assessment (LCA) standpoint, using post-consumer glass decreases environmental burdens associated with raw material extraction, transportation, and end-of-life waste management. Diverting glass from landfills further avoids disposal impacts and supports resource circularity in the construction sector.

When properly processed, waste glass powder also offers performance benefits. Its pozzolanic activity contributes to long-term strength and durability [23], which can extend service life and reduce maintenance needs. Because waste glass requires less energy to process than manufacturing new cement, its use decreases resource consumption and can reduce material costs [24]. Collectively, these advantages strengthen both the environmental performance and resource efficiency of concrete pavement systems [23].

5. CONCLUSIONS AND RECOMMENDATIONS

Taking into account the 28 days compressive strength of both concrete and mortar, the study indicates that a 15% replacement of cement with waste glass powder provides the most favorable balance of strength, workability, and durability. At this level, compressive strength exceeded that of the control mix, confirming that WGP can function as an effective supplementary cementitious material. Both 75 μm and 300 μm particle sizes showed broadly similar behavior; however, the 75 μm powder offers environmental advantages, as it requires less energy for grinding and provides the highest improvement in workability.

Beyond the laboratory results, these findings carry several practical implications for engineering and construction: Replacing 15% of cement with waste glass powder can lower material costs in concrete production without compromising mechanical performance, increased slump at lower replacement levels which means improvement in workability, may reduce the need for chemical admixtures, simplifying mix design and handling on construction sites, reduced water absorption suggests potential improvements in long-term durability, particularly in environments where moisture penetration is a

concern, every six tons of concrete produced with WGP significantly reduces CO₂ emissions associated with cement manufacturing. This positions WGP concrete as a practical option for sustainable construction and green-building certification, using glass powder in concrete offers a scalable method for diverting large volumes of waste glass from landfills, turning an environmental burden into a valuable resource. Overall, the study demonstrates that waste glass powder is not only technically feasible but also presents strong economic and environmental incentives for real-world adoption. Future research may explore field-scale performance, durability under aggressive exposure conditions, and optimization of particle size distribution to further refine the material's practical potential. For future work, it is recommended to conduct comprehensive durability and morphology tests to further evaluate the long-term behavior of the material.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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