

COMPATIBILITY AND MECHANICAL PERFORMANCE OF HIGH-STRENGTH SELF-COMPACTING CONCRETE PRODUCED WITH RECYCLED GLASS POWDER

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Abstract

Due to its large activity and raw material use, construction offers great recycled material potential. Demolition and construction waste affect the cycle. Broken window glass powder can replace self-compacting concrete due to its pozzolanic properties. This study will quantify high-strength self-compacting concrete's compatibility and mechanical characteristics (HSSCC) with varied amounts of waste glass powder. This study explored using limestone powder with 0.46 μm waste glass powder (WGP) as a filler in self-compacting concrete (SCC) mixtures. Waste glass powder (WGP) was tested as limestone filler powder replacements at 25%, 50%, 75%, and 100% by weight. Waste glass powder (WGP) was tested on compatibility with self-compacting concrete (SCC). This was done via slump flow, L-box, T500, and V-funnel testing. Furthermore, compressive, splitting tensile, and flexural strengths were to be assessed. SCC with WGP at varied replacement percentages had good flowability, passing ability, and viscosity in newly mixed concrete. Due to its filler effect and pozzolanic activity, WGP improves self-compacting concrete (SCC) compatibility and mechanical qualities. The efficiency of WGP replacement was substantially higher at 50%, resulting in a more marked influence on enhancement, particularly among those in older age groups.

Keywords:

Self-compacting concrete (SCC);
 waste glass powder (WGP);
 Compatibility;
 mechanical performance.

1 Introduction

In recent years, the construction sector has encountered mounting pressure to implement sustainable practices, propelled by an expanding ecological movement to diminish raw material consumption. This transition has compelled the industry to investigate novel materials and techniques that reduce environmental impact while preserving or enhancing structural performance. A promising strategy entails employing alternative materials sourced from industrial waste, which provides considerable benefits in cost reduction, energy conservation, and environmental protection [1]. As a primary construction material, Concrete has undergone ongoing advancements to satisfy contemporary requirements for efficiency and sustainability. One of these innovations is self-compacting concrete (SCC), a highly fluid concrete that autonomously flows, filling intricate molds and voids without requiring mechanical vibration. SCC streamlines placement, diminishes labor expenses, and improves the quality and longevity of completed structures. Its solidified form demonstrates elevated density, uniformity, and mechanical characteristics similar to traditional vibrated concrete. The environmental impact of SCC production is a considerable concern due to its dependence on cement, a primary contributor to carbon dioxide (CO₂) emissions, which significantly elevates global greenhouse gas levels. Researchers have concentrated on creating alternative materials and methods that diminish the ecological impact of SCC while maintaining its exceptional performance attributes [2].

SCC typically incorporates a significant proportion of fine particles to attain the necessary homogeneity for self-compatibility [3]. This often leads to combinations with elevated levels of Portland cement, resulting in higher values of both initial and final strength than what is strictly necessary for the project. Consequently, the expenses associated with the constituent elements of SCC are higher

than those of ordinary concrete with equivalent strength. Various researchers have conducted studies on the fines content (physical process) and have successfully produced SCC by including different kinds of additives, silica fume, fly ash, metakaolin, etc., as partial replacements for cement [4].

One promising approach is the incorporation of recycled materials, such as glass powder, into SCC. Glass powder is derived from waste glass; due to their non-biodegradable nature and environmental incompatibility, transporting glass trash to waste disposal facilities is deemed undesirable. In contrast to other forms of waste, such as paper or organic matter, a significant proportion of glass waste persists as residue inside disposal sites even after purification [5]. However, it is essential to note that despite the ability to recycle glass several times without compromising its quality, significant quantities still find their way into landfills. The amount of glass recycling exhibits considerable variation across different countries, with the European Union member states demonstrating the most significant recycling percentage globally, averaging 73%. Conversely, other nations such as the United States (34%) and Singapore (20%) significantly trail behind in glass recycling rates [6].

One of the most appealing alternatives for giving value to waste glass is its usage in the building sector, which may use many materials and have relatively low-quality standards. Various alternatives to cement may be found in both mortars and concrete, serving as substitutes for either aggregate or cement. Nevertheless, using glass as an aggregate replacement does not provide favorable outcomes owing to the adverse consequences resulting from the interaction between the alkali in cement and the reactive silica in the glass. However, when employed as a substitute for cement, glass exhibits pozzolanic qualities, hence mitigating the issues as mentioned above. Due to the delay in glass powder (GP) pozzolanic reactions compared to clinker hydration, Ortega et al. [7] found that mortars containing GP acquire microstructure and service characteristics slower than control mortars. However, up to 20% GP did not reduce mortar durability or mechanical qualities in the medium or long term against control mortars. Studies confirm the advantages of employing finer GP (<50 μm): increased pozzolanic reactivity, reduced shrinkage, improved mortar strength, and resistance to sulfuric acid attack [8].

The integration of recycled glass powder into SCC has been the subject of numerous studies in recent years. For instance, Amin et al. demonstrated that the use of glass powder in high-strength SCC could improve fresh properties and transport characteristics. However, there was a decrease in compressive strength with increasing replacement rates. The study highlights the potential of glass powder to enhance the sustainability of SCC while maintaining its performance in specific applications [9]. Similarly, Rasoul et al. investigated the mechanical properties and high-temperature performance of reactive powder concrete containing waste glass powder, showing improved mechanical properties without addressing the spalling issue at high temperatures up to 600°C [10].

The mechanical performance of SCC incorporating glass powder has also been studied using advanced modelling techniques. Aidjouli et al. developed a statistical model using response surface methodology (RSM) to predict the fresh and hardened properties of high-strength SCC containing waste marble and glass powder. This study provides a comprehensive understanding of how different factors influence the performance of SCC and offers a predictive tool for optimizing the mix design [11]. Similarly, Guan et al. used machine learning strategies, such as gene expression programming (GEP) and multi-expression programming (MEP), to analyze the efficacy of waste marble and glass powder in improving the compressive strength of SCC. Their findings indicate that curing time is the most significant factor influencing compressive strength, with an R^2 value of 0.94 for MEP, demonstrating the potential of these materials to enhance the performance of SCC [12].

Despite the promising results, using glass powder in SCC is challenging. The compatibility of glass powder with other components of SCC, such as cement and aggregates, can vary depending on particle size, chemical composition, and replacement percentage. Tariq et al. reported that while glass powder could reduce strength in the short term, it produced comparable strengths in the longer term, with consistent tensile strength and elastic modulus aligning with design guidelines. This suggests that careful consideration must be given to the mix design and curing conditions when incorporating glass powder into SCC [13]. While self compactive concrete (SCC) is fluid, durable, and easy to place, it uses cement and traditional filler materials that are harmful to the environment. WGP can enhance the pozzolanic properties of SCC and reduce environmental impact, but its effect on the mechanical performance and compatibility of high performance SCC remains under studied. While many SCC studies have considered traditional fillers, recycling options such as WGP have been ignored by them. The investigation into SCC made with WGP as a sustainable filler has yet to address its feasibility, performance and applications. To fill this gap, this study explores how WGP filler affects SCC compatibility, mechanical properties and performance. This study compares construction sustainability of control mixtures (traditional fillers) to WGP-containing mixtures.

2. Materials

2.1. Cementitious Materials:

The cement utilized in this investigation was identified as sulfate-resistant Portland cement (Type V) as specified by the ASTM C150. This particular cement is manufactured in Iraq and is commercially known as Al-Mass. Additionally, silica fume was employed in the study, characterized by spherical particles ranging in size from 0.1 μm to 1 μm and possessing a specific surface area of 17,500 cm^2/g . The properties of the silica fume comply with the standards outlined in ASTM C1240-03a. Table 1 presents the chemical and physical characteristics of cement and silica fume.

2.2. Waste Glass Powder (WGP):

The waste glass used in this study was obtained from transparent glass windows. Its chemical composition is indicated in Table 1. The glass powder is prepared by collecting the trash glass from the construction demolition land, cleaning it to be crushed, dry grinding it, and finally milling it using an artificial miller to get the appropriate particle sizes of 460 nm. The particle size analysis was performed using the apparatus BROOKHAVEN 90 Plus. Fig. (1) presents the XRD test results and particle size distribution of WGP.

2.3. Limestone Powder (LP):

Limestone powder is a by-product of the limestone quarry and has been used in cement-based materials for many years. In the present work, locally available limestone obtained from the north of Iraq was used as partial cement replacement materials. Table (1) shows the chemical composition and physical properties of the LP.

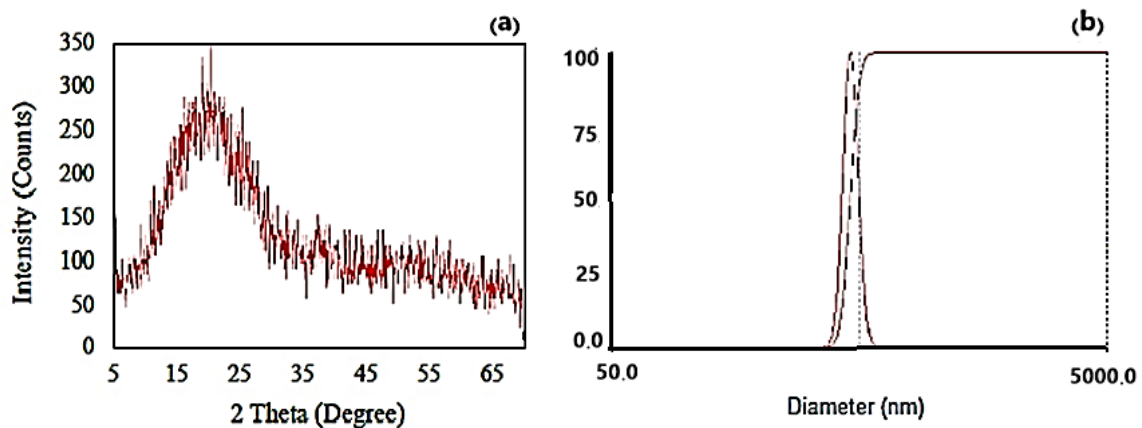


Fig. 1: Waste Glass Powder, (a) X-ray diffraction pattern, and (b) particle size distribution.

Table 1: Chemical and Physical Properties of Cement, Silica Fume, WGP, and LP.

Chemical Composition %				
Composition	Cement Type V	Silica Fume	WGP	LP
SiO ₂	20.9	92	88.26	8.20
Al ₂ O ₃	3.52	0.88	0.16	1.53
CaO	61.15	0.4	9.14	CaO
Fe ₂ O ₃	4.68	1.96	1.104	0.96
MgO	3.21	0.90	2.9	1.27
SO ₃	1.86	0.32	0.058	1.20
Na ₂ O	0.27	---	11.2	0.36
K ₂ O	0.5	0.2	1.316	0.72
Physical properties				
Specific Gravity	3.14	2.32	2.49	

Fineness (m ² /kg)	355	17.200	12.450	
Setting time (min.)	Initial (72) Final (340)			
Compressive strength (N/mm ²)	2-days (28.3) 28-days (51.6)			

2.4. High-range Water Reducer:

In this investigation, it was essential to use a high-range water-reducing admixture, namely a superplasticizer (SP) formulated with modified polycarboxylic ether polymers known as Master Glenium® 54. The primary characteristics observed in the substance were liquid with a hue ranging from white to straw-coloured, a relative density of 1.07, and a pH of 5 to 8. This admixture complies with the ASTM C-494 Type F and G classifications. Its inclusion in the study is due to the low water-to-binder ratio required for the highly-strength self-compacting concrete (HSSCC) being investigated. Superplasticizers (SP) were employed to get the desired consistency of SCC.

2.5. Aggregate

The coarse aggregate in the concrete mixes consisted of crushed stone with a stipulated maximum size of 12.5 mm, whereas river sand was used as the fine aggregate. The fine and coarse aggregates were comfortable to the specifications stated in ASTM C33. The findings of assessing various aggregate properties using the ASTM standard are shown in Table 2.

Table 2: Physical properties of aggregates.

Aggregate type	Fineness modulus	Unit weight (kg/m ³)	Water absorption (%)	Specific gravity (SSD)
Coarse	----	1620	0.64	2.72
Fine	2.68	1740	0.6	2.67

3. Experimental Study

3.1. Waste Glass Powder (WGP) preparation

Transparent recycled window glass was collected from construction demolition garbage and employed in this investigation. The first stage was cleaning and washing the glass pieces and then letting them air dry with time until the water was removed, as presented in Fig. 2-a.

The second stage was grinding these glass pieces with a locally manufactured grinder (see Fig. 2-b), which was a cylinder shape with internal lips and a sealed gate containing two smooth surface rods of 7.5 kg each. In this stage, glass powder can be produced by grinding up to 2.5 mm particle size with a grinding period of 10 min, as shown in Fig. 2-c. After that, a two-blade industrial grinder with a capacity of 250 grammes, as shown in Fig. 2-d, for 75 seconds, was used to obtain glass powder with a particle size of 460 nm, as shown in Fig. 2-e.



Fig. 2: Preparation process of Recycled Glass Powder.

3.2. Mix proportions

Experimental castings were conducted to ascertain the most favorable SCC mixing ratios, following the procedures outlined in the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) guidelines [14].

The distribution of the various compositions is shown in Table 3. This study used several weight replacement percentages to substitute limestone powder with recycled Glass powder (GP). Specifically, the weight replacement percentages utilized were 25%, 50%, 75%, and 100% of the GP by mass.

These respective percentages are called G1, G2, G3, and G4. The concentration of superplasticiser (SP) in each mixture was 2.2% relative to the weight of cementitious materials. The aggregates were thoroughly mixed in a dry setting for one minute. After adding cement and supplementary cementing components, the dry constituents were combined with one-third of the water and stirred for an additional minute. Subsequently, the water and superplasticizer constituting the remaining two-thirds of the combination were included, and the blending process was prolonged for an extra duration of two minutes.

Table 3: Proportion of Mixtures.

Materials (kg/m ³)	Control Mix (C)	25% GP (G1)	50% GP (G2)	75% GP (G3)	100% GP (G4)
Cement	450	450	450	450	450
Silica Fume	45	45	45	45	45
Lime Stone Powder	50	37.5	25	12.5	0
Recycled Glass Powder	---	12.5	25	37.5	50
Fine Aggregate	830	830	830	830	830
Coarse Aggregate	800	800	800	800	800
W/Powder	0.38	0.38	0.38	0.38	0.38
SP	12	12	12	12	12

4. Experimental Tests

4.1. Compatibility Properties (Filling, Passing ability, and segregation resistance)

The traditional fresh properties such as slump flow, T500 time flow, V-funnel, and L-box were investigated as per the specifications of EFNARC [14]. Figure 3 shows the slump flow, L-box, and the V-funnel tests in progress. The tests for fresh properties were conducted soon after the mixing protocol and were performed simultaneously to eliminate the effect of time. The repeatability of fresh properties was performed during the mix design trials. After finalizing the mix, the test was done once to see the direct effect of materials on the fresh properties, not the effect of time.



Fig. 3: Compatibility test progress (a) Slump Flow, (b) T500, (c) V-funnel, and (d) L-Box.

4.2. Mechanical properties

4.2.1. Compressive and Splitting Strength Tests

A 2000 kN compressive testing equipment was used to conduct the compressive and splitting strength tests, as shown in Figure 4-a and 4-b, respectively. The compressive test specimens are 100 mm long cubic, whereas the splitting test specimens are 100 × 200 mm cylinders. The compressive and splitting tensile strengths of concrete were measured per BS EN 12390-3 [15] and ASTM C496-04 [16] at 7, 28, and 91 days after normal curing at 23 °C, as shown in Figure 4-c.

4.2.2. Flexural Strength Test

Prism specimens of 100×100×400 mm were used to assess the flexural strength following the ASTM C78 standard [17]. Each mixture was tested using a universal testing machine capable of exerting a force of 200 kilonewtons. Three prisms were examined at each different ages (7, 28, and 91 days) after standard curing at a temperature of 23 °C. These details are shown in Figure 4-d. The flexural strength is quantified as the rupture modulus (R) using Equation (1).

$$R (MPa) = \frac{PL}{bd^2} \quad (1)$$

where P is the flexure load in (Newton), L is the prism length between two supports in mm, b is the width of the prism section in mm, and d is the depth of the prism section in mm.

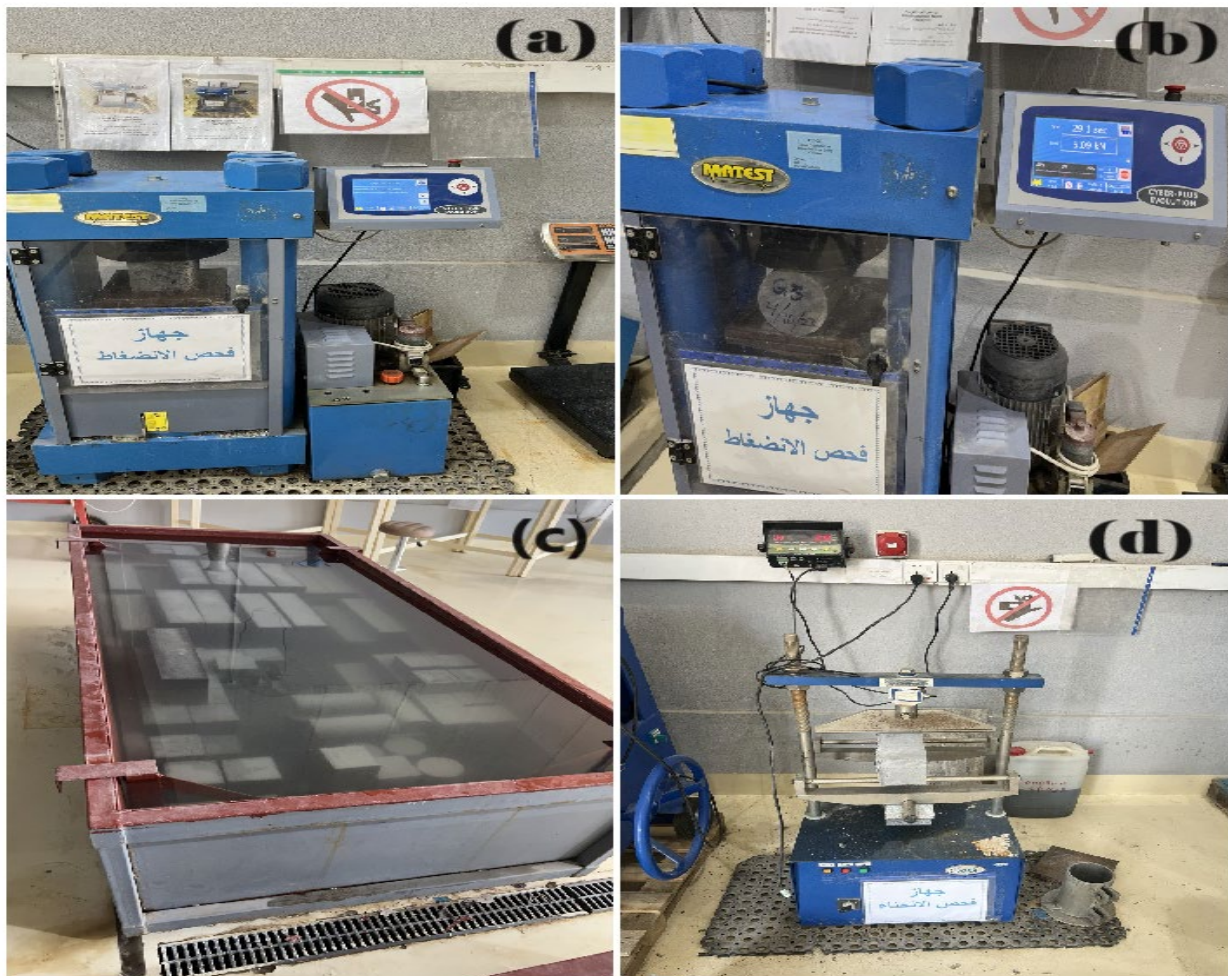


Fig. 4: Mechanical properties (a) compressive strength test, (b) Splitting tensile strength test, (c) curing tank (d) Flexural tensile strength test.

5. Results and Discussion

According to EFNARC requirements, it was observed that the time taken for HSSCC mixes to reach a slump flow diameter of 50 cm, known as T50, fell within an average slump range of 3.4 seconds. This occurred at a diameter of around 700 ± 20 mm, as shown in Table 4. Based on the slump flow test results, it was noted that the width of the slump flow decreased by 7.9%, 6.6%, 9.3%, and 9.9% with the 25%, 50%, 75%, and 100% of GP content increases. According to the EFNARC regulations [18], the trend is considered acceptable at 3 seconds. Moreover, a negative correlation is observed between the increase in GP and the decrease in slump flow time. The extended duration of slump flow may be due to the larger surface area of GP compared to the surface area of cement, which increases the viscosity of the paste.

Table 4 demonstrates the correlation between the replacement ratio of GP and the decrease in V-funnel timings. All mixes complied with the strict EFNARC regulations [14]. The minimum time recorded was 6 seconds. The glass powder's smooth texture enhanced the flowability of the concrete, leading to a smoother and faster flow, which was responsible for the observed performance patterns. The V-funnel results have been confirmed by the research conducted by Md. Munir et al. [19]. Also, it can be observed that there is an increase with the increment of GP instead of LP, leading to an increase in the passing ability of all HSSCC mixes with an upper limitation of EFNARC regulations [20].

Table 4: Compatibility test results were identified by fluctuating the RGP replacement percentage.

Mix ID		Slum flow (mm)	T500 (sec)	V-funnel (sec)	L-box (H2/H1)
C		760	3.4	7.4	0.9
G1		700	3.7	6.6	0.95
G2		710	3.42	6.5	1
G3		690	3.3	6.5	1
G4		685	3.1	6	1
EFNARC requirements	(Min.)	650	2	6	0.8
	(Max.)	800	5	12	1

As can be seen in Fig. 5, it has been found that replacing LP with WGP in different proportions can improve the compatibility characteristics of HSSCC. The mixes containing various replacement percentages of glass powder (GP) were tested for slump flow, V-funnel, and T500. These tests showed that all mixtures (G1, G2, G3, and G4) exhibited the same pattern of compatibility behaviour. Furthermore, the L-box test results showed that all HSSCC had excellent flowability. The behaviour reported was due to the weight difference between glass and cement. When glass is used as a substitute for cement powder, the ratio of solid particles to water rises. This leads to an increase in the inter-particle friction between the cement-glass paste, resulting in a minor performance improvement [21], [22].

Table 5 presents the mechanical properties of various HSSCC mixes. Figure 6 shows the compressive strength values of all HSSCC mixtures that were naturally cured under laboratory temperature and humidity conditions for different time intervals. These mixtures included varied amounts of glass powder.

Table 5: Mechanical Properties of HSSCC at different ages.

Mix ID		Compressive strength (MPa)			Splitting strength (MPa)			Flexural strength (Mpa)			
		7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days	
Control	C	47.0	53.4	58.8	3.29	3.74	4.12	5.17	5.87	6.47	
Recycled Glass Powder	25%	G1	47.6	68.9	75.8	3.33	4.82	5.31	5.24	7.58	8.34
	50%	G2	50.9	74.4	77.6	3.56	5.21	5.43	5.6	8.18	8.54
	75%	G3	46.7	61.7	64.5	3.27	4.32	4.52	5.14	6.79	7.1
	100%	G4	46.8	58	62.5	3.28	4.06	4.38	5.15	6.38	6.88

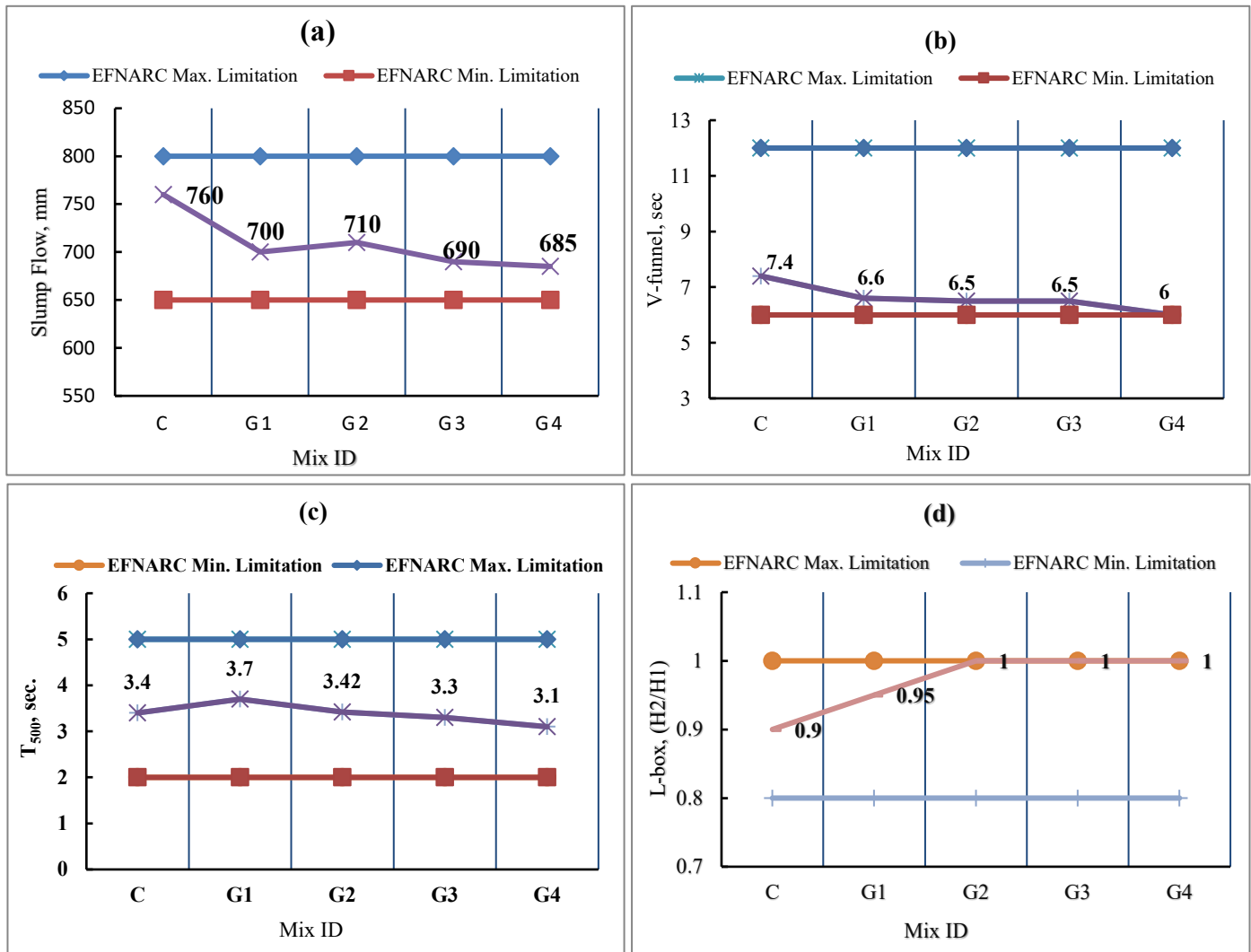
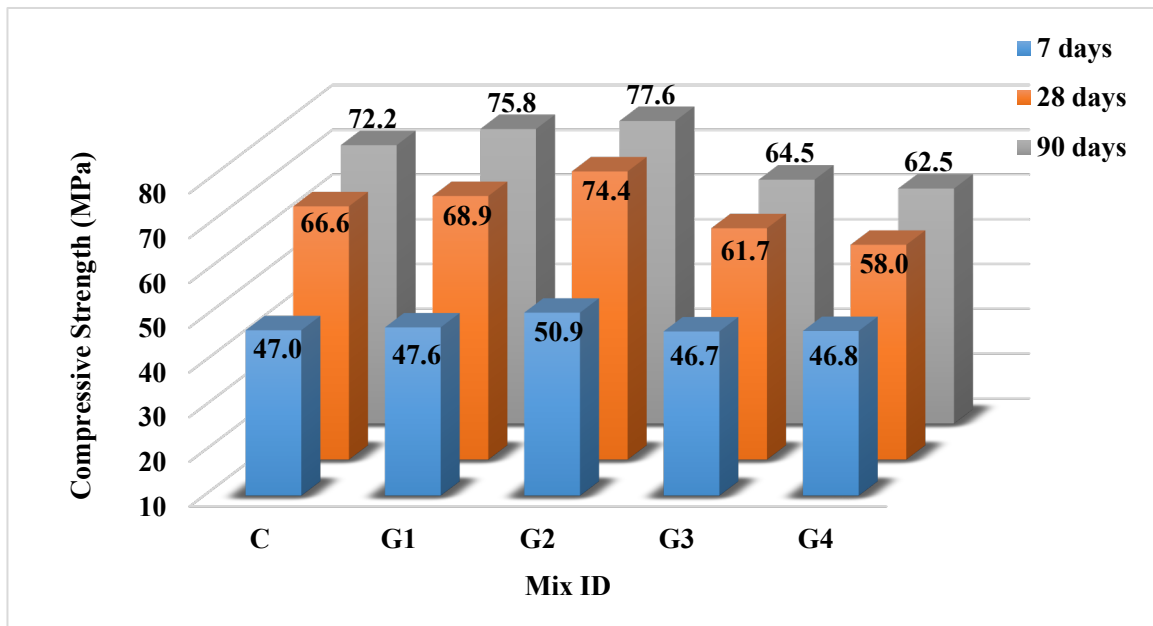


Fig. 5: Compatibility properties results: (a) Slump flow, (b) V-funnel, (c) T500, and (d) L-box.

Replacing LP with 25%, 50%, 75%, and 100% GP resulted in better compressive strength values at 28 and 90 days, as compared to the control mixture. The control mix had a compressive strength of 53.4 Mpa at 28 days and 58.8 Mpa at 90 days. In contrast, the compressive strength values for G2 (50% RGP) were 74.4 Mpa at 28 days and 77.6 Mpa at 90 days. This represents a 39% increase in compressive strength for G2 at 28 days and a 32% increase at 90 days, as compared to the control mix. Therefore, G2 is considered a superior HSSCC mix with glass replacement as compared to the control mix. Furthermore, the compressive strength of all mixtures (G1, G2, G3, and G4) was lower than that of the reference at early stages.

The use of RGP with HSSCC mixes as a replacement for LP can contribute to producing superior mechanical properties of concrete after 90 days. This is due to the pozzolanic interaction between the recycled glass powder (RGP) and the hydrate cement product, which occurs later. The hydraulic interaction between cement and water creates calcium hydroxide (CH), which then reacts with glass powder to form new calcium-silicate-hydrate (C-S-H) compounds. These compounds fill the pores in the concrete, leading to significant improvements in its mechanical properties at a later stage [23], [24], [25], [26].

However, in G3 and G4 (75% and 100% recycled glass powder), the compressive strength drops to 64.5 MPa and 62.5 Mpa after 90 days, respectively. This indicates that unbalanced cementitious materials cannot produce more C-S-H due to insufficient calcium hydrates (CH). As a result, the residual recycled glass powder will agglomerate in a weak form, reducing its compressive strength [27], [28].



Figures 7 and 8 demonstrate the results of the splitting tensile and flexural strengths tests conducted
 Fig. 6: Compressive strength of different GP content at different curing ages.

on the cylinders and prisms, respectively. The findings indicate that mixtures of HSSCC containing up to 50% glass powder exhibit a significant improvement in both splitting and flexural strengths, as compared to the control mixture, after 90 days. The G1, G2, G3, and G4 mixtures showed improvements in splitting tensile strength of 28.8%, 31.8%, 7%, and 6.3%, respectively, when compared to the control mix. Similarly, the G1, G2, G3, and G4 mixes exhibited increases in flexural tensile strengths of 28.9%, 32%, 9.7%, and 6.7%, respectively, compared to the control mix. The inclusion of glass powder enhances the splitting and flexural strength due to its potent pozzolanic reactivity and filler properties. This leads to a reduction in the amount of weak calcium hydroxide and its replacement with C-S-H, a substance with superior strength [29], [30].

When compared to the control mix, G3 and G4 (75% and 100% RGP replacements, respectively) show a decrease in tensile strength, reaching 4.52 MPa and 4.38 MPa at 90 days. The elevated replacement level may compromise the matrix's structural integrity and weaken its tensile strength, rendering it ineffective in preserving its tensile properties [31], [32].

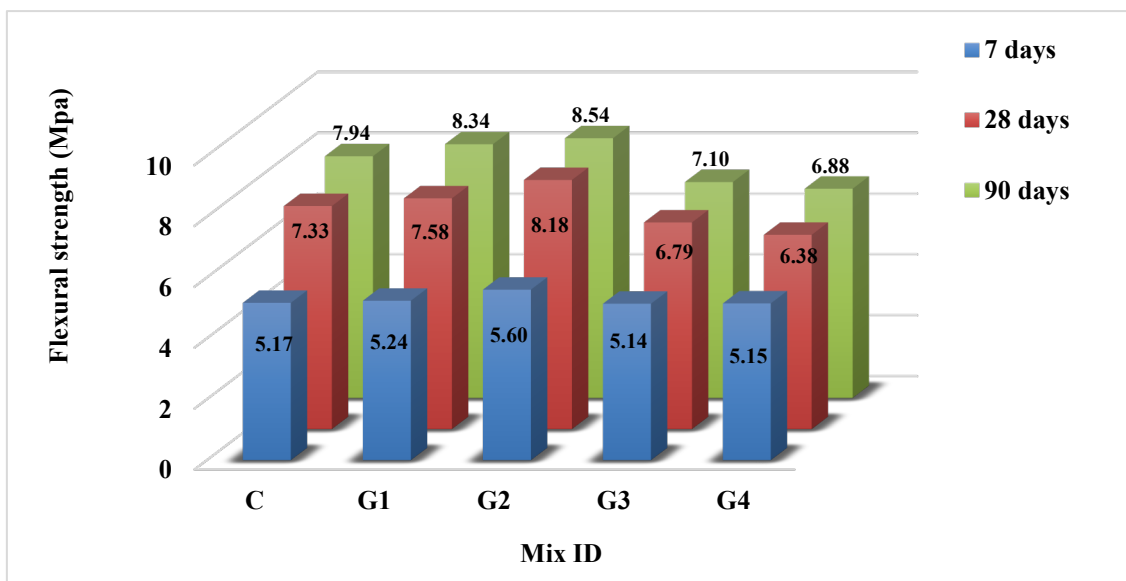


Fig. 7: Flexural strength of different GP content at different curing age.

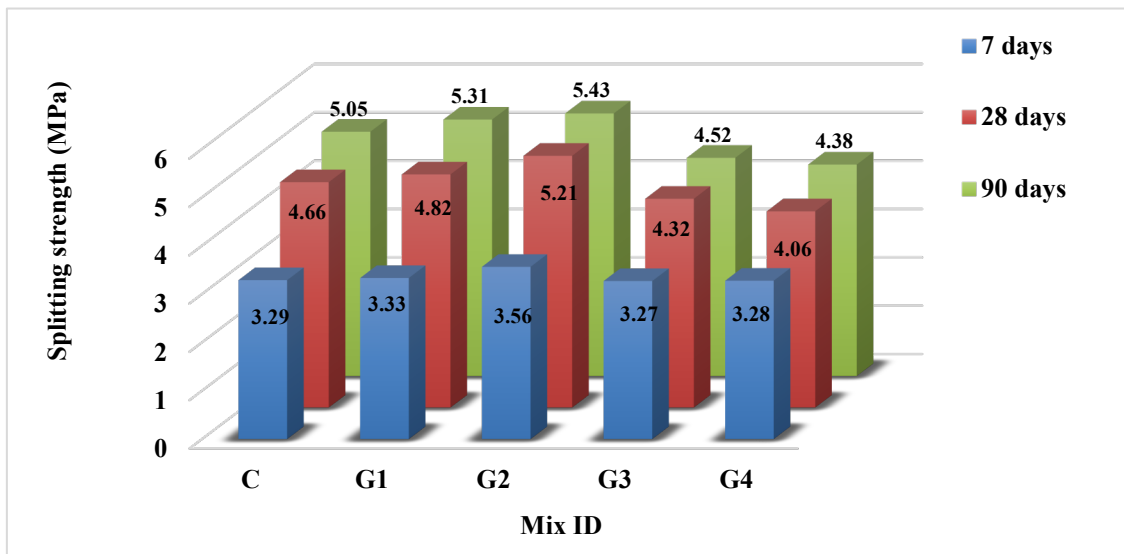


Fig. 8: Splitting strength of different GP content at different curing age.

6. Conclusion

The study explored the feasibility of using waste glass powder (WGP) as a partial replacement for limestone powder in high-strength self-compacting concrete (HSSCC). The research demonstrated that incorporating WGP significantly improves both the fresh and hardened properties of HSSCC. Specifically, a 50% replacement of limestone powder with WGP (labelled as G2) was found to be the most effective, providing the best balance between flowability and mechanical performance. The results showed that the G2 mix's compressive strength increased by 39% at 28 days and 32% at 90 days compared to the control mix.

Additionally, the G2 mix also exhibited enhanced splitting tensile and flexural strengths, demonstrating the potential of WGP to enhance the long-term durability and performance of HSSCC. The pozzolanic activity of the glass powder contributes to the formation of additional calcium-silicate-hydrate (C-S-H) compounds, filling pores and enhancing the microstructure of the concrete over time. In conclusion, using waste glass powder in HSSCC provides a sustainable alternative to traditional materials and enhances the concrete's performance, particularly in terms of mechanical strength and durability. This makes WGP a viable option for sustainable construction practices.

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