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Enhancing Concrete Performance and Sustainability Using Waste Glass Powder as a Cement Substitute

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ABSTRACT

Concrete is the most widely used construction material, but its dependence on Portland cement contributes substantially to global CO_2 emissions. This study explores the partial replacement of cement with Waste Glass Powder (WGP), a silica-rich industrial byproduct, to enhance both sustainability and concrete performance. WGP was added at 10%, 12.5%, 15%, 17.5%, and 20% by weight of cement. Mechanical and durability properties including compressive strength, splitting tensile strength, flexural strength, and water permeability were evaluated at 28 days. The mix containing 17.5% WGP exhibited optimal performance, with compressive strength reaching 49.5 MPa (a 33.7% increase over the 37.0 MPa control), tensile strength rising to 4.3 MPa (compared to 3.2 MPa), and flexural strength peaking at 5.6 MPa (versus 4.2 MPa). Water absorption dropped from 5.2% in the control to 2.8% in the WGP17.5 mix, reflecting significant permeability reduction. These enhancements are attributed to the pozzolanic reactivity of WGP and improved microstructural densification. The results confirm that incorporating 17.5% WGP offers a balanced improvement in strength and durability while promoting sustainable construction through waste valorization and reduced cement usage.

1. Introduction

Concrete is the most extensively used construction material in the world due to its versatility, durability, and relatively low cost[1]–[3]. As urbanization and infrastructure development continue to accelerate globally, the demand for concrete has surged dramatically. Cement, a key constituent of concrete, plays a critical role in binding the composite material; however, its production comes with significant environmental repercussions[4]–[7]. The manufacturing of cement is an energy-intensive process that contributes substantially to greenhouse gas emissions, particularly carbon dioxide (CO_2). It is estimated that cement production accounts for approximately 7–8% of global CO_2 emissions, thereby exacerbating the phenomenon of global warming and posing a substantial challenge to sustainable development goals[8]–[10]. In light of these environmental concerns, there has been a growing interest among researchers and practitioners in the construction industry to identify sustainable alternatives to conventional Portland cement[11]–[13]. One of the promising strategies in this direction involves the use of supplementary cementitious materials (SCMs), which are often industrial by-products or recycled materials that can partially replace cement in concrete mixes[14]–[17]. Among these alternatives, waste glass powder (WGP) has emerged as a viable and environmentally responsible option. Glass waste is generated in vast quantities worldwide, and its disposal poses a serious environmental issue due to its non-biodegradable nature[18], [19]. Converting this waste into a fine powder for use in concrete not only addresses the problem of waste management but also reduces the dependency on traditional cement[20]–[23].

Waste glass powder is rich in amorphous silica, making it suitable for use as a pozzolanic material. When finely ground, it reacts with the calcium hydroxide released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel, which enhances the strength and durability of the concrete matrix[24], [25]. Several studies have investigated the mechanical performance of concrete containing WGP and have reported improvements in compressive, tensile, and flexural strength at varying replacement levels[26]–[28]. However, despite these advancements, inconsistencies remain regarding the optimum percentage of WGP replacement and its influence on the permeability of concrete a key parameter affecting the long-term durability and resistance to environmental degradation[29]–[32].

This study aims to contribute to the ongoing exploration of sustainable concrete by investigating the effects of using waste glass powder as a partial replacement for cement in concrete mixtures. Specifically, WGP was incorporated at replacement levels of 10%, 12.5%, 15%, 17.5%, and 20% by weight of cement. The experimental program included an assessment of compressive strength, split tensile strength, flexural strength, and water permeability after a 28-day curing period. A control sample with no WGP was also tested for comparison purposes.

2. Material and method

2.1. Materials

The materials used in this study include Ordinary Portland Cement (OPC), fine and coarse aggregates, potable water, and waste glass powder (WGP), as illustrated in **Fig 1**. The OPC conformed to ASTM C150 Type I standards, ensuring reliable performance in cementitious applications. Natural river sand, clean and well-graded in accordance with ASTM C33, was used as the fine aggregate. Crushed granite with a nominal maximum size of 20 mm served as the coarse aggregate. Waste glass, predominantly composed of clear and green soda-lime glass, was sourced from local recycling facilities. The glass was meticulously washed to remove contaminants, then crushed and ground into a fine powder using a laboratory ball mill. The resulting WGP exhibited a fineness of approximately 400–500 m^2/kg (Blaine), finer than typical cement particles. The particle size distribution curves (see **Fig 2**) confirmed that the majority of WGP particles were below 75 µm, meeting the fineness requirements for pozzolanic reactivity. Chemical characterization using X-ray fluorescence (XRF) revealed that WGP contained a high proportion of silica (SiO_2) at 72.5%, along with other oxides such as CaO, Al_2O_3, and Na_2O, as detailed in **Table 1**. These compositional attributes support its suitability as a supplementary cementitious material in concrete.

Fig.1. Materials used: Ordinary Portland Cement (OPC), fine and coarse aggregates, potable water, and waste glass powder (WGP).

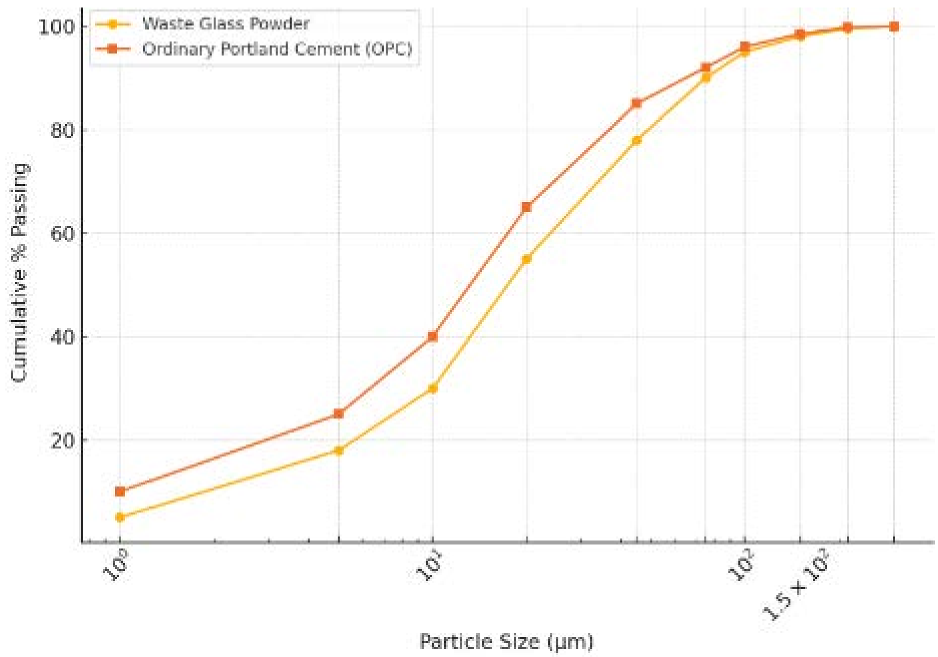

Fig.2. Particle Size Distribution (PSD) Curves of Glass Powder, and Ordinary Portland Cement (OPC).

TABLE 1

Chemical composition of Waste Glass Powder.

Oxide	Content (%)
SiO_2 (Silicon Dioxide)	72.50
Al_2O_3 (Aluminum Oxide)	1.80
Fe_2O_3 (Ferric Oxide)	0.30
CaO (Calcium Oxide)	9.70
MgO (Magnesium Oxide)	3.20
K_2O (Potassium Oxide)	0.10
Na_2O (Sodium Oxide)	13.20
TiO_2 (Titanium Dioxide)	0.05
P_2O_5 (Phosphorus Pentoxide)	0.02
SO_3 (Sulfur Trioxide)	0.02
MnO (Manganese Oxide)	0.01
Cl (Chloride)	0.002
Loss on Ignition (LOI)	0.50

2.2. Mix Design

The experimental program involved the preparation of multiple concrete mixes incorporating varying proportions of waste glass powder (WGP) as a partial replacement for ordinary Portland cement (OPC) to improve both the mechanical performance and sustainability of concrete. The WGP replacement levels were set at 10%, 12.5%, 15%, 17.5%, and 20% by weight of cement. A control mix with 100% OPC (no WGP) was included for comparison. The water-to-binder (w/b) ratio was maintained at 0.45 across all mixes to ensure consistency in hydration and workability as listed in **Table 2**.

To assess mechanical and durability performance, standard cylindrical specimens measuring 100 mm in diameter and 200 mm in height were cast for each mix. After 24 hours, all specimens were demolded and placed in water curing at 20 ± 2°C until the specified testing age. Laboratory tests were conducted to evaluate compressive strength, tensile strength, flexural strength, and water permeability at 28 days in accordance with relevant ASTM standards (ASTM C39 for compressive strength, ASTM C496 for tensile strength, ASTM C78 for flexural strength, and ASTM C1202 for permeability). The purpose of this program was to determine the optimal WGP replacement level that offers the greatest performance enhancement, while also reducing reliance on cement and utilizing industrial waste sustainably.

TABLE 2

Mix proportions for different WGP replacement levels.

Mix ID	Cement (kg/m³)	WGP (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	WGP Replacement (%)
M0	400	0	650	1200	200	0%
M10	360	40	650	1200	200	10%
M12.5	350	50	650	1200	200	12.5%
M15	340	60	650	1200	200	15%
M17.5	330	70	650	1200	200	17.5%
M20	320	80	650	1200	200	20%

2.3. Specimen Preparation

Concrete specimens were cast in standard steel molds and compacted using a vibrating table to eliminate air voids. The following specimens were prepared for each mix:

- Compressive strength: Cubes of 150 mm × 150 mm × 150 mm
- Split tensile strength: Cylinders of 150 mm diameter × 300 mm height
- Flexural strength: Prisms of 100 mm × 100 mm × 500 mm
- Water permeability: Cylindrical specimens with 150 mm diameter × 150 mm height

All specimens were demolded after 24 hours and then cured in clean water at room temperature for 28 days.

2.4. Testing Procedures

All mechanical and durability tests were conducted at 28 days following standard ASTM procedures:

- Compressive Strength: Tested in accordance with ASTM C39.
- Split Tensile Strength: Tested following ASTM C496.
- Flexural Strength: Conducted according to ASTM C78 using third-point loading.
- Water Permeability: Evaluated based on DIN 1048, where specimens were subjected to water pressure for 72 hours, and the depth of penetration was recorded.

The experimental setup and equipment used for these tests are shown in **Fig.3**.

Fig.3. Testing Setup.

3. Results

3.1. Workability

The workability of fresh concrete mixes incorporating varying percentages of Waste Glass Powder (WGP) was evaluated using the flow table test as per ASTM C1437. The results showed that the addition of WGP slightly reduced the flow diameter compared to the control mix, indicating a marginal decrease in workability. The control mix exhibited the highest flow diameter of 175 mm, while the WGP mixes ranged between 168 mm and 155 mm as the replacement level increased as shown in **Fig 4**. This reduction is attributed to the angular shape and high surface area of glass powder particles, which tend to absorb more water and increase internal friction within the mix. Nevertheless, all mixes maintained acceptable flow characteristics suitable for proper casting and compaction. The results confirm that while WGP affects workability to a limited extent, it does not hinder the practical application of the concrete, especially when optimized at the 17.5% replacement level.

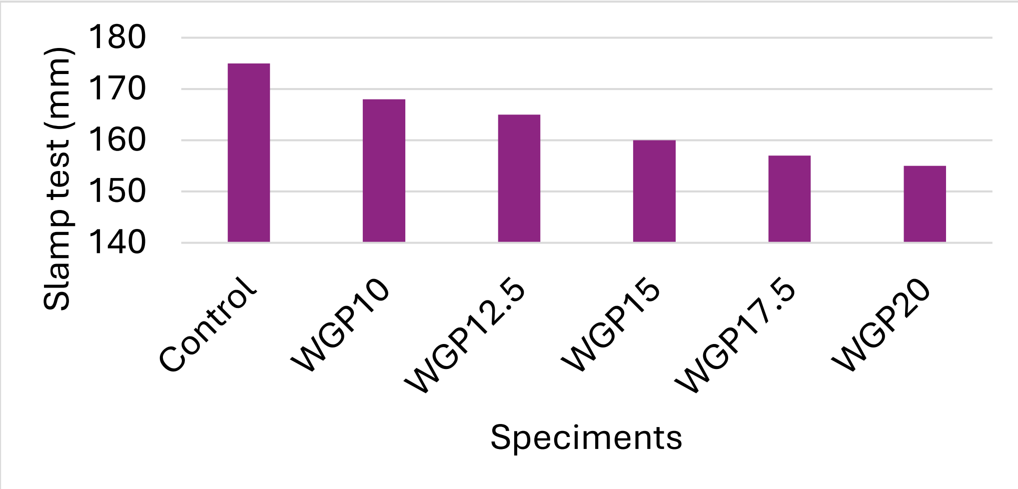

Fig.4. Effect of using WGP on Slump test

3.2. Compressive Strength

The results presented in **Table 3** and illustrated in **Fig 5** reveal a consistent improvement in compressive strength with the incorporation of Waste Glass Powder (WGP) up to a 17.5% replacement level. At 3, 7, and 28 days, mixes containing WGP outperformed the control, with WGP17.5 showing the highest strength gain achieving 49.5 MPa at 28 days compared to 37.0 MPa in the control. This indicates a strong pozzolanic reaction due to the high silica content in WGP, which contributes to the formation of additional calcium silicate hydrate (C–S–H) gel. However, at 20% replacement, a slight decline was observed, suggesting that excessive WGP might reduce early cement hydration due to dilution effects.

TABLE 3

Compressive Strength Results (MPa)

Mix ID	3 Days	7 Days	28 Days
Control	21.5	29.8	37.0
WGP10	22.8	31.2	39.5
WGP12.5	23.5	32.5	41.2
WGP15	24.1	33.8	43.0
WGP17.5	25.0	35.5	49.5
WGP20	23.0	32.0	44.0

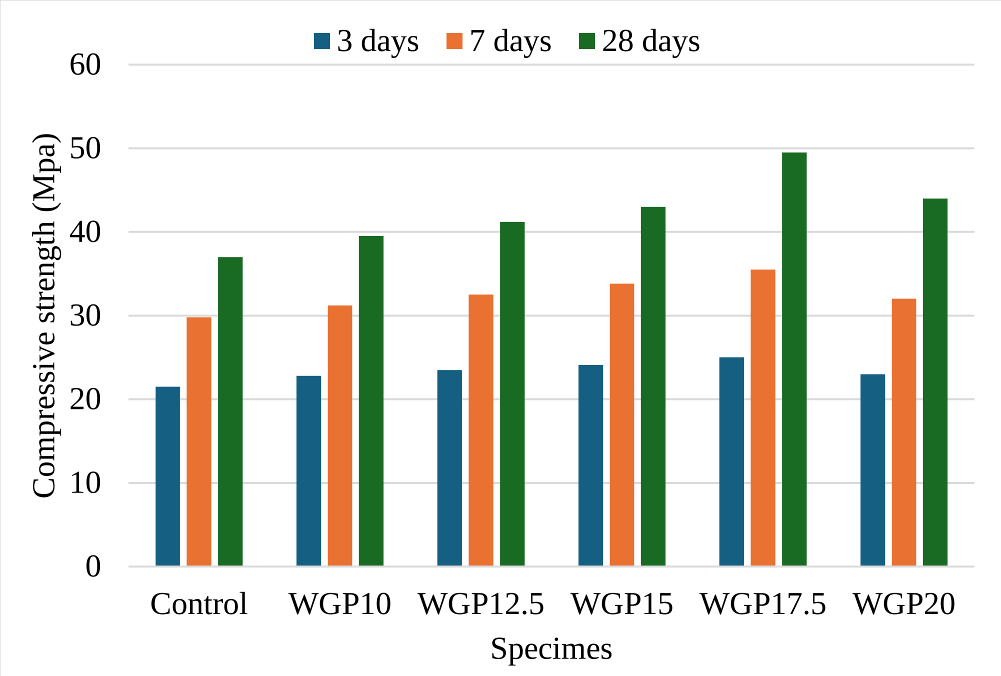

Fig.5.Results of Comparison of results at 7, 14, and 28 days

3.3. Tensile Strength

As shown in **Table 4**, and **Fig 6**, the splitting tensile strength followed a trend similar to compressive strength. The WGP17.5 mix achieved the highest tensile strength of 4.3 MPa at 28 days, a significant improvement over the control mix which reached only 3.2 MPa. The increase in tensile strength can be attributed to the refined microstructure and enhanced interfacial bonding due to the fine glass particles filling voids in the matrix. The enhancement was most pronounced between 15% and 17.5% WGP content, while the WGP20 mix showed marginal strength loss, likely due to excess replacement reducing available cementitious content.

TABLE 4

Splitting Tensile Strength Results (MPa)

Mix ID	**3 Days**	**7 Days**	**28 Days**
Control	1.8	2.5	3.2
WGP10	1.9	2.6	3.5
WGP12.5	2.0	2.7	3.7
WGP15	2.1	2.8	3.9
WGP17.5	2.3	3.1	4.3
WGP20	2.0	2.7	3.8

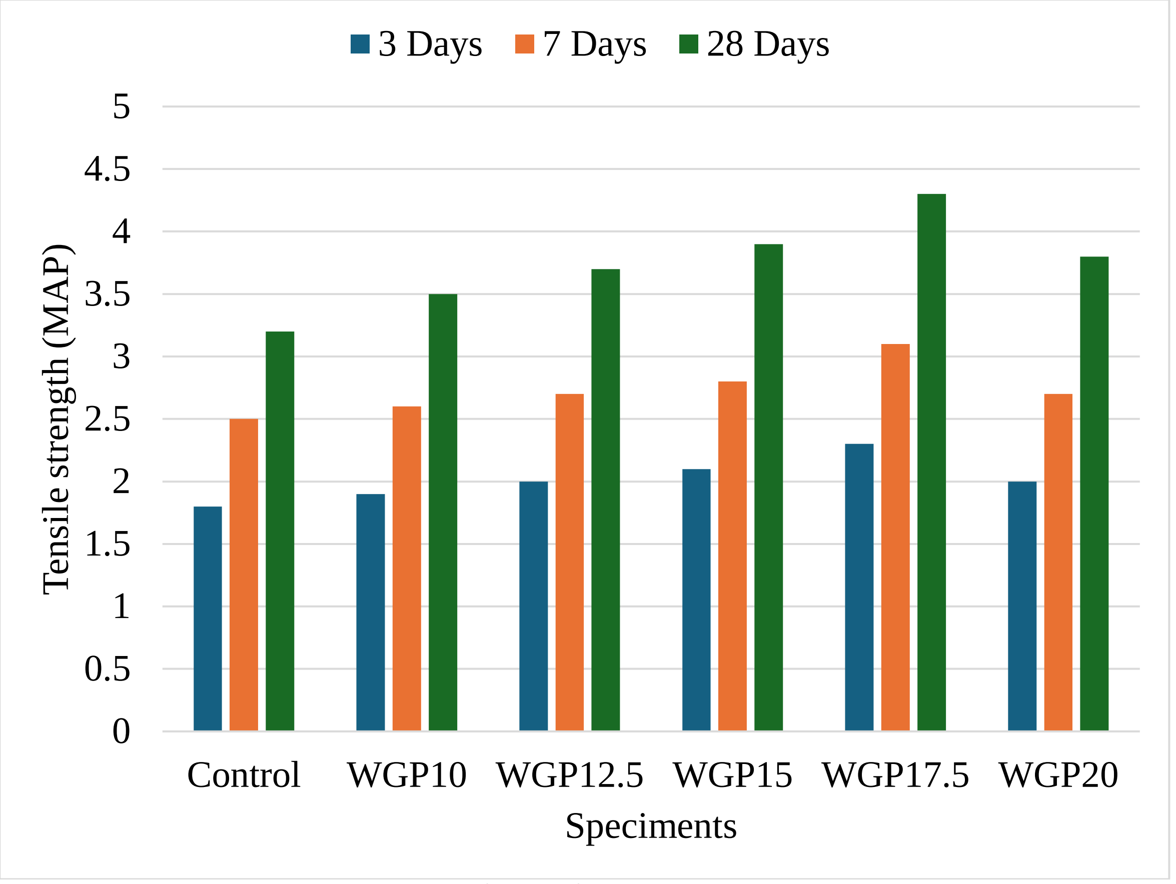

Fig.6. Results of Tensile of results at 7, 14, and 28 days

3.4. Flexure Strength

Flexural strength test results in **Table 5**, and **Fig7** highlight a gradual increase in performance with higher WGP content, peaking at 17.5% replacement. The WGP17.5 mix recorded a flexural strength of 5.6 MPa at 28 days, representing a 33% increase compared to the control (4.2 MPa). This improvement can be linked to the densification of the cementitious matrix and improved stress distribution across the concrete section, resulting from better particle packing and supplementary pozzolanic action. The decline at 20% replacement suggests the optimal limit had been surpassed, which aligns with observed trends in compressive and tensile strength.

TABLE 5

Flexural Strength Results (MPa).

Mix ID	3 Days	7 Days	28 Days
Control	2.4	3.1	4.2
WGP10	2.6	3.3	4.5
WGP12.5	2.8	3.5	4.8
WGP15	2.9	3.7	5.0
WGP17.5	3.1	4.0	5.6
WGP20	2.7	3.5	4.9

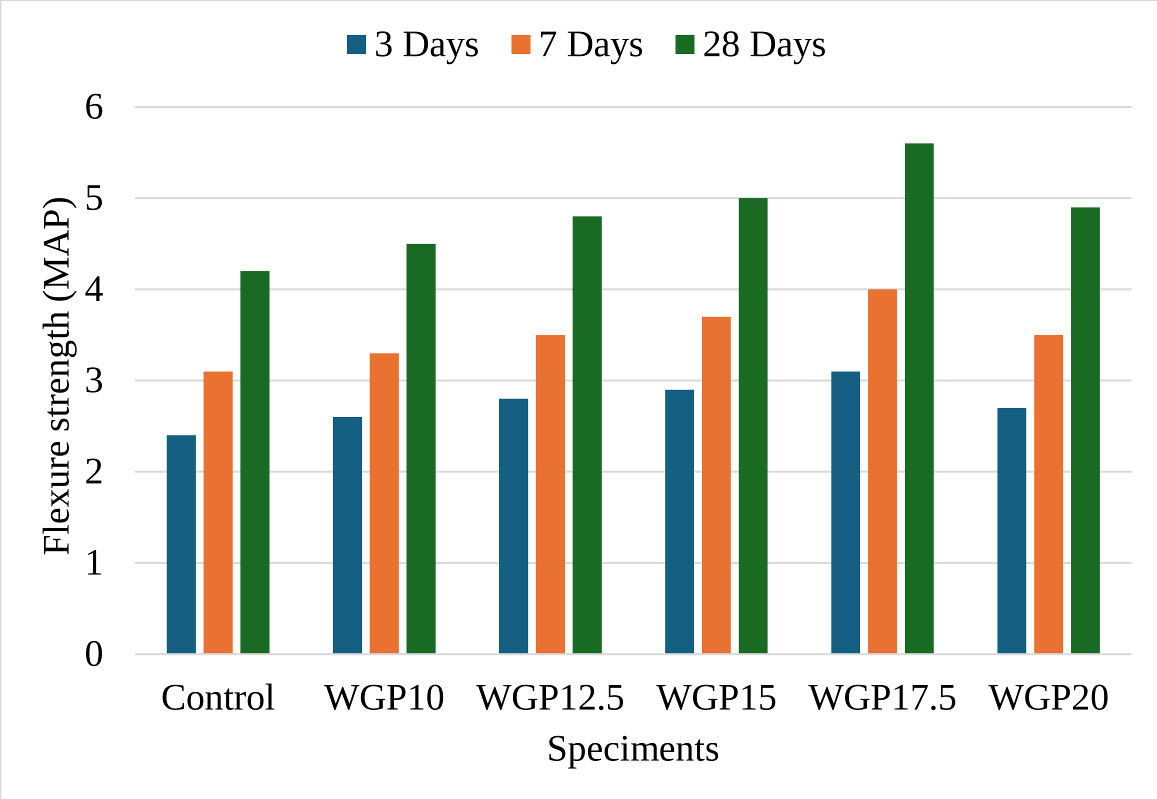

Fig.7. Results of Flexural of results at 7, 14, and 28 days.

3.5. Water Permeability

The water permeability of the concrete mixtures was evaluated using the conventional immersion method, which remains a widely accepted approach for assessing the resistance of concrete to water ingress. This procedure involved oven-drying concrete cubes to a constant mass, immersing them in water for 24 hours, and then re-weighing to determine the percentage of water absorbed, following the guidelines outlined in ASTM C642.

As shown in **Table 6, and Fig 8**, the control mix recorded the highest water absorption value of 5.2%, indicating a more porous and less durable matrix. With the incorporation of waste glass powder (WGP) as a partial cement replacement, a progressive reduction in water absorption was observed across all modified mixes. This reduction is attributed to the pozzolanic activity of WGP, which contributes to pore refinement, reduced capillary connectivity, and enhanced matrix densification. The mix containing 17.5% WGP demonstrated the lowest absorption value of 2.8%, indicating a significant improvement in permeability. While the mix with 20% WGP also outperformed the control, its performance was slightly inferior to that of the WGP17.5 mix, suggesting that 17.5% replacement is the optimal level for reducing water permeability under the conditions of this study.

TABLE 6

Water Absorption Results Using the Immersion Method.

Mix ID	Water Absorption (%)	Permeability Classification*
Control	5.2	High
WGP10	4.6	Moderate
WGP12.5	3.9	Moderate
WGP15	3.4	Low
WGP17.5	2.8	Very Low
WGP20	3.0	Low

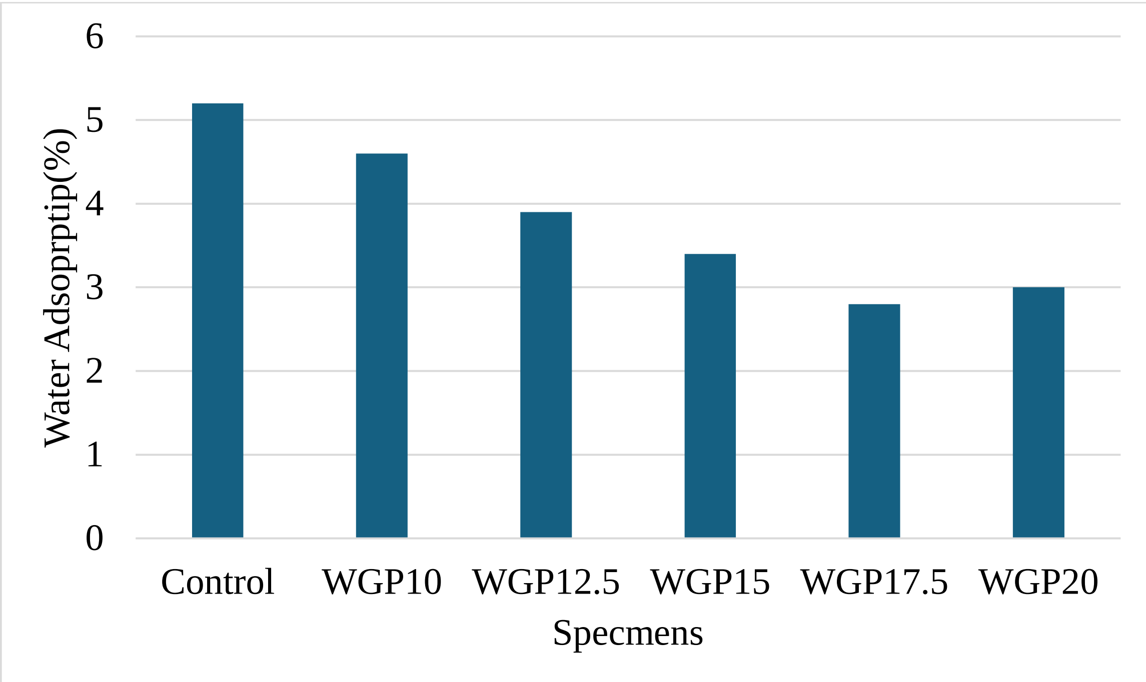

Fig.8. Results of Water Permeability of results at 28 days.

4. Discussion

4.1. Workability

The observed decline in workability with increasing Waste Glass Powder (WGP) content (from 175 mm in the control to 155 mm at 20% WGP) can be attributed to the physical characteristics of WGP particles. Unlike spherical cement grains, WGP particles are angular and possess a relatively high surface area, which increases internal friction and absorbs more water, thus reducing the mix's fluidity. However, the flow reduction remained within acceptable limits, demonstrating that even at higher replacement levels, concrete remained workable without the need for chemical admixtures. The best balance between workability and performance appeared at 17.5% WGP, where the flow diameter was slightly reduced but still allowed proper casting and compaction.

4.2. Compressive Strength

The compressive strength results show a positive correlation between WGP content and strength gain, up to the 17.5% replacement level. At 28 days, WGP17.5 achieved a strength of 49.5 MPa, a 33.8% increase over the control. This improvement is driven by multiple synergistic effects:

- Pozzolanic reaction: The high silica content of WGP reacts with calcium hydroxide to produce additional calcium silicate hydrate (C–S–H), enhancing matrix strength.
- Micro-filling effect: Fine WGP particles fill voids, leading to a denser matrix and fewer micro-cracks.
- Improved particle packing: Leads to reduced porosity and better load distribution.

However, at 20% WGP, a slight decline in strength occurred (44.0 MPa), likely due to dilution effects where excessive replacement reduces available cement, thereby slowing early hydration and compromising long-term bonding.

4.3. Tensile Strength

Tensile strength, being more sensitive to microcracks and interfacial transition zones (ITZ), followed a trend consistent with compressive strength. The WGP17.5 mix reached 4.3 MPa, compared to 3.2 MPa in the control. This 34% increase reflects:

- Enhanced bond strength between paste and aggregates due to WGP-induced pore refinement.
- Densified ITZ owing to finer particle distribution, reducing crack propagation paths.

Again, strength declined at 20% replacement due to over-saturation of non-cementitious material, resulting in inadequate binder content to bridge microcracks effectively.

4.4. Flexural Strength

Flexural strength showed a steady rise with increasing WGP content, peaking at 5.6 MPa for WGP17.5, indicating a 33% improvement over the control. This improvement can be attributed to:

- Better stress transfer across the cement matrix due to reduced porosity.
- Enhanced bridging ability across micro-cracks from the refined particle distribution.

Flexural performance is particularly influenced by matrix cohesion and crack resistance, which were substantially improved by the pozzolanic activity of WGP. However, similar to compressive and tensile results, the 20% mix slightly underperformed due to excess WGP limiting cement hydration.

4.5. Water Permeability

Permeability results showed a strong inverse relationship with WGP content. Water absorption decreased from 5.2% in control to 2.8% in the WGP17.5 mix, indicating a transition from a highly permeable to a very low permeable matrix. This is due to:

- The pore-refining ability of WGP through secondary C–S–H gel formation.
- Enhanced packing density, minimizing capillary pore connectivity.
- Reduced micro voids and water pathways, improving long-term durability.

At 20% WGP, absorption increased slightly to 3.0%, confirming the trend that excessive WGP begins to reduce performance. Nonetheless, this value remains significantly better than the control, further verifying the durability-enhancing potential of WGP.

5. Conclusion

This study explores the use of Waste Glass Powder (WGP) as a sustainable partial replacement for cement in concrete. The investigation focused on its influence on workability, mechanical properties, and durability. The incorporation of WGP demonstrated potential benefits in enhancing concrete performance while promoting environmental sustainability through the recycling of glass waste. The findings support WGP's suitability as a supplementary cementitious material when used in optimized proportions, the following key conclusions can be drawn:

1. Workability decreased slightly with higher WGP content due to increased water demand and internal friction but remained suitable for casting.
2. Compressive strength improved significantly up to 17.5% WGP replacement, with a 33.8% gain at 28 days compared to the control mix.
3. Tensile and flexural strengths followed similar trends, peaking at 17.5% WGP, confirming enhanced mechanical performance.
4. Water permeability reduced substantially with WGP, indicating refined pore structure and enhanced durability.
5. 20% WGP replacement showed diminishing returns, likely due to dilution effects and reduced cement hydration.
6. The optimal WGP content was identified as 17.5%, offering the best combination of mechanical strength, workability, and impermeability.

6. Future Work

1. Microstructural Analysis: Future studies should include SEM and XRD analyses to better understand the microstructural development and pozzolanic reaction mechanisms of WGP in concrete.
2. Long-Term Durability Tests: Extend the evaluation to long-term performance metrics such as carbonation resistance, sulfate attack, freeze-thaw cycles, and alkali-silica reaction (ASR).
3. Hybrid Pozzolanic Systems: Investigate the combined effect of WGP with other supplementary cementitious materials like fly ash or slag to enhance both mechanical and durability properties.
4. Field Applications: Pilot-scale field trials are recommended to validate the laboratory results under real environmental and structural conditions.

5. Life Cycle Assessment (LCA): Conduct a comprehensive LCA to quantify the environmental benefits of WGP-based concrete in terms of carbon footprint and embodied energy reduction.

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