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Effect of Waste Glass on the Workability and Mechanical Properties of Geopolymer Concrete: Towards Sustainable Geopolymer Concrete

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Abstract
The global shift toward sustainable construction necessitates the development of innovative materials to reduce environmental impacts while maintaining superior structural performance. This study explores the integration of waste glass as a partial substitute for fly ash and sand in geopolymer concrete, aiming to enhance durability, mechanical properties, and ecological efficiency. Substitution levels of 10%, 20%, and 30% for fly ash and 15%, 30%, and 50% for sand were evaluated, along with a dual replacement strategy involving 10% replacement for both components. Experimental results demonstrate significant improvements in mechanical performance, with compressive, flexural, and splitting tensile strengths increasing by up to 22%, 30%, and 15%, respectively. The dual replacement mix exhibited outstanding performance, achieving superior matrix densification and reduced water absorption, indicative of enhanced durability. Microstructural analysis revealed a refined matrix with reduced porosity and well-distributed binding phases, attributed to the synergistic effects of waste glass particles. These findings underscore the transformative potential of waste glass in geopolymer concrete production, offering a sustainable and high-performance alternative to conventional construction materials. This research contributes to advancing eco-conscious construction methodologies, aligning with global sustainability objectives.

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1. Introduction

The conventional cement and concrete sectors significantly contribute to environmental deterioration, chiefly due to considerable carbon dioxide (CO_2) emissions and extensive resource utilization. Cement production constitutes roughly 8% of global CO_2 emissions, predominantly from limestone calcination, which emits CO_2. Moreover, extracting and processing raw materials like limestone, clay, and sand intensifies resource depletion, habitat destruction, and ecological imbalance. These activities contribute to biodiversity loss and ecosystem degradation **(Ghazy et al. 2022; Sun et al. 2024; Wang et al., 2024; Xu et al., 2024; Zhang et al., 2024)**. In response to urgent environmental issues, researchers and industry experts have progressively promoted sustainable alternatives to traditional concrete that reduce CO_2 emissions and preserve natural resources **(Zhang et al. 2020b; Zhang et al. 2020; Ghazy et al. 2022; Dinh, 2024b; Manikandan et al. 2024)**. Among these alternatives, geopolymer concrete, conceived by Joseph Davidovits in the 1970s, has emerged as a viable, sustainable substitute for conventional concrete. This novel material is derived from alumino-silicate sources, including fly ash and ground granulated blast-furnace slag, activated by alkaline solutions to create a resilient binder independent of Portland cement,
(Davidovits, 1991; Fernández et al. 2004; Habert et al. 2010). Geopolymer concrete reduces CO_2 emissions by up to 80% compared to traditional concrete, supporting global environmental sustainability objectives while preserving structural integrity **(Cheeseman et al.1999; Bakharev, 2005; Kong and Sanjayan, 2010; Schneider et al., 2011; Olivier et al., 2012; Rashad, 2014a)**. Moreover, the incorporation of industrial by-products like fly ash and ground granulated blast-furnace slag in geopolymer concrete fosters a circular economy by minimizing landfill waste **(Cyr et al., 2011; Pacheco-Torgal et al., 2013; Roberts and Johnson, 2014)**.Research indicates that geopolymer concrete satisfies structural criteria while providing substantial environmental advantages **(Scrivener, 2014; Qiao and Qiu, 2015; Ahmad et al., 2019).**

Alongside geopolymer concrete, waste glass (WG) constitutes a significant pathway for sustainable construction practices. Each year, more than 100 million tons of waste generated worldwide are produced, with merely 21% recycled and the rest relegated to landfills **(Ashour et al. 2019; Wang, et al 2021).** Recycling rates in numerous regions, such as the United States, the United Kingdom, Hong Kong, and Singapore, remain under 50%, in contrast to the elevated rates not ed in the European Union **(Heriyanto et al., 2018; Hama et al., 2019; Jiang et al., 2019).** The inadequate recycling rates highlight the pressing necessity for improved waste management strategies.

Recent studies have demonstrated the potential of WG as a sustainable alternative to traditional materials like fly ash and sand in geopolymer concrete. Replacing up to 30% of fly ash with WG has been shown to increase compressive strength by 20%, owing to the enhanced microstructural densification facilitated by the amorphous nature of WG **(Tahwia et al., 2022)**. Additionally, substituting sand with WG in similar proportions improves workability, as evidenced by higher slump values that reflect better workability **(Dinh., 2024)**. However, exceeding a 50% replacement level can lead to decreased performance, including micro-cracking, due to alkali-silica reactions, highlighting the need for careful optimization **(Çelik et al., 2023).**

The concentration of alkaline activators, such as sodium hydroxide (NH) and sodium silicate (NS), plays a critical role in geopolymer concrete's performance. The concentration of alkaline activators, such as NH and NS, plays a critical role in geopolymer concrete's performance**. Ghazy et al., 2022a** found that a concentration of 14 M NaOH, coupled with curing at 60°C for 24 hours concentration yields optimal compressive strength and flexural confirming the importance of balancing both alkaline activator concentration and curing conditions **(Ghazy et al., 2022b)**. Commonly, an14 M NH solution with a NS to NH ratio of 2.5:1 is used to activate the geopolymer matrix, improving mechanical properties like compressive strength. A concentration of 14 M NH, coupled with a 2.5:1 ratio, has been shown to further enhance the material's strength by up to 25%, underscoring the importance of alkalinity in optimizing the geopolymerization process. Furthermore, curing temperature also significantly influences the final properties of the material **(Dinh, 2024; Ghazy et al., 2024)**.

This study examines the improvement of fresh properties, mechanical properties, and microstructural characteristics of geopolymer concrete through the inclusion of WG as a partial substitute for sand at replacement rates of WGS (0%, 15%, 30%, and 50%), and fly ash replacement levels of WGP (0%,10%, 20%, and 30%). A 14 M sodium hydroxide solution served as the alkaline activator, and the curing process was performed at 60°C for 24 hours. The mechanical properties of the geopolymer concrete were rigorously evaluated by determining its compressive strength, flexural strength, and indirect tensile strength at 7 and 28 days of curing. This method aims to investigate the viability of utilizing industrial waste materials to enhance the strength characteristics of geopolymer concrete and promote more sustainable construction practices.

2. Experimental work

2.1 Materials

In the present study, class F low-calcium fly ash (FA), conforming to **ASTM C618-08**, was employed as a primary pozzolanic material. The FA was sourced from a coal-fired power plant and exhibited a specific gravity of 2.31 and a specific surface area of 5000 cm²/g. The chemical composition of the FA, analyzed via X-Ray Diffraction (XRD), is summarized in **Table 1 and Figure 1 (a)**. To partially replace both fly ash and sand in geopolymer concrete (GPC). The waste glass (WG) obtained from a local supplier in Egypt was incorporated in two distinct forms. The first form, waste glass powder (WGP), was produced by grinding and pulverizing the glass to achieve a particle size finer than 75 µm, with an absorption rate of 0.09%, as reported by **Tahwia et al., (2023)**, thus serving as a binder substitute for FA. The chemical composition of the WG was also determined through XRD analysis, and its physical properties are also presented in **Table 1 and Figure 1 (b).**

Table 1: Chemical oxides and physical characteristics of used FA and WG

Chemical oxides												Physical properties		
Oxides	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**P_2O_5**	**SO_3**	**K_2O**	**TiO_2**	**Na_2O**	**MgO**	**LOI**	**Fineness modulus**	**Absorption (%)**	**Specific gravity**
Fly ash %	60.28	28.59	4.99	1.19	0.52	0.06	1.09	2.42	0.01	0.27	0.58	2.31	0.3	2.23
WG%	83.34	-	-	7.28	-	-	-	-	9.38	-	-	2.2	0.09	2.41

Figure 1. The fine materials used: (a) FA and (b) WGP

The second form of WG was utilized as a fine aggregate replacement for natural sand and noted as waste glass sand (WGS), exhibiting a specific gravity of 2.41 and a fineness modulus of 2.4. The natural medium well graded sand, employed as the control fine aggregate, had a specific gravity of 2.55 and a fineness modulus of 2.5. Crushed limestone was utilized as the coarse aggregate in the GPC mix, characterized by a specific gravity of 2.6 and a crushing modulus of 23% in accordance with **ASTM C33-07** and **ES 1109/2021** standard. Prior to incorporation into the concrete mix, both fine and coarse aggregates were conditioned to a saturated surface-dry state to ensure uniform moisture content. The grain size distribution curve of the sand and WGS utilized in this study, graded in accordance with **ASTM C33-18** and **ES 1109/2021** specifications, is presented in **Figure 2 and Figure 3**.

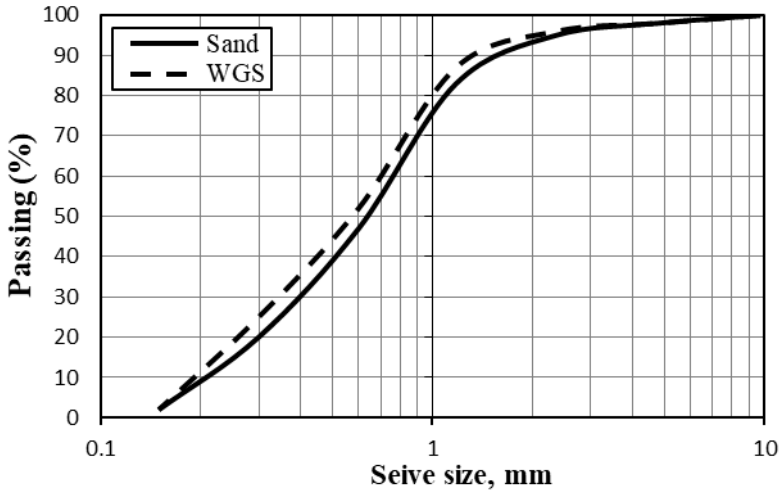


Figure 2. Sieve analysis of sand and WGS

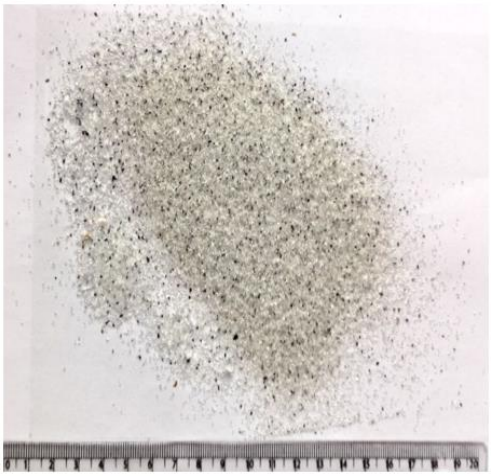


Figure 3. Images for WGS

The alkaline activator solution, essential for geopolymerization, was composed of sodium hydroxide (NH) and sodium silicate (NS). NH, in pellet form with 98% purity, was dissolved in potable water to prepare a solution with an optimized concentration of 14 M, as recommended by prior research. The NS solution, containing 29.4% SiO_2, 14.7% Na_2O, and 55.9% water, was sourced from a local chemical industry. The two solutions were combined at NS-to-NH ratio of 2.5, and the total alkaline activator solution accounted for 35% of the binder weight. The high-performance superplasticizer (Sika-Viscocrete 3425), an aqueous solution of modified polycarboxylates, was used in this study. Produced by Sika Egypt, it complies with **ASTM C494** types G and F and **BS EN 934-2:2001** standards. The material is a light-yellow liquid with a density of 1.08 kg/lit. To evaluate the bond strength of the developed geopolymer concrete, A steel reinforcement bar with a diameter of 12 mm and grade B400DWR, complying with Egyptian Standard **ES 262/2023**, was embedded in the specimens. **Table 2** outlines the mix proportions for the GPC samples, detailing the substitution levels of WG. FA was replaced with WGP at levels of 0%, 10%, 20%, and 30%, while sand was substituted with WGS at levels of 15%, 30%, and 50%. This systematic variation enabled a comprehensive evaluation of the effects of WG substitution on the physical and mechanical properties of the resulting GPC. The flowchart provides a comprehensive summary of the experimental work, as illustrated in **Figure 4**.

Table 2: Geopolymer concrete mix design (kg/m^3)

Mix ID	FA	CA	Sand	WG		Alkaline solution*			SP$^+$
				WGP	WGS	NH	NS	NS/NH	
GPC	500	1074	630	0	0	52	129	2.5	5
WGF10	450	1074	630	50	0	52	129	2.5	5
WGF20	400	1074	630	100	0	52	129	2.5	5
WGF30	350	1074	630	150	0	52	129	2.5	5
WGS15	500	1074	535.5	0	94.5	52	129	2.5	5
WGS30	500	1074	441	0	189	52	129	2.5	5
WGS50	500	1074	315	0	315	52	129	2.5	5
WGF10S10	450	1074	567	50	63	52	129	2.5	5

Where;
FA: Fly ash, CA: Coarse aggregate, WG: Waste glass, WGP: Waste glass powder, WGS: Waste glass sand, SP: Superplasticizer, NS: sodium silicate, NH: Sodium hydroxide (14M),
* (Alkaline solution /(FA+WGP) = 0.35)
$^+$ SP/(FA+WGP) = 1% by weight.

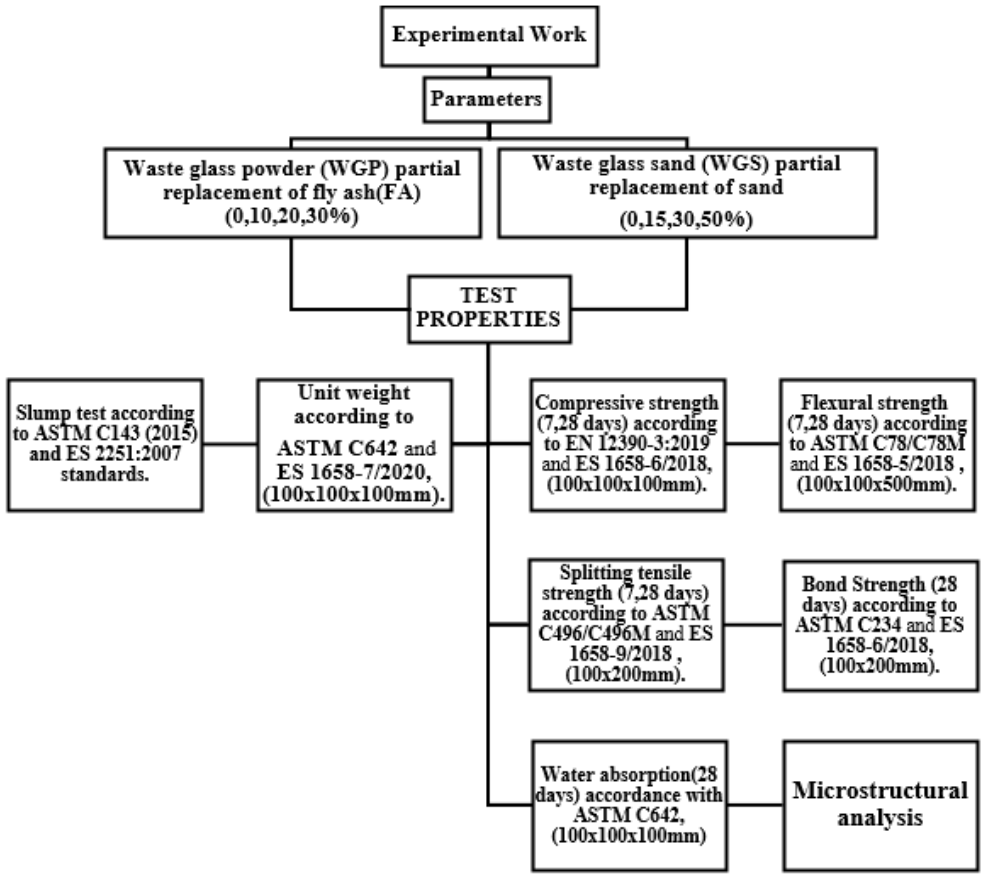


Figure 4. Flow chart of the experimental work

2.2 Preparation of samples

The alkaline solution was prepared by dissolving 560 grams of NH pellets or flakes in one liter of water to achieve a 14M concentration (**Ghazy et al., 2022**), calculated based on the molecular weight of NH (40). NS was then added to the solution, which was prepared 24 hours in advance of casting.

The GPC mixtures, comprising 8 different mixtures, were prepared using a 100 L drum mixer to ensure consistent blending of all components. Initially, the aggregates, WG (if applicable as WGP or WGS), and FA were dry-mixed for 1 to 3 minutes to achieve a uniform distribution. Following this, an alkaline solution was gradually incorporated into the dry mixture, and the blend was further mixed for an additional 8 minutes to ensure complete homogeneity. The freshly mixed GPC was cast into molds and compacted using a vibrating table to eliminate air voids. The specimens were initially left to set at laboratory conditions (25±2 °C and 50% relative humidity) for 24 hours. Subsequently, the samples were heat-cured in an oven at 60°C for 24 hours to enhance polymerization **(Ghazy et al., 2023)**. After heat curing, the specimens underwent ambient curing and were placed in front of the laboratory, where they were allowed to cure under natural conditions. **Figure 5** illustrates the outdoor temperature variations during the July-August period when the specimens underwent sun curing. The specimens were then tested at 7 days and 28 days.

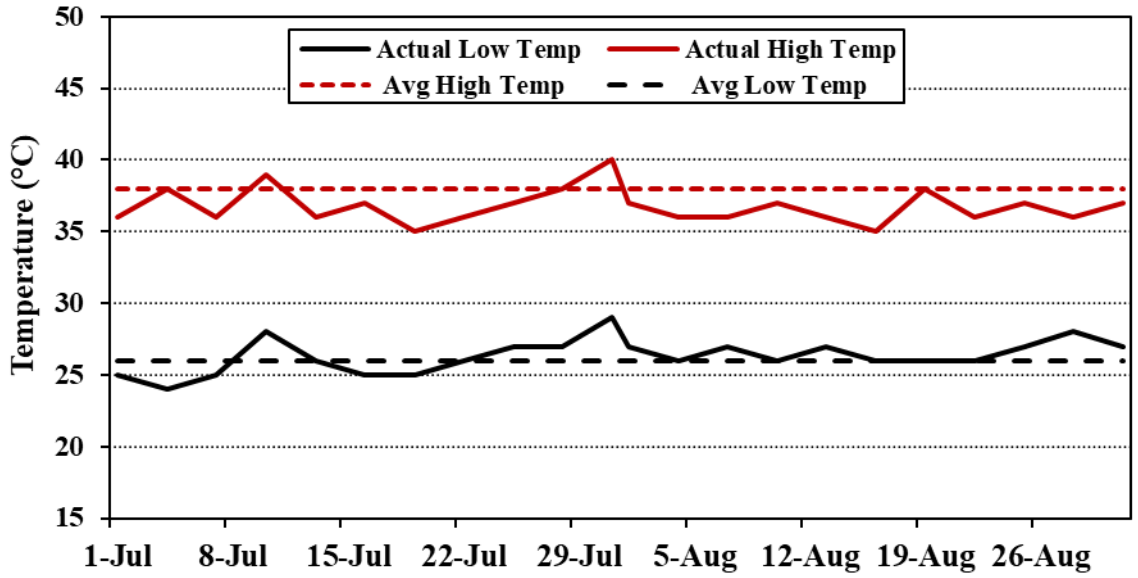


Figure 5. The outdoor temperatures along the July-August month (Source: AccuWeather)

2.3 Testing methods

2.3.1 Slump test

The slump test was utilized to assess the flowability of fresh GPC, reflecting its homogeneity and mixability. The workability of concrete is crucial, as it directly affects the strength and durability of the cured substance. The evaluation of the fresh concrete's workability, accordance with **ASTM C143** and **EN 12350-2/2019** standards.

2.3.2 Unit weight

The unit weights of the hardened cube mixtures were determined in accordance with **ASTM C642** and **ES 1658-7/2020** at 28 days.

2.3.3 Compressive strength test

The compressive strength test was performed on 3 cubes for each age (7 and 28 days) with dimensions of (100×100×100 mm), following **EN 12390-3:2019** and **ES 1658-6/2018**. The compression testing machine had a maximum capacity of 2000 kN.

2.3.4 Flexural strength test

Flexural strength tests were performed by **ASTM C78/C78M** and **ES 1658-5/2018** utilizing a simple beam with center loading (Three-point loading). a 300 kN capacity Universal Testing Machine equipped with a data acquisition system was utilized. The Prismatic specimens of (100×100×500mm) were prepared to be tested at age of 7 and 28 days, with a total of 28 specimens, with 3 specimens tested for each age.

2.3.5 Splitting tensile strength test

The Splitting Tensile Strength test, commonly known as the Brazilian Test, was conducted on 28 GPC cylindrical specimens (100×200 mm), with 3 specimens tested for each age (7 and 28 days), in accordance with **ASTM C496/C496M** and **ES 1658-9/2018** standards.

2.3.6 Bond strength test

Bond strength was measured through the pullout test, performed according to **ASTM C234** and **ES 1658-6/2018**, on steel bars with a 12 mm diameter embedded in 100×200 mm cylinders, with 3 specimens tested at 28 days.

2.3.7 Water absorption test

Water absorption was measured at 28 days in accordance with **ASTM C642**, using 3 cube specimens of (100×100×100 mm) for each mix. The specimens were oven-dried at 100–110°C until achieving a constant mass, then immersed in water for 24 hours. The water absorption was calculated as the percentage increase in weight from the oven-dried to the saturated surface-dry condition.

3. Slump test geopolymer concrete using waste glass

The workability results of GPC incorporating WGP as a partial replacement for FA demonstrated slight improvements in slump values, as illustrated in **Figure 6**. Specifically, workability increased by 10%, 18%, and 23% at replacement levels of 10%, 20%, and 30% WGP, respectively, compared to the control mix. These findings align with recent studies conducted by **Çelik et al., (2023) and Manikandan et al, (2024),** which reported comparable improvements in flowability when WGP replaced FA in GPC. For instance, **Çelik et al.,**

(2023) observed a 12% improvement in slump at 20% WGP replacement and a 20% improvement at 30% replacement, attributing enhanced workability to finely ground glass particles' physical and chemical properties . Although WGP is slightly coarser than FA, the grinding process smoothens the edges of the particles and produces particles with a Smooth surface and semi-spherical morphology, which plays a significant role in improving the fresh properties of the GPC mix. This smooth surface reduces internal friction between the particles, allowing for better flowability and lower resistance during mixing. The fineness modulus of WGP typically ranges between 2.2 and 2.6, compared to the slightly finer FA, which has a fineness modulus of approximately 2.0 to 2.4. Additionally, the specific surface area of WGP is around 350–400 m^2/kg, whereas FA exhibits a higher surface area, approximately 450–550 m^2/kg **(Zhang et al., 2023; Manikandan et al., 2024)**. Despite this slight difference, the smooth surface of WGP compensates for its lower surface area, reducing the resistance to particle movement during mixing. The low water absorption of WGP plays a crucial role in maintaining workability. Due to its dense, non-porous nature, WGP absorbs only 0.9% of its weight in water, whereas FA, depending on its classification and fineness, absorbs between 3% and 7% **(Dey et al., 2024; Manikandan et al. 2024).** This minimal water absorption ensures that a higher proportion of the available water remains in the mix, enhancing fluidity and preventing early stiffening. The combination of these factors smooth surface, semi-spherical shape, and low water absorption—enables WGP to effectively improve workability while maintaining the cohesion of the fresh mix. Additionally, the alkali-reactive nature of WGP in a geopolymer environment forms a cohesive gel-like structure that aids in maintaining fluidity without sacrificing mix stability **(Manikandan et al. 2024).**

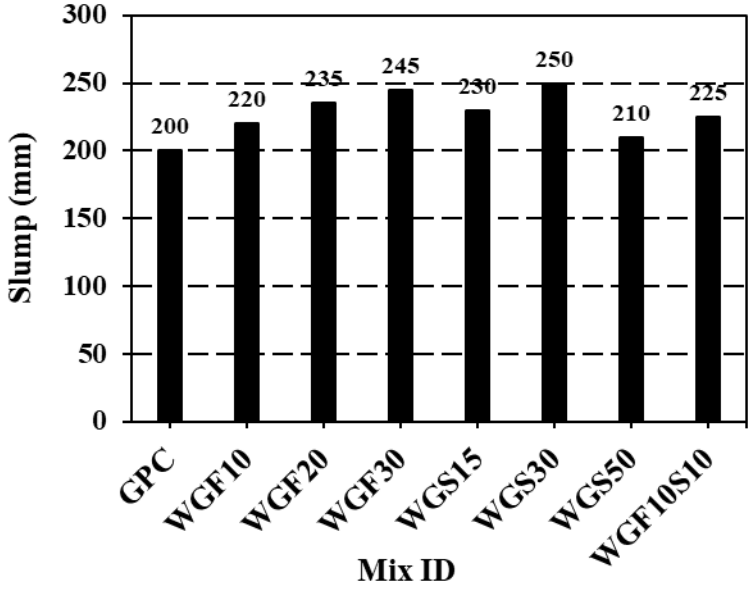


Figure 6. Slump test for GPC mixes using WG

When glass waste sand (WGS) was utilized as a partial replacement for fine aggregates (sand), the results revealed similar trends but with varying levels of improvement. Replacement levels of 15%, 30%, and 50% led to improvements of 15%, 25%, and 5%, respectively. The slight enhancements at 15% and 30% replacement can be attributed to the filler effect of WG particles. At these levels, the smaller glass particles effectively fill the voids between larger sand grains, optimizing particle packing density and reducing void ratios. This enhances flowability and lowers the water demand for achieving similar workability **(Singh and Kumar, 2024)**. Similar findings were reported by **Çelik et al., (2023)**, where replacing natural sand with 20% and 30% WGP led to 14% and 22% improvements in workability. The researchers attributed this improvement to the smooth and dense surface of WG, which minimizes water absorption. Additionally, the low water absorption of WG typically less than 0.9%ensures that more water remains available for enhancing the flow of the mix. In contrast, natural sand may absorb more water due to its higher porosity, which increases water demand for achieving similar workability **(Manikandan et al., 2024).** However, at 50% replacement, the improvement in workability was reduced to 5%. This decline can be explained by the higher proportion of WGS, which introduces coarser particles with greater angularity and surface area. These characteristics increase interparticle friction and require more water to maintain flowability **(Zhang et al., 2023)**.Despite this reduction, it is noteworthy that the workability at 50% WGS replacement still surpassed that of the control mix. This highlights the continued technical viability and practical effectiveness of WG in enhancing the fresh properties of GPC, even at higher replacement ratios. Furthermore, the incorporation of WG at such levels aligns with the broader goals of

sustainable construction, as it reduces dependence on natural sand resources while promoting the beneficial reuse of non-biodegradable WS in eco-friendly concrete production.

When employing dual substitutions in the GPC mix WGF10S10, which includes 10% FA replacement with WGP and 10% sand replacement with WGS, a marked improvement in workability was observed compared to both the control mix and the mix with 10% FA replacement alone. Specifically, the slump value increased by 13% compared to the control mix, highlighting the significant impact of the dual replacement strategy. This enhancement can be attributed to the combined effects of WGP and WGS in the geopolymer matrix. The smooth surface texture and angularity of WGS contributed to reduced interparticle friction and enhanced flowability, while the pozzolanic activity of WGP facilitated the formation of denser sodium-alumino-silicate-hydrate (N-A-S-H) gels, which improved the fresh-state behavior of geopolymer mixtures **(Zhang et al., 2023)**. Compared to the single-variable substitution of 10% FA, the dual replacement strategy optimizes particle packing density and minimizes void spaces, thereby enabling significantly improved workability.

4. Unit weight of geopolymer concrete using waste glass

The unit weight of GPC is a significant indicator of its structural performance and durability. This study evaluates the effect of substituting FA with WGP and sand with WGS at 28 days, as illustrated in **Figure 7**. When FA was partially replaced with WGP, the unit weights recorded for GPC (control), WGF10, WGF20, and WGF30 were 2.24 t/m³, 2.26 t/m³, 2.27 t/m³, and 2.30 t/m³, respectively. These increases are primarily attributed to the dense packing of WGP particles, which reduce voids and improve compaction. The fine texture and pozzolanic reactivity of WGP also contribute to the formation of secondary gel phases, such as sodium aluminosilicate hydrate (N-A-S-H), which enhance the matrix density and cohesion. Studies by **Rashidian et al., (2017) and Tahwia et al., (2022)** support these findings, highlighting the role of WGP in densifying the matrix through efficient particle packing and geopolymerization reactions. These optimal replacement levels are consistent with findings by **Tho-In et al., (2018)**, which emphasize balancing particle size distribution and matrix reactivity for maximum performance.

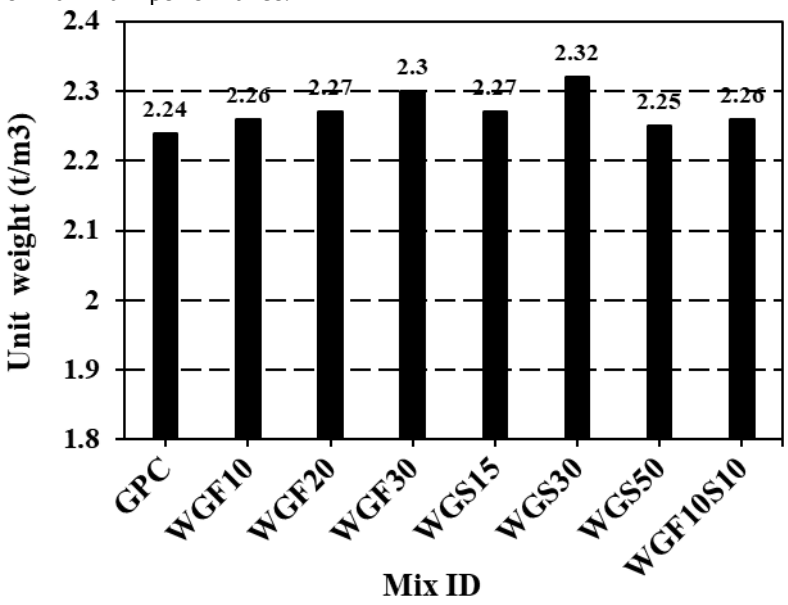


Figure 7. Unit weight for GPC mixes using WG

When sand was partially replaced with WGS, the unit weights recorded for WGS15, WGS30, and WGS50 were 2.27 t/m³, 2.32 t/m³, and 2.25 t/m³, respectively. The enhancements at 15% and 30% substitution levels are attributed to the smooth surface texture and high density of WGS particles, which facilitated better packing and compaction within the geopolymer matrix. at 30% replacement, the improvement demonstrates the capacity of WGS to enhance matrix compaction and cohesiveness. These findings align with research by **Vafaei et al. (2017) and Jiang et al., (2020)**, who reported that WGS significantly reduces voids and enhances packing density, contributing to a more compact and impermeable structure. at 50% replacement, despite the reduction in unit weight, the mix still performed better than the control mix. This phenomenon highlights the potential of WGS in enhancing matrix density at optimal replacement levels, while excess incorporation can disrupt homogeneity and introduce weak zones.

When a dual replacement strategy was employed in the GPC mix WGF10S10, involving the substitution of 10% FA with WGP and 10% sand with WGS, the unit weight demonstrated a slight improvement, reaching 2.26 t/m³.

This represents a marked enhancement compared to the control mix, highlighting the effectiveness of this approach. The observed increase in unit weight can be attributed to the refined packing density facilitated by the fine particles of WGP and the angular morphology of WGS, which collectively minimized void ratios and enhanced the compactness of the GPC matrix.

5. Mechanical properties

A total of 8 mixes have been allocated to study the influence of WG on mechanical properties. **Table 3** presents the results of the impact of WG on mechanical properties, including compressive strength tests, splitting tensile strength, flexural strength at 7 days and 28 days, and bond strength at 28 days.

Table 3. Test results of mechanical properties

Mix ID	Compressive strength (MPa)		Flexural strength (MPa)		Splitting tensile strength (MPa)		Bond strength (MPa)
	7 days	28 days	7 days	28 days	7 days	28 days	28 days
GPC	30	37.2	5.1	6.6	3.1	3.8	7.5
WGF10	32.5	40.2	6.1	7.1	3.3	3.9	8.1
WGF20	35.4	42.7	7	7.7	3.5	4.1	8.5
WGF30	36.8	45.2	7.5	8.6	3.6	4.4	9.4
WGS15	32.5	40.5	6.6	7.4	3.4	4	8.4
WGS30	37.1	47.9	8.3	9.6	4	4.8	10.4
WGS50	31.2	39	5.4	6.6	3.2	3.9	7.9
WGF10S10	33.2	40.9	6.5	7.2	3.4	4	8.3

5.1 Compressive strength for geopolymer concrete using waste glass

The compressive strength results for GPC incorporating WG as a partial replacement for FA and sand demonstrated clear trends of enhancement, with varying performance at different replacement levels, as illustrated in **Figure 8** and **Table 3**. These results provide valuable insights into the influence of WG on the mechanical behavior and microstructural development of GPC.

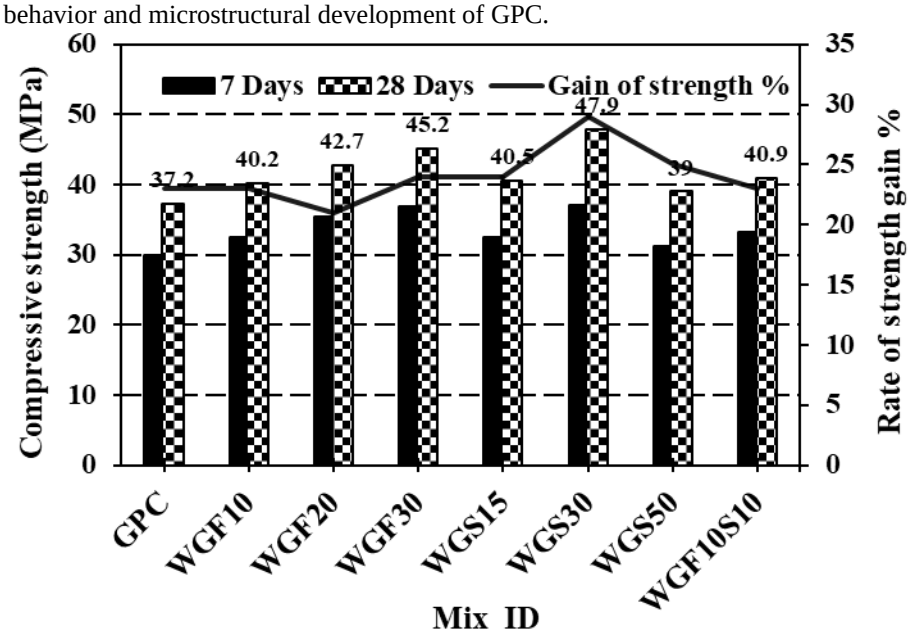


Figure 8. Compressive strength for GPC mixes using WG at different ages and gain of strength

When the FA is partially replaced with WGP. The compressive strength at 7 days for GPC (control), WGF10, WGF20, and WGF30 were 30.0 MPa, 32.5 MPa, 35.4 MPa, and 36.8 MPa, reflecting improvements of 0%, 9%, 18%, and 23%, respectively. at 28 days, the strengths further increased to 37.2 MPa, 40.2 MPa, 42.7 MPa, and 45.2 MPa, with corresponding improvements of 0%, 8%, 15%, and 22%. This steady increase in compressive strength highlights the positive influence of WGP on the geopolymerization process. The primary reason for this enhancement lies in the pozzolanic reactivity of WGP. WGP, being rich in amorphous silica (SiO_2), reacts with the alkaline activators in the geopolymer matrix to form a dense calcium-alumino-silicate-hydrate (C-A-S-H)

gel. This gel binds the matrix particles effectively, leading to a denser and stronger structure **(Dey et al. 2024)** .Furthermore, the filler effect of finely ground WGP optimizes the packing of particles, reducing microstructural voids and improving density **(Manikandan et al., 2024)**. Similar findings by **Çelik et al. (2023)** demonstrated a 22% improvement in compressive strength at 30% WGP replacement, confirming that moderate WGP content provides the optimum balance between reactivity and particle packing**.**

The compressive strength results at 7 days and 28 days highlight the critical role of early-age and long-term strength development in GPC. Testing at 7 days captures the early geopolymerization reactions, where the partial dissolution of FA and WGP contributes to the initial formation of binding gels. by 28 days, the geopolymerization process reaches a more advanced stage, resulting in a well-developed microstructure with improved bonding and densification. The rate of strength gain from 7 to 28 days was 23%, 23%, 21%, and 24% for GPC, WGF10, WGF20, and WGF30, respectively. The slight variation in the rate of improvement among the mixes can be attributed to the increasing content of WGP at higher replacement levels, where the saturation of glass particles limits further reactivity while maintaining a compact microstructure.

When WGS was used as a partial replacement for sand in the mixes WGS15, WGS30, and WGS50, the compressive strengths at 7 days for the mixes were 32.5 MPa, 37.1 MPa, and 31.2 MPa, respectively, representing improvements of 9%, 24%, and 4% over the control mix. By 28 days, the strengths further increased to 40.5 MPa, 47.9 MPa, and 39.0 MPa for the WGS15, WGS30, and WGS50 mixes, corresponding to enhancements of 9%, 29%, and 5%, respectively. This steady increase in compressive strength highlights the positive influence of WGS on the geopolymerization process. The significant improvement at 15% and 30% sand replacement is attributed to the filler effect of WGS, which improves the particle packing within the concrete matrix. The smaller WGP particles effectively fill voids between larger sand grains, reducing internal porosity and enhancing the bond within the geopolymer matrix **(Singh and Kumar, 2024)**. Additionally, the low water absorption of WG (<0.9%) ensures that sufficient moisture remains in the mix for effective geopolymerization, unlike natural sand, which tends to absorb more water due to its porous nature **(Manikandan et al. 2024).**

However, at 50% replacement, the compressive strength declined despite remaining higher than the control mix. This reduction can be explained by two key factors:

Increased Particle Angularity: At high replacement levels, the angular and irregular geometry of glass particles introduces interparticle friction, reducing compaction efficiency and creating weak zones within the matrix **(Zhang et al., 2023)**.

Reduced Cohesion in the Matrix: Excessive replacement of sand with WGS leads to reduction in cohesion in the matrix and lower bonding, being inert at higher content, disrupt the continuity of the binder phase **(Çelik et al. 2023)**.Despite this decline, the performance of WGS at 50% replacement remains superior to the control mix, supporting its use as a sustainable alternative to natural sand. This result underscores the environmental benefits of incorporating WG into concrete production. By reducing reliance on non-renewable natural aggregates and utilizing non-biodegradable WG, the use of WG promotes the development of eco-friendly and sustainable concrete solutions **(Singh and Kumar, 2024).**

The compressive strength gain between 7 days and 28 days across all mixes reflects the progressive geopolymerization process. The average increase in compressive strength was 23% to 29%, with the higher replacement levels showing slight variations due to differences in particle reactivity and packing efficiency. At moderate replacement levels (10%–30%), the geopolymer matrix benefits from both the pozzolanic reactivity and the filler effect of WG, which enhances strength development. However, at higher replacement levels (50%), the angular nature and reduced reactivity of glass particles limit further densification of the matrix.

When the dual replacement strategy was applied in the GPC mix WGF10S10, involving a simultaneous substitution of 10% FA with WGP and 10% sand with WGS, the compressive strength exhibited a slight enhancement compared to both the control mix and single-replacement mixes. The compressive strength values achieved were 33.2 MPa at 7 days and 40.9 MPa at 28 days, representing improvements of 11% and 10%, respectively, over the control mix. Moreover, these values surpassed the strengths of mixes with individual replacements of 10% FA and 15% sand.

This slight improvement in compressive strength can be attributed to the combined effects of the dual replacement strategy. The integration of WGP provided a fine pozzolanic material that contributed to the formation of additional calcium-alumino-silicate-hydrate (CASH) and sodium-alumino-silicate-hydrate (NASH) gels, enhancing the binder's overall reactivity. Concurrently, the inclusion of WGS improved particle packing and minimized voids, resulting in a denser and more cohesive matrix. The angular morphology of WGS also enhanced the interlocking mechanism between aggregate particles, contributing to the GPC's overall load-bearing capacity **(Çelik et al. 2023)**.

5.2 Flexural strength for geopolymer concrete using waste glass

The flexural strength results for GPC incorporating WGP as a partial replacement for FA demonstrate significant improvements over the control mix, as illustration the **Figure 9** and **Table 3**. at 7 days, the flexural strengths for GPC, WGF10, WGF20, and WGF30 were 5.1 MPa, 6.1 MPa, 7.0 MPa, and 7.5 MPa, respectively. These results indicate corresponding enhancements of 0%, 20%, 37%, and 47% relative to the control mix. at 28 days, the values were 6.5 MPa, 7.1 MPa, 7.7 MPa, and 8.6 MPa, reflecting improvements of 0%, 8%, 17%, and 30%, respectively.

The observed improvement in flexural strength is attributed to the pozzolanic reactivity of the glass powder, which promotes additional geopolymer gel formation. This aligns with findings from **Nassar et al. (2019)**, who reported that fine glass powder can enhance mechanical performance by increasing the calcium-silicate-hydrate (C-S-H) gel content and improving particle packing within the matrix **(Nassar et al. 2019)**. Moreover, **Shaikh et al. (2020)** demonstrated that the replacement of FA with 10%-30% WGP led to improvements in strength properties of GPC, comparable to the results observed in this study.

The increase in flexural strength from 7days to 28 days was 27%, 16%, 10%, and 15% for GPC, WGF10, WGF20, and WGF30, respectively. The gradual reduction in the rate of improvement with higher glass powder content can be attributed to the saturation of reactive glass particles, which limits further pozzolanic activity **(Islam A. and Patel, 2017)**.

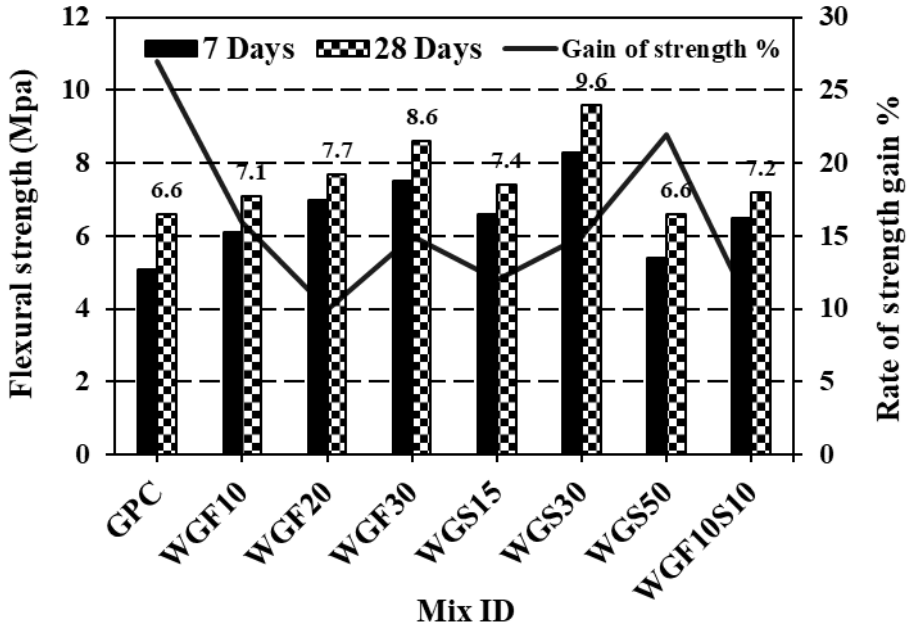


Figure 9. Flexural strength for GPC mixes using WG at different ages and gain of strength

The rationale for testing flexural strength at 7 days and 28 days stems from the need to evaluate early-age performance and long-term development. at 7 days, the strength reflects the initial geopolymerization process, where the alkaline activator reacts with the WGP and FA to form C-S-H and aluminosilicate gels. At 28 days, the strength reflects the full maturation of these gels, with slower hydration and polymerization reactions contributing to continued strength gains **(Davidovits, 2018).** Notably, the non-linear improvement across mixes suggests that higher WGP content accelerates early-age reactions but may plateau as the system stabilizes.

When WGS was used as a partial replacement for sand, the flexural strength at 7 days for WGS15, WGS30, and WGS50 mixes was 6.6 MPa, 8.3 MPa, and 5.4 MPa, respectively, corresponding to improvements of 29%, 60%, and 5% compared to the control. at 28 days, the respective strengths were 7.4 MPa, 9.6 MPa, and 6.6 MPa, with improvements of 12%, 45%, and 2%. These results highlight that a 30% replacement level (WGS30) yielded the most substantial improvement in Flexural strength.

The enhanced performance at lower replacement levels (15-30%) is attributed to the angular geometry and fineness of glass particles, which improve the interfacial bond between the geopolymer matrix and aggregates. Such evidence aligns with the findings of **Ali and Al-Tayeb, (2021)**, who reported that glass sand enhances load transfer and matrix densification due to its favorable packing properties and pozzolanic reactivity. However, at 50% replacement (WGs50), a decrease in strength was observed. This decline can be attributed to an increase in void content and reduced cohesion within the concrete, as excess glass particles disrupt the homogeneity of the mix. Similar trends were reported by **Zhang et al. (2020a).**

Despite the slight reduction in strength at higher glass content, the values remained higher than the control mix, underscoring the environmental and economic benefits of using glass waste as a sustainable alternative to natural sand. The results align with the global trend toward resource conservation and waste utilization, as advocated by **Gopalakrishnan et al., (2020).**

The rate of flexural strength improvement from 7 to 28 days was 12%, 15%, and 22% for WGS15, WGS30, and WGs50, respectively. The higher percentage increase for WGS50 may reflect delayed pozzolanic reactivity due to reduced alkalinity and fewer reactive sites at early ages. According to **Torkittikul and Chaipanich, (2018)**, WS exhibits slower pozzolanic reactions compared to fine glass powder, which explains the delayed strength gain at higher replacement levels**.**

Testing at 7 days and 28 days is critical for understanding both the early-age and mature mechanical performance of GPC. at 7 days, the majority of the geopolymerization process occurs due to rapid reactions between the alkaline activator, glass powder, and FA. This phase is essential for evaluating the potential of alternative materials to accelerate strength development. at 28 days, the concrete reaches a stabilized state, where the long-term hydration and polymerization reactions complete the densification of the matrix. These time intervals are widely accepted as benchmarks for assessing mechanical properties in geopolymer research **(Davidovits, 2018)**.

When employing a dual replacement strategy in the GPC mix WGF10S10, involving a 10% substitution of FA with WGP and a 10% replacement of sand with WGS, the flexural strength demonstrated a slight enhancement compared to the control mix and the single-replacement mix WGF10. at 7 days, the flexural strength reached 6.5 MPa, representing a 27% improvement, while at 28 days, it increased to 7.2 MPa, reflecting a 10% improvement over the control mix.

This marked improvement in flexural strength is attributed to the enhanced interfacial bond and structural integration within the geopolymer matrix facilitated by the dual replacement strategy. The incorporation of WGP enriched the binder with pozzolanic material, promoting the formation of additional calcium-alumino-silicate-hydrate (CASH) and sodium-alumino-silicate-hydrate (NASH) gels. These gels significantly enhanced the matrix's ability to withstand applied loads, thereby improving the flexural strength and structural stability of the GPC. Simultaneously, the replacement of sand with WGS improved aggregate interlock due to the angular geometry of glass particles, fostering a more cohesive and compact structure.

5.3 Splitting tensile strength for geopolymer concrete using waste glass

The splitting tensile strength results for GPC incorporating WGP as a partial replacement for FA and sand demonstrated clear trends of enhancement, with varying performance at different replacement levels, as illustration the **Figure 10** and **Table 3**. These results provide valuable insights into the influence of WGP on the mechanical behavior and microstructural development of GPC.

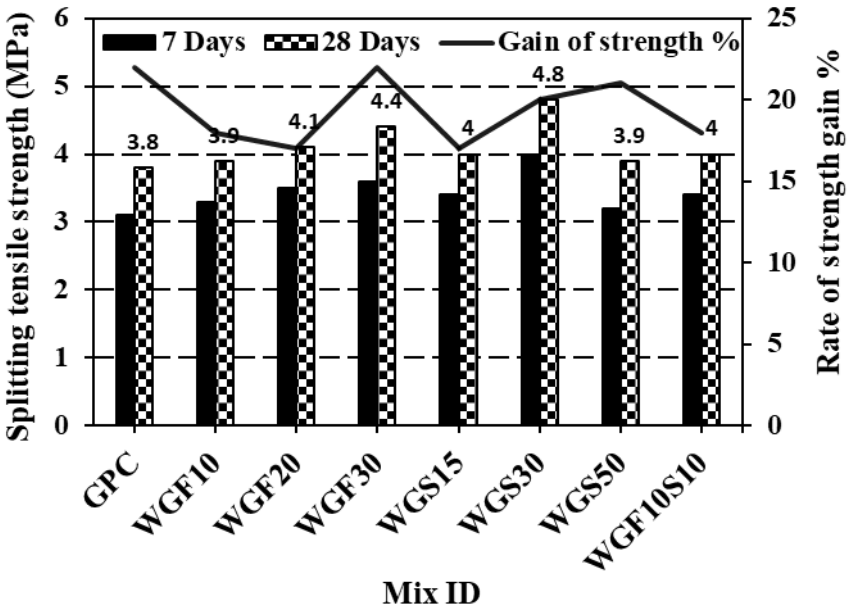


Figure 10. Splitting tensile strength for GPC mixes using WG at different ages and gain of strength

When the FA is partially replaced with WGP, the compressive strength at 7 days, the splitting tensile strength values for GPC, WGF10, WGF20, and WGF30 were 3.1 MPa, 3.3 MPa, 3.5 MPa, and 3.6 MPa, respectively, reflecting improvements of 0%, 6%, 13%, and 16% compared to the control mix. at 28 days, the splitting tensile strength increased to 3.8 MPa, 3.9 MPa, 4.1 MPa, and 4.4 MPa, achieving enhancements of 0%, 2%, 8%, and 15%, respectively. These results indicate that increasing the replacement of FA with WGP enhances the splitting tensile strength of GPC by up to 30% substitution. The improvement can be attributed to the pozzolanic activity of glass powder, which enhances the geopolymerization reaction. Glass powder provides a silica-rich source that reacts with alkaline activators, leading to the formation of additional aluminosilicate gel, which densifies the matrix and improves splitting tensile strength. Similar findings have been reported in the literature. For example, **Pacheco-Torga et al. (2018)** observed a 15% improvement in splitting tensile strength when 30% glass powder replaced FA, aligning well with the present study. The reason for testing at 7 and 28 days is to assess both early-age and long-term strength development. Early-age strength provides insights into the reactivity of materials and their initial performance, while 28-day strength serves as a standard benchmark for concrete performance. The results show that WGF30 achieved the highest strength at both testing ages, suggesting an optimum glass powder replacement ratio of 30%. The rate of increase in splitting tensile strength from 7 to 28 days demonstrated variations across the mixtures, reflecting differences in material reactivity and the extent of geopolymerization. The control GPC exhibited a 22% increase, highlighting steady hydration and aluminosilicate gel formation over time. In contrast, WGF10 and WGF20 showed increases of 18% and 17%, respectively, which are slightly lower than the control mix. This reduction can be attributed to the faster early-age reactivity of glass powder, which leads to the rapid consumption of alkaline activators at the initial stages. as **Zhang et al. (2020a)** noted, excessive consumption of activators early in the reaction limits further geopolymerization, thereby slowing strength development at later stages. On the other hand, the WGF30 mix achieved a consistent 22% increase, comparable to the control. This indicates that a 30% replacement level provides an optimal balance between early-age reactivity and long-term geopolymerization. The higher silica content and particle fineness of glass powder at this replacement level enhance the formation of aluminosilicate gel, leading to improved matrix densification and sustained strength development. The results align with previous studies, such as those conducted by **Islam et al. (2017)**, who reported optimal long-term strength at 25-30% glass powder replacement.

when WGS replaced natural sand at 15%, 30%, and 50% levels. At 7 days, the splitting tensile strengths for WGS15, WGS30, and WGS50 were 3.4 MPa, 4.0 MPa, and 3.2 MPa, respectively, reflecting improvements of 10%, 30%, and 4% compared to the control mix. at 28 days, the corresponding strengths were 4.0 MPa, 4.8 MPa, and 3.9 MPa, yielding improvements of 5%, 25%, and 3%, respectively. The significant improvement observed at 30% replacement (WGS30) can be attributed to the particle packing effect and pozzolanic activity of glass sand, which enhances the microstructure of concrete. This aligns with the results reported by **Du and Tan, (2017)**, where a 25% improvement in splitting tensile strength was achieved with 30% glass sand replacement. However, at 50% replacement (WGS50), the strength decreased compared to WGs30 but remained higher than the control mix. The reduction can be explained by the excessive glass content disrupting the particle distribution and causing a decrease in bond strength within the matrix **(Shi et al. 2019)**. The rate of increase in splitting tensile strength from 7 to 28 days for WGS15, WGS30, and WGs50 was 17%, 20%, and 21%, respectively. The higher increases for WGS30 and WGS50 suggest that glass sand contributes more significantly to long-term strength development compared to early-age strength. This behavior can be attributed to the gradual pozzolanic reaction of glass particles, which enhances the formation of secondary hydration products over time. Similar observations were reported by **Shaikh et al., (2019)**, who identified a gradual strength increase in concrete mixes containing WG due to ongoing pozzolanic activity. Additionally, **Rashad, (2014)** noted that glass sand improves the densification of the microstructure, leading to sustained strength gain over time. The decline in splitting tensile strength at 50% glass sand replacement is slight but expected. Excessive glass sand replacement reduces the availability of fine particles for proper packing, leading to void formation and weaker bonds. **Shi et al., (2019)** confirmed that high glass content can disrupt the matrix continuity, reducing mechanical performance. However, the results still demonstrate the sustainability potential of using WGS, as the strength remains above the control mix. This highlights the dual benefit of improving mechanical properties while reducing reliance on natural sand, supporting environmental sustainability goals.

Incorporating a dual replacement strategy in the GPC mix WGF10S10, involving the substitution of 10% FA with WGP and 10% sand with WGS, demonstrated remarkable improvements in splitting tensile strength. The results revealed that at 7 days, the splitting tensile strength reached 3.4 MPa, reflecting a 10% enhancement compared to the control mix, while at 28 days, it increased to 4 MPa, corresponding to a 5% improvement. These findings surpass the performance of mix WGF10, where only 10% of FA was replaced with WGP, highlighting the efficacy of the combined replacement approach.

The observed enhancements can be attributed to the complementary effects of WGP and WGS within the geopolymer matrix. The pozzolanic reactivity of WGP promoted the formation of dense sodium-alumino-silicate-hydrate (NASH) gels, which enhanced the matrix's cohesion and strength. Simultaneously, WGS contributed to superior packing density and improved interfacial bonding, reducing void spaces and reinforcing the structural integrity of the GPC. These effects collectively improved the matrix's splitting tensile resistance and minimized the propagation of microcracks under splitting tensile stresses.

5.4 Bond strength for geopolymer concrete using waste glass

The bond strength results for GPC incorporating WG as a partial replacement for FA and sand demonstrated clear trends of enhancement, with varying performance at different replacement levels, as illustration the **Figure 11** and **Table 3**. These results provide valuable insights into the influence of WG on the mechanical behavior and microstructural development of GPC.

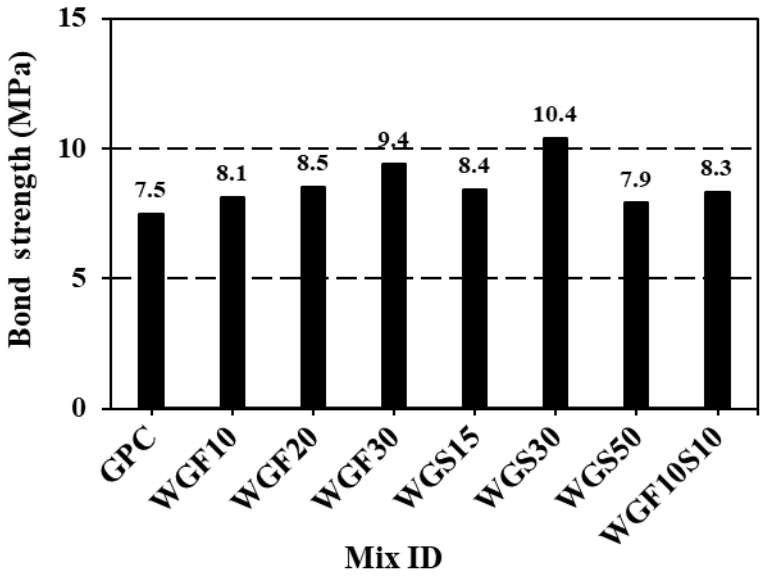


Figure 11. Bond strength for GPC mixes using WG at 28 days

When FA was partially replaced with WGP, the bond strength at 28 days for GPC (control), WGF10, WGF20, and WGF30 was 7.5 MPa, 8.1 MPa, 8.5 MPa, and 9.4 MPa, corresponding to improvements of 0%, 8%, 13%, and 25%, respectively. This progressive enhancement highlights the role of WGP as a pozzolanic material in strengthening the bond between the steel reinforcement and the GPC matrix. The increase in bond strength can be attributed to the pozzolanic reaction of WGP, which generates an additional calcium silicate hydrate (C-S-H) gel that densifies the interfacial transition zone (ITZ), reduces porosity and improves adhesion. This densification not only strengthens the bond strength at the steel-concrete interface but also enhances overall matrix cohesion. Recent studies, such as those by **Mohammed et al., (2022)**, have reported similar findings, indicating bond strength improvements of up to 22% with comparable replacement levels of finely WGP. Likewise, **Al-Hadithi et al., (2021)** noted that WGP enhanced the ITZ properties, leading to significant increases in bond strength, particularly at replacement levels up to 30%.

When WGP was used as a partial replacement for fine aggregates (sand), the bond strength values at 28 days for GPC (control), WGS15, WGS30, and WGS50 were 7.5 MPa, 8.4 MPa, 10.4 MPa, and 7.9 MPa, representing improvements of 12%, 38%, and 5%, respectively. The maximum bond strength observed at WGS30 underscores the importance of achieving an optimal balance between particle packing efficiency and microstructural development. At this level, WGS effectively fills voids within the matrix, reduces porosity, and improves the mechanical interaction at the steel-concrete interface, leading to better bond strength. Similar observations were reported by **Singh et al.,(2023)**, who recorded a 35% increase in bond strength when glass powder replaced fine aggregates at 30%, attributing the improvement to enhanced ITZ properties and microstructural refinement. The reduction in bond strength observed at WGS50 highlights the challenges associated with excessive glass content. at this level, the brittle nature of WGS and potential micro-crack formation compromise the concrete's cohesiveness, leading to a reduction in mechanical interlock and bond strength. Despite this decrease, the bond strength remained higher than the control mix, underscoring the

viability of WGS as a sustainable alternative to natural sand. This outcome is particularly significant in the context of resource conservation and environmental sustainability, as it promotes the reuse of industrial byproducts and reduces the depletion of natural aggregates. **Tan and Du, (2021)** corroborated this observation, emphasizing that sand replacement levels up to 30% optimized mechanical performance, while higher levels resulted in diminishing returns due to increased brittleness**.**

When employing a dual replacement strategy in GPC mix WGF10S10, where 10% of FA was substituted with WGP and 10% of sand was replaced with WGS, the bond strength exhibited a remarkable improvement compared to both the control mix and the single-replacement mix WGF10. at 28 days, the bond strength reached 8.3 MPa, reflecting an 11% enhancement relative to the control mix. This improvement highlights the combined effects of dual replacement in enhancing the interfacial bonding characteristics between the geopolymer matrix and the reinforcing steel.

The enhanced bond strength observed in WGF10S10 can be attributed to the interdependent contributions of WGP and WGS on the microstructural properties of the geopolymer matrix and its interface with the steel reinforcement. The pozzolanic reactivity of WGP promoted the formation of additional sodium-alumino-silicate-hydrate (N-A-S-H) gels, which contributed to densifying the matrix around the steel surface, thereby improving adhesion. Simultaneously, the incorporation of WGS improved the mechanical interlock at the steel-GPC interface. The finer particle size and angularity of WGS ensured better compaction and packing density, reducing voids around the reinforcing steel and enhancing the matrix-to-steel contact area.

Additionally, the dense microstructure developed due to the combined influence of WGP and WGS reduced the ingress of aggressive agents, thereby improving the durability of the steel-concrete bond.

6. Water absorption for geopolymer concrete using waste glass

The integration of WG as a partial replacement material in GPC significantly impacts its water absorption characteristics, an essential metric for assessing durability and resistance to environmental degradation. For the mixes GPC (control), WGF10, WGF20, and WGF30, the water absorption values were 4.5%, 2.9%, 2.3%, and 2.1%, respectively. The progressive reduction in water absorption with increasing levels of FA replacement by WGP underscores its role in refining the microstructure and enhancing matrix densification. Such outcomes emphasize WGP's ability to reduce void content and refine pore structures, thereby improving impermeability and extending durability.

This improvement is primarily attributed to the pozzolanic reactivity of WGP, which promotes the formation of denser sodium-alumino-silicate-hydrate (N-A-S-H) gels during geopolymerization. Moreover, the fine particle size and smooth surface of WGP contribute to better packing density, minimizing capillary pores that facilitate water ingress. These advancements mitigate moisture-related deterioration and significantly extend the service life of concrete structures, showcasing WGP's value in advancing sustainable construction practices. These findings align with existing literature, which demonstrates that WGP enhances water resistance by improving matrix integrity and reducing porosity **(Vafaei and Allahverdi, 2017a)**, as illustration the **Figure 12.**

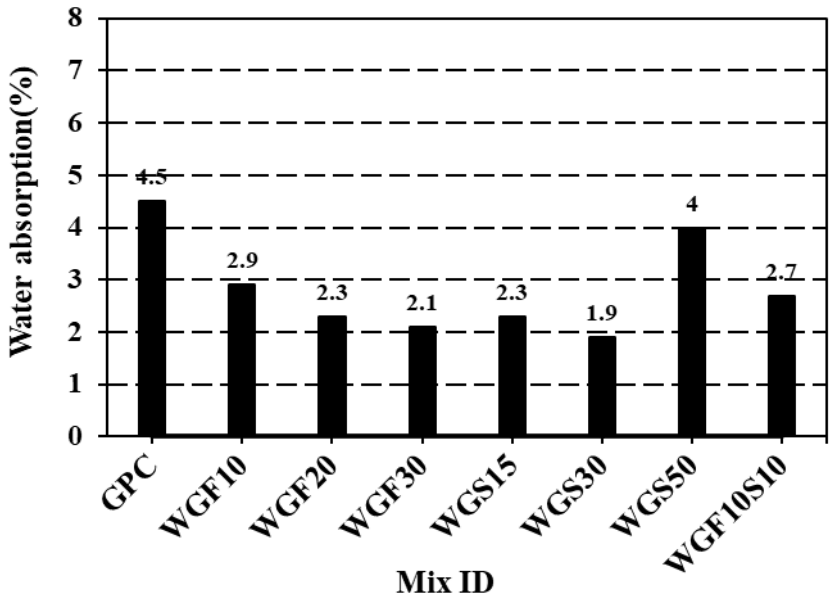


Figure 12. Water absorption for GPC mixes using WG

When natural sand was replaced with WGS in GPC, substantial effects on water absorption were observed, underscoring the fundamental role of aggregate selection in enhancing durability. For the mixes WGS15, WGS30, and WGS50, water absorption values were recorded at 2.3%, 1.9%, and 4%, respectively. At replacement levels of 15% and 30%, the absorption values decreased, likely due to enhanced packing density and reduced void connectivity facilitated by the smooth texture of glass particles. These particles effectively filled voids within the matrix, limiting pathways for water ingress and thereby lowering absorption. However, at a 50% replacement level, absorption increased to 4%, potentially due to higher porosity introduced by the excessive angularity and reduced stability of the mix. Nevertheless, the absorption value for WGS50 remained below the control mix, reinforcing the environmental advantages of incorporating substantial quantities of waste glass materials in sustainable concrete production.

In comparison to studies on conventional concrete, similar trends have been observed. Moderate replacement levels of natural sand with WGS improve durability characteristics such as reduced permeability and increased resistance to environmental degradation. Excessive replacement levels, however, compromise performance by increasing porosity and diminishing matrix integrity, emphasizing the need for carefully optimized mix designs **(Ismail and Al-Hashmi, 2009; Rashad, 2014c)**.

For the geopolymer concrete mix WGF10S10, where 10% FA was replaced with WGP and 10% sand with WGS, water absorption was recorded at 2.7%. This value is notably lower than both the control mix and the mix with only FA replacement (WGF10), highlighting the complementary enhancements achieved through a dual-replacement strategy. The pozzolanic reactivity of WGP facilitated the formation of dense N-A-S-H gels, while the incorporation of WGS enhanced packing efficiency and reduced void content. Together, these effects improved matrix compactness and significantly mitigated water absorption, resulting in a highly durable and impermeable geopolymer concrete material.

7. Microstructural analysis

The SEM analysis of the GPC mix (control) reveals a porous microstructure with visible cracks and the presence of unreacted FA particles, illustrates **Figure 13 (a)**. These deficiencies indicate incomplete geopolymerization and weak interfacial zones between the matrix and aggregate. The lack of sufficient binding phases, such as calcium-silicate-hydrate (C-S-H) gel and alumino-silicate networks, leads to lower mechanical properties. Unreacted FA particles suggest that the chemical activation process was insufficient to dissolve the precursors fully, limiting the formation of binding gels critical for strength development. This result is consistent with prior studies, such as **Shi, (2019)**, which attributed diminished strength in GPCs to unreacted particles and poor microstructural connectivity.

The SEM images of Mix WGF30, where 30% of the FA is replaced with WGP, demonstrate a significantly improved microstructure compared to the control mix. The presence of fewer pores and reduced cracks suggests enhanced material cohesion, illustrates **Figure 13 (b)**. The introduction of WGP increases the dissolution rate of silica and alumina from the source materials, facilitating the formation of denser C-S-H gel and alumino-silicate frameworks. These phases enhance the strength and durability of geopolymer matrices **(Dinh, 2024a).**

While minor unreacted FA and WGP particles are observed, their presence does not significantly compromise the structural integrity, as the overall microstructure is markedly more compact and cohesive. The smooth surface of WGP particles promotes better packing and reduces voids, contributing to a more homogeneous matrix. This effect aligns with findings by **Kumar et al. ,(2023)**, who highlighted that WGP enhances pozzolanic reactions and accelerates the geopolymerization process, resulting in improved binding and reduced porosity.

Additionally, the interaction between WGP and the activator solution likely increases the availability of reactive silicates, further supporting the development of binding phases. The improved microstructure of Mix FA-30%WGP translates into enhanced mechanical properties, validating the potential of WGP as a sustainable and effective substitute for FA in geopolymer formulations.

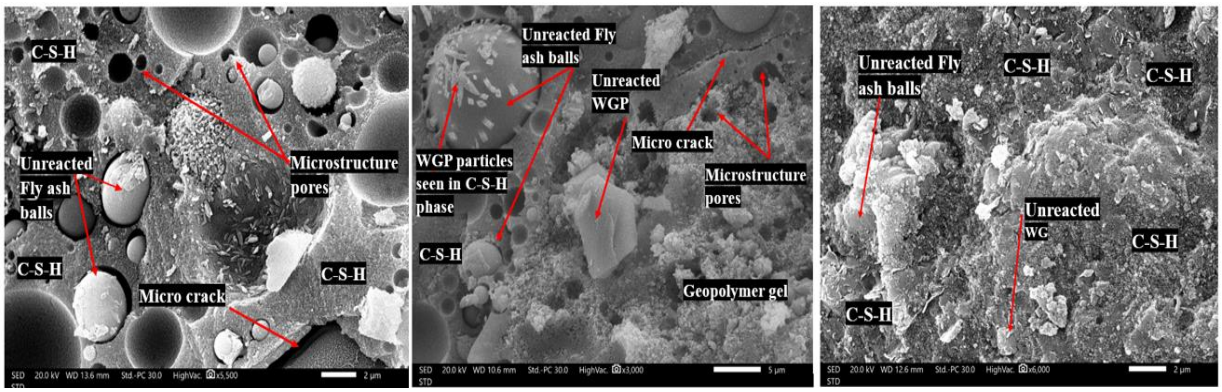
The SEM analysis of Mix WGS30, where 30% of the sand is replaced with WGS, reveals the most cohesive and well-structured microstructure among the Mixtures, illustrates **Figure 13 (c)**. The dissolution of source materials is particularly pronounced in this mix, forming extensive C-S-H and alumino-silicate binding gels. These phases fill voids and bridge gaps between aggregates, creating a dense and interconnected matrix.

The observed microstructure shows minimal unreacted particles, indicating that substituting sand with WGS facilitates a more complete geopolymerization process. This aligns with **Zheng et al. (2020)**, who emphasized that the fine particle size and smooth surface of WGS enhance the reactivity of silica and alumina, leading to superior material properties. Furthermore, eliminating larger sand grains and replacing them with WGP likely improves particle packing density, reducing voids and internal defects.

The improved performance of Mix WGF30 and Mix WGS30 can be attributed to the chemical and physical properties of WG. Its smooth surface texture reduces internal friction within the mix, while its low water

absorption promotes better dispersion and reactivity. The increased dissolution of silica and alumina enhances the availability of reactive precursors, facilitating the formation of robust binding phases like C-S-H gel and alumino-silicate frameworks.

The findings highlight those substituting traditional materials with WG enhances mechanical properties and aligns with sustainability objectives by recycling glass waste into high-performance concrete. These results are consistent with the literature, which underscores the potential of WG to improve microstructure, reduce porosity, and enhance mechanical performance in geopolymer systems **(Shi, 2019)**.



a) b) c)

Figure 13. SEM image: (a) GPC, (b) WGF30, (c) WGS30

8. Conclusions

This study emphasizes the transformative potential of waste glass powder (WGP) and waste glass sand (WGS) as partial replacements for fly ash (FA) and natural sand in geopolymer concrete (GPC), enhancing both performance and sustainability. In the light of the test results and discussion of the current study, the following conclusions can be drawn:

- The incorporation of WGP and WGS significantly enhanced workability, achieving slump improvements of 23% and 25% at 30% replacement with WGP and WGS, respectively. This improvement is due to the smooth texture and low water absorption characteristics of the glass particles.
- Unit weights increased at optimal replacement levels with waste glass, reaching a maximum of 2.30 t/m³ and 2.32 t/m³ for 30% WGP and 30% WGS, respectively, compared to 2.24 t/m³ for geopolymer concrete without waste glass. This increase is attributed to improved particle packing density.
- The mechanical properties exhibited slight enhancements, with compressive strength, flexural strength, splitting tensile strength, and bond strength increasing by 29%, 45%, 25%, and 38%, respectively, at a 30% WGS replacement level compared to the control mix without waste glass at 28 days. This improvement reflects enhanced matrix cohesion and the properties of the interfacial transition zone.
- The dual replacement mix, which incorporates 10% fly ash replacement with WGP and 10% sand replacement with WGS, demonstrated the synergistic benefits of combined substitutions. This mix achieved enhancements in compressive strength, flexural strength, splitting tensile strength, and bond strength by 10%, 10%, 5%, and 11%, respectively, compared to the control mix without waste glass at 28 days.
- The percentage of water absorption significantly decreased by 57.8% for 30% WGS, while the dual replacement mix recorded a reduction of 40%, compared to the control mix without waste glass at 28 days.
- SEM analysis confirmed the presence of denser and more cohesive microstructures, characterized by reduced porosity and enhanced binding gel formations in the optimized mixes. This further validates the role of waste glass in refining GPC matrices.
- The findings of this research highlight the dual benefits of enhancing GPC performance while simultaneously reducing environmental impact through the utilization of waste glass. The study emphasizes the feasibility of repurposing waste glass in sustainable construction, effectively addressing landfill challenges and conserving natural resources.
- Future research should concentrate on assessing long-term durability, economic feasibility, and large-scale applications to fully leverage the potential of GPC that incorporates waste glass.

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