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Performance of Eco-Friendly Self-Compacting Concrete Incorporating Waste Glass Powder as Fine Aggregate Replacement

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ABSTRACT: This study examines the influence of waste glass powder (WGP) as a partial replacement for fine aggregate on the fresh, mechanical, and absorption properties of self-compacting concrete (SCC). Replacement levels of 0 %, 5 %, and 10 % were investigated in accordance with ASTM and EFNARC standards. The incorporation of WGP enhanced workability, increasing slump flow from 650 mm in the control mix to 750 mm at 10 % replacement. Mechanical performance improved significantly, with compressive strength rising from 26.3 MPa to 49,2 MPa at 28 days, and splitting tensile strength increased from 1.9 MPa to 3,4 MPa. These improvements are attributed to the micro-filling capability of fine glass particles and the pozzolanic reaction of amorphous silica, which contribute to matrix densification. Nevertheless, there was a 60% and 58% increase in absorption for cubic and cylindrical specimens (5.5% to 8.78% and 2.15% to 3.39%, respectively), thereby indicating that additional durability tests are necessary and freeze-thaw. In general, the results have shown that waste glass powder can be effectively used as a partial replacement of fine aggregate to enhance the mechanical properties and workability of SCC as well as encourage the sustainability of the environment and recycling of waste in the construction industry.

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1- Introduction

The concept of sustainability in construction has taken a central stage following the growing importance of reducing environmental impact and ensuring natural resources are conserved. As the most consumed construction material in the world, concrete is a major contributor to carbon emissions and the depletion of natural resources. Thus, investigators have examined the integration of industrial by-products and recycled materials as a semi-replacement for standard components without affecting performance.[1], [2], [3] [4]. Researchers have, in turn, investigated the use of alternative ions that can supplement the traditional constituents without affecting the performance of concrete. Self-compacting concrete (SCC) is non-segregating concrete with very high flowability, which can be placed in formwork, using only non-vibratory methods, by its own weight. Despite its contribution to construction efficiency and structural quality, standard mix designs of SCC regularly need higher proportions of binder and fine materials than traditional requirements, and this may create additional expense and environmental challenge [5]. Therefore, there is an emerging demand for the indiscriminate inclusion of industrial by-products and recycled materials into SCC to improve its sustainability footing. The waste glass, which has been reduced by grinding to recycled glass powder (RGP), has also been proposed as a potentially useful additive material because of its pozzolanic activity and due to its abundance as a post-consumer waste product. It has been demonstrated that glass powder to a size of up to 90 micra fines may be used as a partial replacement for cement or fine aggregate in concrete, resulting in better mechanical properties and less environmental impact [6]. Further, glass powder has excellent particle packing and provides a micro-filling effect to the concrete mix, raising its density and strength. Several investigators considered the impact of integrating RGP into SCC. An increase in the volume of waste glass used as part-replacement material with the fine aggregate in the concrete was used to investigate by Park et al. (2004) [7] . The study was based on its impacts on both the fresh and hardened properties. In their experimental program, they considered the level of 0%, 30%, 50%, and 70% replacement, as well as the possibility of using the SBR latex polymer, which could increase performance. The research concluded that as the waste content of the glass increased, workability (slump and compacting factors) was diminished, and lift air content was increased since the angular shape and larger surface area of glass particles occurred. Further, increased content of waste glass resulted in decreased compressive, tensile, and flexural strength, and the optimum content of replacement was 30 %, especially when it was combined with 10 % SBR latex, which assisted in augmenting mechanical properties. The researchers concluded that waste glass makes an efficient material to replace fine aggregates in concrete to

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a replacement percentage of 30% with relevant admixtures, thereby contributing to the spread of sustainable usage of concrete materials. Addition of waste glass powder, as a partial replacement of sand, was seen to improve the ease of flow and the compressive strength and reduce the environmental footprint of concrete as a whole this was guaranteed by the study by Islam et al. (2017) [8] who conducted the study to employ the use of waste glass powder in place of cement as a component of concrete to develop sustainable environmental construction practices. It was investigated that the chemical properties of the clear and colored waste glass powders were studied, and that they were appropriate pozzolanic materials based on a high concentration of silica. Milled waste glass powder, substituent of cement, was distributed at rates of 0-25 % in a mortar and concrete mix containing fixed proportions of water to binder, and the compressive strength was tested at various ages up to 365 days. Findings indicated that when up to 20 percent cement was replaced by waste glass powder, then there was an improvement in the long-term compressive strength of mortar and concrete in general, but the strength was equal to or slightly higher when compared to the control samples after 90 and 365 days. The present study further ascertained that waste glass, which could be in the form of powder, would decrease the CO 2 emissions and costs of concrete production, thus making it sustainable as a cementitious material used in concrete production. M. Adaway et al. (2015) [9]also noted that concrete mixes with finely ground waste glass showed sufficient strength and durability properties, especially when applied at a replacement rate of less than 20 per cent. Moreover, Aliabdo et al. (2016) [10] performed a thorough study of waste glass powder (WGP) as a source of cement replacement and cement additive in concrete manufacture. It was the purpose of the study to determine the pozzolanic properties of WGP and its suitability to cement requirements, as well as their impact on the concrete's mechanical and physical characteristics. The waste glass powder, whose particle size was less than 75 microns, was added at a substitution level and an addition level of zero percent to twenty-five percent by weight of the cement. The findings showed that WGP can fulfill ASTM C618 [11] standards that demand pozzolanic materials to be satisfactory in terms of strength activity indices with values above 75 % at the seventh and 28days. Additions of WGP in cement quantities as much as 10 % increase the compressive strength of mortars by about 9 %, whereas the compressive strength tends to be decreased by increased replacement levels because of the dilution of cement material, unless the water-to-cement ratio can be decreased. Also, WGP, when used as a cement manufacturer at the rate of 15%, enhanced the compressive and tension strength of cement, lowered the voids ratio, and increased the density of concrete at 25% as well on an upgrading level of high-strength (45 MPa) concrete. In the study, it was pointed out that WGP can not only serve the interest of improving the mechanical performance and workability of concrete but can also help in sustainable activities like the reduction of cement usage and landfill waste in connection with the goals of sustainable concrete practices. Performance of concrete with recycled glass powder (GP) as an alternative to cement, partially, by experimenting with it under real field conditions this was conducted by Omran et al. (2016) 12]] Their findings have indicated that addition of up to 20% of GP has enhanced long-term strength characteristics of concrete, viz compressive strength, tensile strength, and markedly enhanced durability due to less penetration of chloride ions and resistance to freeze-thaw conditions. The research determined that glass powder can significantly improve the durability and the mechanical characteristics of the concrete and also help in the sustainability measure, i.e., recycling of the material and also reduction of the CO 2 emission.

The use of recycled glass powder (RGP) as a partial replacement in limestone calcined clay cement (LC3) to enhance the sustainability and performance was studied by Wang et al. (2023) [13] in the framework of an experimental study. They have tested 10% and 20% RGP additions and established that the addition of RGP enhanced workability as it had a smooth surface area and low water absorption. Mixes with a 10% RGP added mix were compressively strong in a similar way to the control at 90 days, whereas the 20% mix resulted in a loss of strength because of its dilution and low clinker concentration. There was a high reduction of CO 2 emissions, especially at 10% of the replacement. The calculated pozzolanic activity and stable C-S-H gel formation were confirmed by the microstructural analysis (XRD, TG-DTG, and SEM-EDS). However, increased content of RGP contained an insufficient amount of calcium hydroxide (CH), which restrained pozzolanic interactions. The paper emphasized the two advantages of RGP in terms of lower environmental impact and acceptable mechanical performance when using replacements that are less than 10%.Jia and Zhao [14] studied how glass powder could be used as a partial substitute of cement in lightweight aggregate concrete to use in marine applications. The results of the experiment showed that the addition of up to 20% GP increased the resistance of concrete to chloride penetration and reduced water absorption, besides raising the electrical resistivity, thereby improving its resistance to corrosion in a marine setting. The microstructure revealed increased internal structure and less porosity, which helped in enhancing the interfacial bonding. The researchers conclude that the waste glass powder can be effectively used to create lightweight, durable, and sustainable concrete that may be used in marine engineering structures. Table 1 presents a comparative summary of selected past studies.

The use of WGP in concrete has been investigated in several studies (Park et al., 2004; Islam et al., 2017; Aliabdo et al., 2016; Omran et al., 2016; Wang et al., 2023). Nonetheless, most of them concentrated on cement replacement, rather than sand replacement, creating a gap in the knowledge of the effectiveness of WGP as an alternative aggregate in SCC. This study fills that gap by assessing the impact of WGP on the fresh and hardened properties of SCC.

The study also helps to learn about the possibilities of recycled glass powder in improving the mechanical properties

Table 1. Comparative summary of selected past studies.

Study	Replacement (%)	Target property	Main finding
Park et al. (2004	0-70% sand	Strength and workability	Optimum at 30% with SBR latex
Islam et al. (2017)	0-25% cement	Compressive strength	+15 at 20% WGP
Aliabdo et al. (2016)	0-25% cement	Strength, density	+9% in at 10% WGP
Omran et al. (2016)	0-20% Cement	Durability	Improved chloride resistance
Wang et al. (2023)	10-20% cement	Strength , CO2 emissions	Improve strength and reduce 10% emissions
Jia and Zhao (2025)	0-40% cement	Chloride resistance and water absorption	Up to 20% of WGP improve chloride resistance and reduce water absorption

Table 2. Physical properties of constituent materials.

Material	Specific Gravity	Sio2 Content	Particle size	Test Standard
Cement	3.14	-	-	ASTM C188 [17]
Natural Sand	2.62	-	0-5mm	ASTM C128 [18]
Coarse Aggregate	2.69	-	2-20mm	ASTM C127[19]
Waste glass powder	2.48	70%	75 µm	ASTM C128 [18]

and sustainability of SCC by concentrating on parameters like workability, compressive strength, tensile strength, and water absorption.

2- Material

Ordinary Portland cement was used as the binder of choice in the experimental program because it is common, and mainly because of the stability with which it produces concrete[15]. The fine aggregate used was the natural sand, which has sufficient particle grading to meet the requirements of the mix designs. In the case of the coarse aggregate, locally available gravel with particles between 2 and 20 mm was employed to offer the required skeleton to the concrete mixes [16]. To study the effect on concrete properties, the ground waste window glass, ground in the same way as glass powder (i.e., 15 minutes grinding, fine particle size), was used as a partial replacement material by weight. Even though the ground waste glass powder (WGP) has a significantly smaller particle size 75 µm on average, 45 µm than typical sand, it is not applied as a full-sized sand replacement but as a partial replacement (5 to10% by weight of sand). The specific gravity of the constituent material was determined in accordance with standard test methods. The values are presented in Table 2, and Figure 1 shows the particle size distribution curves of the constituent materials. At these low replacement levels, WGP is an effective micro-filler, enhancing the packing and filling of interstitial spaces between sand and cement particles. At the same time, its reactive silica has provided pozzolanic reactions, which form the secondary C -S- H that compacts the matrix. In this way, the combined filler and pozzolanic effects have contributed to the strength improvements even though the particle size is much finer than sand. The chemical composition of WGP was mostly composed of SiO_2 (70%), CaO (10%), and Al_2O_3 (8%). To guarantee the prerequisite workability of the blend without interfering with the volume of water, a superplasticizer was introduced, and this made it possible to achieve adequate compaction and flowability when casting in an appropriate manner with the intended ratio of water-cement.

3- Mixing and Casting

This study used three mixes of concrete with different contents of glass powder to determine their effects on the behavior of concrete. The first mix, which acted as the control, had no glass powder, whereas the second mix and third mix had 5 % and 10 % glass powder, respectively, as

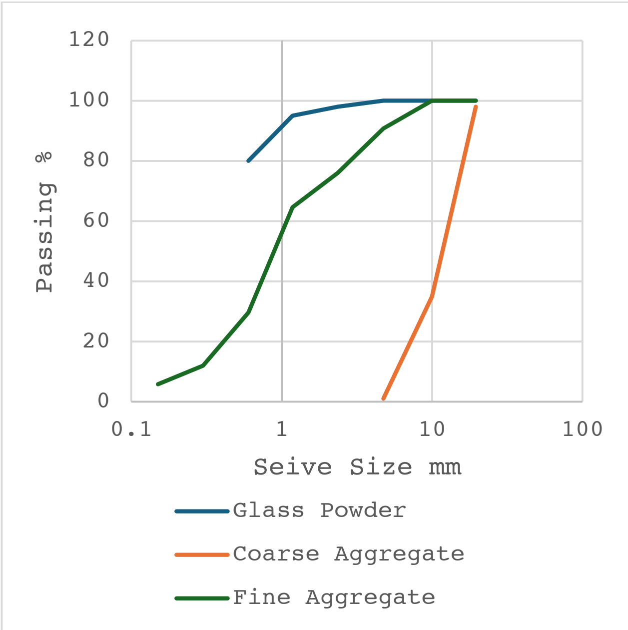

Fig. 1. Particle size distribution curves of the constituent materials.

a partial substitute for the weight of the fine aggregate. In all mixes, the measurement of cement, water, and coarse aggregate remained unchanged; 450 kg/m³ of cement, 158 kg/m³ of water, and 855 kg/m³ of gravel were used to make each batch of mixes to allow comparisons to be made similarly. Fine aggregate (sand) was modified based on glass powder replacement, whereby the control mix had 540kg/m³ of sand compared to the 5% glass mix of 513kg/m³ of sand, 27 kg/m³ of glass powder, and 486kg/m³ of sand and 54 kg/m³of glass powder in the 10% glass mix. Table 3 shows the mix proportions of all concrete mixes evaluated in this study. This controlled change enabled us to determine the impact of the

Table 3. Mix Proportions of Concrete with Different Concentrations of Glass Powder

Material	0% Glass	5% Glass	10% Glass
Cement (kg/m³)	450	450	450
Sand (kg/m³)	540	513	486
Gravel (kg/m³)	855	855	855
Water (kg/m³)	158	158	158
Glass Powder (kg/m³)	0	27	54
Water-to-Cement Ratio	0.35	0.35	0.35

recycled glass powder to the fresh and hardened values of the concrete mixes.

The fresh density of every concrete mixture was tested at the time of mixing as specified in ASTM C138 [20]. The resulting densities of the 0%, 5%, and 10% WGP mixes were found to be 2350 kg/m³, 2345 kg/m³, and 2338 kg/m³, respectively. The theoretical density was calculated using the absolute volume method based on ASTM C138[21] which assumes a perfectly compacted solid matrix with no entrapped air. The calculation based on the mix proportions and the specific gravities, following equation 1,2:

$$\rho\_th = \frac{W\_total}{V\_abs} \quad (1)$$

$$V\_abs = \frac{Wc}{SGc} + \frac{Ws}{SGs} + \frac{Wg}{SGg} + \frac{Ww}{SGw} + \frac{Wwgp}{SGwgp} \quad (2)$$

Where Wc, Ws, Wg, Ww, and Wwgp are the weights of cement, sand, gravel, water, and waste glass powder, respectively, and SG denotes the specific gravity of each material.

The calculated theoretical densities, measured fresh densities, and the derived implied air/ porosity content are summarized in Table 4.

After the completion of the mixing process, the concrete was cast into regular steel molds as per ASTM C192 [22] using the cubic specimens (100 mm x 100 mm x 100 mm) to perform the compressive strength tests (ASTM C39) [23] and cylindrical specimens (100 mm diameter x 200 mm height) to conduct tensile strength test in splitting (ASTM C496) [24]. These samples were stored under constant conditions at 23 o C +/- 2 degree C and 95 percent relative humidity to provide sufficient early strength gain before demolding, which prevents damage to the edges. The samples were then placed in the limewater saturation solution at 23 + 2 C until the required ages of 7, 14, and 28 days had passed according to ASTM C511 [25]specifications to ensure that samples underwent constant hydration to reduce the tendency of micro-cracking caused by moisture loss and thus mirror actual field curing conditions of structural concrete components. Mold surfaces were cleaned with mineral oil drops so as not to stick, as to guarantee reproducibility and reliability of results. Each of the specimens was marked with mixed identification and casting date to ensure good traceability in the testing program. Such an ordered process made the preparation and curing of specimens quite consistent, and hence, the data was credible to analyze the effect of glass powder incorporation in the performance of self-compacting concrete.

The result in Table 4 indicates a consistent trend: while the theoretical density shows only a marginal decrease with increasing WGP content, the measured fresh density decreases more noticeably. Consequently, the implied air / porosity provides a quantitative basis for understanding the observed rise in water absorption in the hardened concrete,

Table 4. Density analysis of concrete mixtures.

WGP content (%)	Theoretical density $\rho\ th$ (kg/m^3)	Measured fresh density (kg/m^3)	Implied air/porosity content* (%)
0	2427	2350	3.2
5	2425	2345	3.3
10	2423	2338	3.5

*Implied content = {(theoretical density- Measured fresh density)/ theoretical density}*100

Table 5. Compressive strength results (MPa).

Replacement (%)	Compressive strength (MPa)			SD± MPa	Change vs control
	7-day	14-day	28-day		
0(Control)	24.3	25.1	26.3	0.9	-
5	32.9	33.8	34.8	1.1	+20.9%
10	43.3	45.8	49.2	0.87	+87%

as a more porous microstructure facilitates greater capillary water uptake.

4- Testing of specimens

Experimental tests were carried out in triplicate, and the mean values are presented. Each of the tests had a standard deviation (SD) with in±5%, which implies that the results were well-reproducible.

4- 1- Testing of fresh concrete

This paper provides a critical analysis of the new characteristics of self-compacting concrete (SCC) that uses recycled glass powder as a partial substitute for sand. To describe the rheological behavior, it was tested under three different conditions: (1) Slump flow testing based on the EFNARC protocol [26]was demonstrated to exhibit improved flowability with rising glass content (650-750 mm diameter range), which is explained by the smooth surface topography and lower friction between particles of the glass. The J-Ring test exhibited high scores in passing ability (PA >0.8) and passed all the levels of replacement (0-10%) highlighting sufficient deformability in restrictive conditions. Results of the L-Box test showed height ratios (h 2 / h 1) of 0.85-0.92, which is above the minimum criterion of 0.80 recommended in SCC use. It was worth noting that T400 was less than 5seconds in all the mixtures, implying suitable viscosity. It was seen during visual inspection that there is no particle segregation or bleeding of mortar in the 10 percent glass mixture, which showed the best balance between the flow properties and stability.

4- 2- Testing of hardening concrete

4- 2- 1- Compressive strength

Axial compression testing as per ASTM C39 [23] showed that glass powder leads to a significant increase in compressive strength. The 28-day compressive strength consistently increased with an increase in the replacement level, as shown in Table 5 and Figure 2, with a comparative increase of 87٪, increasing to 49.2 MPa at a 10 percent replacement level compared with the control mix of 26.3 MPa. The compressive strength of 26.3 MPa for the control mix with a w/c ratio of 0.35 is Lower than some typical values. Although a superplasticizer was used to achieve flowability, the mix lacked cementitious Materials (SCMs) Like fly ash or silica fume, that enhance particle packing density and high porosity in the interfacial translation zone (ITZ) between aggregate and cement paste[27][28]. In SCC mixture bleeding, and segregation may have occurred during placement, resulting in non-uniform microstructure and reduced strength development. This Phenomenon is particularly common in SCC Mixes with high water content relative to the powder volume[29]. The enhancements in compressive strength as the WGP content increases are largely explained by the pozzolanic activity of amorphous silica in the glass powder, which reacts with calcium hydroxide $Ca(OH)_2$ generated as cement is hydrated to form more C -S -H gel. This secondary C -S -H helps to densify the mixture and occupy micro voids. Moreover, the fine glass particles serve as micro fillers, which improve the packing of the particles and minimize the connectivity between pores in the interfacial transition zone (ITZ)[30][31]. The combination of these effects results in a

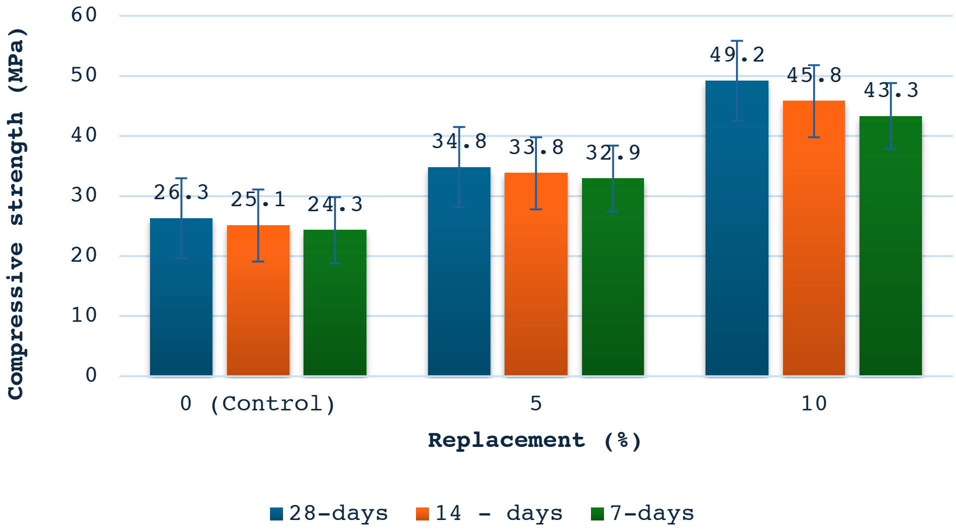

Fig. 2. Compressive strength results.

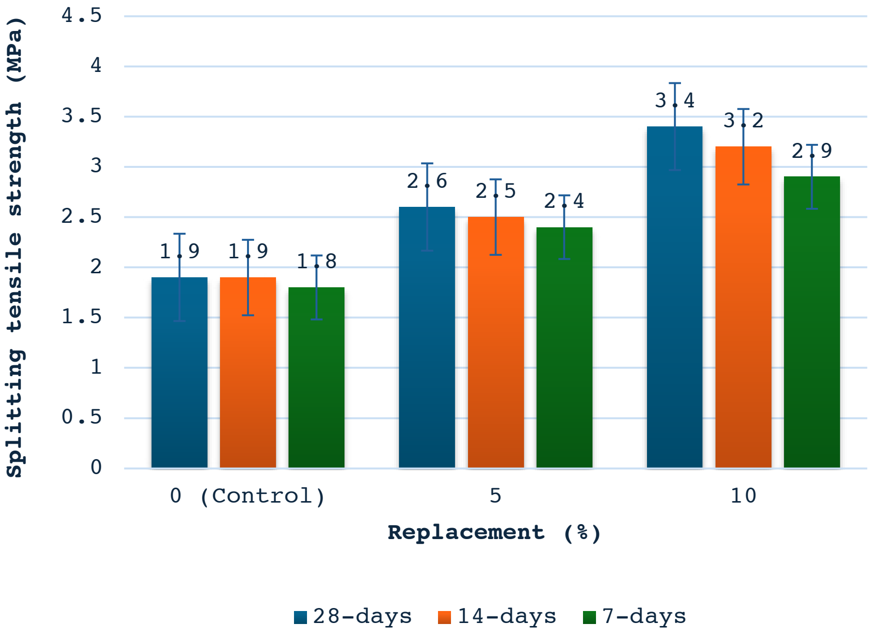

Fig. 3. Splitting tensile strength results.

smaller and stronger microstructure. It was also reported that it happened through similar mechanisms reported by Yuzhuo et al. (2025) [32]and Memduh et al. (2025) [33] in glass-based concretes.

4- 2- 2- Tensile strength

It was found that the splitting tensile tests (ASTM C496) [24]indicated proportional gains in glass content as in Table 6 and Figure 3. The 10 percent replacement mixture had attained 3.4 MPa tensile strength after 28 days, which is 79 % higher than the control mixture. Such an improvement factor (79% vs. 87% compression) implies that the particles of glass behave better to add compressive capacity rather than tensile resistance, perhaps attributable to the angular shapes of particles providing superior mechanical interlock in compression.

4- 2- 3- Absorption

A water absorption test was carried out by following the standard test method of absorption in hardened concrete [34]

Table 6. Splitting tensile strength results (MPa).

Replacement (%)	Splitting tensile strength (MPa)			SD± MPa	Change vs control
	7-day	14-day	28-day		
0 (Control)	1.8	1.9	1.9	0.17	/
5	2.4	2.5	2.6	0.15	+37%
10	2.9	3.2	3.4	0.15	+79%

Table 7. Water absorption results (%).

Replacement %	0%	5%	10%	SD± MPa for 10% replacement	Change vs control
cubes	5.5	8.15	8.78	0.3	+60%
cylinders	2.15	2.4	3.39	0.27	+58%

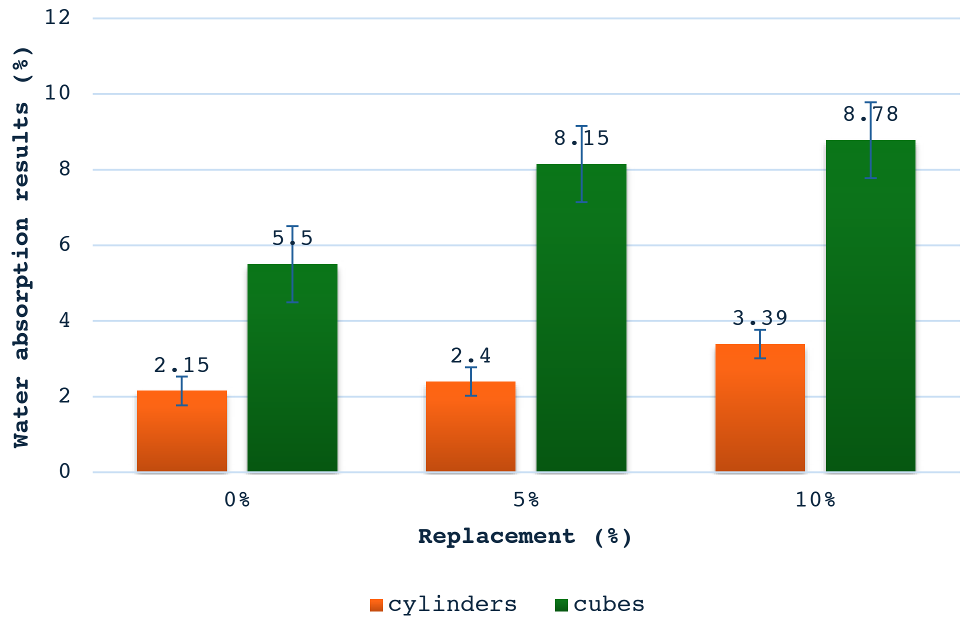

Fig. 4. Water absorption results.

to determine the effects of glass powder on the absorption property of the concrete mixes. These findings, as shown in Table 7 and Figure 4, were that water absorption tended to increase systematically but at a moderate rate with the increment in the level of the glass powder[35]. In the mixture with the concentration of glass powder of 10%, the absorption was equal to 8.78 per cent and 3.39 per cent in the case of the cube and cylinder specimens respectively, which indicated an increase by 60 per cent and 58 per cent as compared to the control specimens. Such behavior can be explained by the existence of two opposing processes:

(1) Possibility of higher porosity at the interface between the glass and the cement paste because of incomplete packing of the particles[36][37], and,

(2) Refinement of pores with time because of the pozzolanic activity of the glass powder itself[38]. Moreover, the monotonic lower values of absorption in the cylindrical specimens (almost half of those of the cubic specimens)

highlight an important role of the shape of the specimen in defining the pattern of water penetration and absorption measurements.

4- 2- 4- Workability and Density Relationship

Subsequent measurements of density at fresh demonstrated that it is decreased by 2.8 % (2475 to 2405 kg/m 3) at the 10% substitution due to the difference in specific gravity between glass and sand. Nevertheless, this is a very small decrease combined with exceptionally large workability enhancement (slump flow was increased by 650 to 750 mm), implying that a change in particle morphology and surface properties are more influential than density in determining the fresh behavior. Density-strength correlation ($R^2 = 0.92$) suggests that the increase in strength can be mainly related to chemical rather than physical mechanisms.

5- Conclusions

This exhaustive study provides these key conclusions as to the performance of glass powder-modified self-compacting concrete:

1. The use of recycled glass powder as a partial sand replacement shows a significant improvement in the mechanical properties of the concrete, and maximum improvement occurs at 10 percent substitution of sand. with 87% increase in 28-day compressive strength (26.3 to 49.2 MPa) and 79 % increase in splitting tensile strength (1.9 to 3.4 Mpa).
2. Development and maintenance of strength are a kinetic problem, but accelerated hydration, especially when curing time is extended to 7-14 days, indicates that glass powder not only acts as a pozzolanic reaction but also improves physical microstructure via better particle packing density[39].
3. The relative rise in water absorption (5.5 upon 8.78 per cent) is not significant enough to make it inappropriate in structural applications, although it raises the issue of paired durability testing, especially on in-depth chloride penetration and carbonation resistance.
4. New property testing ensured that self-compactability was maintained at all replacement levels. J-Ring and L-Box solutions (PA > 0.8) met the EFNARC SCC requirements, whereas the workability (slump flow: 650-750 mm) was enhanced with the addition of glass powder.

6- Limitations and future work

Although this research has established that the partial substitution of fine aggregate with waste glass powder can significantly enhance the mechanical performance and workability of self-compacting concrete, several limitations remain. The properties of durability, like chloride ion penetration, freeze-thaw, and long-term shrinkage, have not been experimentally tested. Additionally, laboratory-scale specimens were tested only, and no field tests were conducted.

Further studies should then be made to determine the long-term durability performance of WGP-based SCC in a real environment, and the various sizes of glass particles and the replacement level, as well as combining microstructural analysis (SEM, XRD) with life-cycle assessment (LCA) to determine the overall benefit of sustainability.

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