Research Article

Samir Saify, Mohammed Sattar Radhi, Samer A. Al-Mashhadi, Basim Mareai, Sarah Fadel Jabr, Zainab Adel Mohammed, Zainab Al-Khafaji* and Fatimah Al-Husseinawi

# Impact of waste materials (glass powder and silica fume) on features of high-strength concrete

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**Abstract:** Pozzolanic materials, glass powder, and silica fume (SF) have all been used in concrete recently as a partial cement substitution to increase the strength of the concrete. The aim of this study is to analyze the impact of waste glass powder (WGP) and SF combination on high-strength concrete (HSC) characteristics. The working methodology of the current research consists of using SF passed through sieve No. 200, and WGP particles that passed through sieve No. 400 (particle size less than 38 μm), maximum size of aggregate (14, 20) mm and W/C + p (0.25, 0.35, and 0.45). The used waste materials were in three different amounts of SF and WGP (5, 10, and 15%) by weight of cement. HSC was tested for compressive strength, density, and ultrasonic pulse velocity (UPV) with various glass powder and SF contents. The obtained results show that after 7 and 28 days, concrete specimens containing 15% glass powder and SF demonstrated an increase in density, UPV, and compressive strength, depending on the test results. Conversely, concrete specimens with 5% SF and WGP had decreased compressive strength, UPV, and density. It was detected that WGP gave high mechanical (compressive strength) and physical properties (density and UPV) than SF with a ratio of 15% and lower properties with a ratio of 5%. In HSC manufacturing, glass powder may be used instead of SF.

**Keywords:** SF, WGP, HSC, UPV, compressive strength, and density.

*** Corresponding author: Zainab Al-Khafaji**, Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia; Building and Construction Engineering Technology Department, Al-Mustaqbal University College, Hillah 51001, Iraq, e-mail: zainabcivil90@gmail.com
**Samir Saify:** College of Engineering, University of Babylon, Babylon, Iraq, e-mail: samirsaify@uobabylon.edu.iq
**Mohammed Sattar Radhi:** Ceramic and Building Materials Department, College of Materials Engineering, University of Babylon, Babylon, Iraq, e-mail: mat.mohammed.sattar@uobabylon.edu.iq
**Samer A. Al-Mashhadi:** College of Engineering, University of Babylon, Babylon, Iraq, e-mail: eng.samerabdul@uobabylon.edu.iq
**Basim Mareai:** Scientific Research Center, Al-Ayen University, Thi-Qar, Iraq
**Sarah Fadel Jabr:** Civil Engineering Department, Babel Tower for Studies and Scientific Research com, Babylon, Iraq, e-mail: sara.fadeljaber97@gmail.com
**Zainab Adel Mohammed:** Civil Engineering Department, Babel Tower for Studies and Scientific Research com, Babylon, Iraq, e-mail: zoozadil97@gmail.com
**Fatimah Al-Husseinawi:** Department of Design, Al-Turath University College, Baghdad, Iraq

## 1 Introduction

The main environmental concerns brought on by releasing carbon dioxide ($CO_2$) were climate change and global warming [1–3]. A considerable portion of $CO_2$ emissions is caused by the building industry, which negatively influences the environment [4,5]. Studies from the past suggest that cement production emits 522 million metric tons of $CO_2$, or around 0.8 tons of $CO_2$ each ton of cement produced [6]. With an annual growth rate of 2.5% and a total output of 4.6 billion tons in 2015 [7], cement production is accelerating rapidly worldwide. The "Getting the Numbers Right" project, run by the International Council for Sustainable Development and its sustainability initiative, offers a $CO_2$ and energy performance database. Researchers from all around the globe are always searching for a new material that might either completely or partly replace cement [8]. Throughout the past 10 years, attention has been focused on using supplemental cementitious materials, including silica fume (SF), rice husk ash, metakaolin, ground granulated blast-furnace slag, and fly ash, as cement replacements [9–11]. Additional cementitious components react in pore solution by hydrating cement hydraulically or pozzolanic ally [12]. In the United States, cementitious elements are typically added during concrete manufacturing; ready-mixed plants use 60% of supplemental cementitious materials [13]. The reactivity of additives or pozzolans is often lower than that of cement; hence, using supplemental cementitious materials has drawbacks [14,15]. Recent studies revealed that the two most often used supplemental cementitious materials worldwide – fly ash, with an annual output of one billion tons, and ground-

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granulated blast-furnace slag, with a yearly production of 360 billion tons – can only partially meet expanding demand. Finding other materials that might be used instead of cement has thus become a need on a worldwide scale [13].

Even when used as a fine aggregate in white cement mortars [16], waste glass powder (WGP) as an active additive to concrete has been proven in prior works to have positive environmental and economic effects [17]. Glass was used as an additional cementitious material in numerous other studies [18–20], but most of them suggested using 10–20 wt% WGP as a cement substitution with a steady decline in compressive strength. However, Carsana [21] found that mortars of ground glass submerged in water for 7 years had not degraded and had higher compressive strengths. Glass has a significant alkali content. Still, according to the study by Schwarz [22], it only discharged a little sodium into the pore solution, making it a safer addition.

The outcomes of three concrete mixtures, namely, SF, fly ash, and ordinary Portland cement (OPC), were reported by Ibrahim [23]. WGP was substituted for 0, 5, 10, 15, and 20% of the cement in the three mixtures. The findings of tests demonstrated that WGP might partly substitute OPC in concrete with tensile and compressive strengths higher than fly-ash- and silica-fume-based concrete when used up to 5 wt%. The compressive and tensile strengths might also be reduced by 13–14%, respectively, with a greater substitution of up to 20 wt% WGP. Notwithstanding the aforementioned results, there are certain drawbacks to using glass in concrete, including low early strength that might be problematic, particularly when early formwork stripping is necessary for building practice [24].

SF is a waste material produced due to ferrosilicon alloy and silicon manufacturing. Environmental solid waste that includes approximately 75% silica [25,26] has contributed to the strength and minimized the bleeding and permeability of concrete owing to its pozzolanic impacts [27–29]. It, nonetheless, has certain drawbacks, including reducing the setting time and workability [30,31] of the concrete mix [32], once the necessary amount is not used. The amount of SF for an efficient performance is stated to be in the range of 10–15 wt% [33]. WGP may be contributed to the concrete mix consistency [34], owing to its glassy surface with minimal water absorption. SF and glass waste up to 10–25 wt% were separately stated to contribute to compressive strength over a time beyond 90 days [20]. Rakhimova and Rakhimov [35] examined glass compositions with a noticeable improvement in workability (flowability) and a reduction in setting time. A similar discovery was observed by Rahma et al. [36], while Sadati and Khayat [37] found a drop in structural networks build-up from (0.118333–0.0133333 Pa/s) 7.1 to 0.8 Pa/min with a rise in viscosity from 0.118 to 0.013 Pa/s. A further advantage of using glass waste was also gained when using cullet glass waste as a replacement for natural sand throughout the synthesis of an alkaline binder by using fly ash and ground granulated blast furnace slag as precursors. Good findings of durability performance have also been obtained for substitute for sand by glass waste at the level of 25–100 wt% within the temperature range of 200–800°C [38,39].

To enhance the compressive strength of concrete, the incorporation of supplementary cementitious materials such as SF has been widely adopted. SF can be used as a filler or as a partial substitute for cement in concrete. The addition of SF has been found to enhance the strength characteristics of concrete; however, a marginal reduction in its workability was noted in a research investigation. The study found that the substitution of SF at levels ranging from 0 to 15% in m25 concrete did not significantly affect the elastic modulus. The observed enhancement in concrete strength can be attributed to a reduction in voids, while the decrease in slump value can be explained by an increase in surface area, which results in greater water absorption during the mixing process [40]. In a comparable manner, the use of WGP in concrete was partially substituted with cement, ranging from 0 to 25% replacement, while maintaining an identical water/cement ratio. At the 90-day mark, there was an observed increase in compressive strength when 10% of cement was replaced with glass powder. The study reported an upward trend in the observed values up to a 20% substitution, followed by a decline thereafter, as indicated [41]. Grinys et al. conducted a study on rubberized concrete that was modified with WGP. Their findings indicated a notable enhancement in the properties of the concrete. The pozzolanic properties of the glass powder exhibited superior performance during the latter phase as compared to the 28th day. According to Grinys [41], the cement is activated by the glass powder, which facilitates the continuation of the hydration process into subsequent stages and ultimately contributes to the attainment of greater strength. Due to its high silica dioxide content, glass powder exhibits pozzolanic properties. The compressive strength of concrete containing glass powder exhibits a decrease during the early stages of curing, followed by an increase in strength during later stages. This phenomenon can be attributed to the pozzolanic activity of glass powder, which becomes more pronounced over time. A decrease in unit weight is observed because of a lower specific gravity in comparison with cement, as reported in Khan et al. [42]. An experimental investigation was carried out by Manikandan and Vasugi [43] to examine the effects of incorporating 25–40% WGP into ground granulated blast furnace slag, in combination with metakaolin, on the mechanical and fresh properties of the resultant concrete. The study found that the ideal substitution rate for WGP was 35%. Nevertheless, the augmentation in the concentration of WGP results in a reduction of the mechanical characteristics.

Regarding the advantages and disadvantages of using SF and glass waste separately, there is little information in the literature on how combining the two substances might affect how the binder is created with regular Portland cement in ternary mixed concrete. To better understand their synergy in concrete manufacturing, this research tries to close this gap. The aim of this research is to open the possibility of using inorganic solid wastes in mortar and concrete manufacturing more often. The current investigation compares how WGP and SF affect high-strength concrete (HSC). Also, this investigation analyze the impact of WGP on the mechanical and physical characteristics of HSC.

# 2 Experimental work

## 2.1 Materials

### 2.1.1 Cement

Commercially available OPC, confirming to ISO 9001:2015, was used in the mixes. The chemical and physical characteristics of OPC are displayed in Table 1.

### 2.1.2 Fine aggregate

Locally available natural sand is applied as fine aggregate conforming to the requirements of No [44]. The fine modulus of 2.42 sulfate content is 0.1% with a density of fine aggregate of 1,600 kg/m$^3$. The grading of fine aggregate is demonstrated in Table 2.

**Table 1:** Physical and chemical characteristics of cement

| Test name | Contents (by wt%) |
|---|---|
| Specific surface (m$^2$/kg) | 310 |
| Specific gravity | 3.15 |
| $SiO_2$ | 20.39 |
| CaO | 62.20 |
| MgO | 2.36 |
| L.O.I | 2.41 |
| $Fe_2O_3$ | 3.81 |
| $SO_3$ | 1.97 |
| $Al_2O_3$ | 4.55 |

**Table 2:** Fine aggregate grading

| Sieve size (mm) | Percent passing (%) |
|---|---|
| 10 | 100 |
| 4.75 | 93.5 |
| 2.36 | 84 |
| 1.18 | 75.5 |
| 0.6 | 50 |
| 0.3 | 20 |
| 0.15 | 4 |

### 2.1.3 Coarse aggregate

The coarse aggregate used was crushed gravel with maximum sizes (14, 20 mm), and with a sulfate content of 0.08%, with a density of coarse aggregate of 1,600 kg/m$^3$. It conforms to the requirements of ASTM 33 [45]. The grading of coarse aggregate is demonstrated in Table 3 (Figures 1 and 2).

### 2.1.4 SF

The SF was German production in powder form, with a $SiO_2$ content of 90%, a loss density of 1.1 g/cm$^3$, a compacted density of 1.6 g/cm$^3$, and a specific gravity of 2.28. It passed sieve No. 200 and the rest of sieve No. 400. It is a light to dark gray, as demonstrated in Figure 3, and Figure 4(a) shows the scanning electron microscope (SEM) images for SF that is used in this study.

### 2.1.5 WGP

Waste glass is available locally, and it was collected, washed, crushed, and milled with small milling for 10 min, resulting in particle size less than 38 μm, and the passed sieved No. 400 was used. The loss density of WGP is 0.91 g/cm$^3$, a compacted density is 1.33 g/cm$^3$, and specific gravity is 2.22. The chemical composition of WGP and the small mill is

**Table 3:** Grading of coarse aggregate for a different size

| Sieve size (mm) | Particle size (20 mm) | Particle size (14 mm) |
|---|---|---|
| 25 | 100 | — |
| 19 | 95 | 100 |
| 12.5 | 60 | 95 |
| 9.5 | 37.5 | 55 |
| 4.75 | 5 | 7.5 |
| 2.36 | 2.5 | 2.5 |
| 1.18 | 0 | 0 |

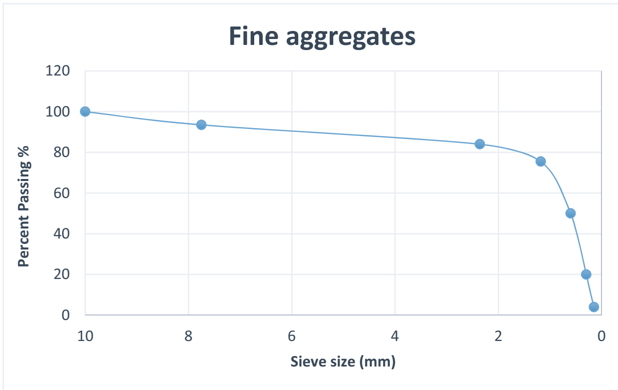



**Figure 1:** Fine aggregate grading.

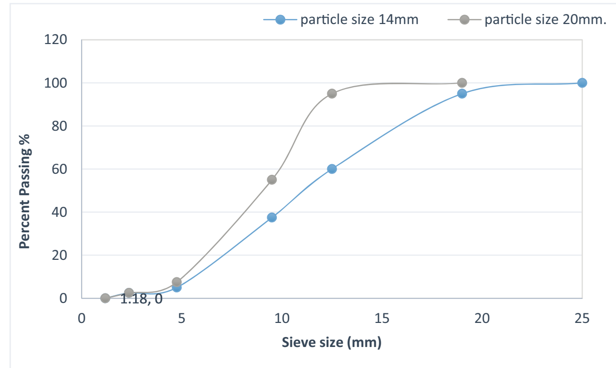



**Figure 2:** Coarse aggregate grading.

demonstrated in Table 4, and Figure 3(a) and (b) and Figure 4(b) show the SEM images for WGP that are used in this study.

Superplasticizer: Euniflow 612i was used in mixes. It was produced in a light brown color in Germany; the properties of the superplasticizer are demonstrated in Table 5 and Figure 4.

### 2.1.6 Water

It was distilled water used through this work for both mixing and curing.

## 2.2 Mixing procedure

Two blends were designed to produce HSC using SF and WGP, according to research by Samir A. Al Mashhad and Dalya Hekmat Hameed [46]. In one blend, concrete prepared with mixed cement was replaced with SF (A, B, and C); in the other, concrete was prepared with WGP instead of SF (A1, B1, and C1). It used three ratios of 5, 10, and 15% by weight of cement with W\C + P for two blends (0.45, 0.35, and 0.25), respectively. The slump was in the range of 5, 10, and 15 mm for SF mix and 1, 5, and 10 mm for waste glass mix. The laboratory mixing procedure was the cement mixed with SF by hand until a homogeneous mixture was obtained. The dry materials (fine and coarse aggregate) were mixed using a portable cement mixer with a drum capacity of 140 L. Then, water and plasticizer were added for 4 min. Cubes with size 100 mm × 100 mm × 100 mm were used for the compressive strength test. The molds were cleaned and lubricated for test specimens before being used to create test specimens. Two layers of concrete were formed in molds, and each layer was

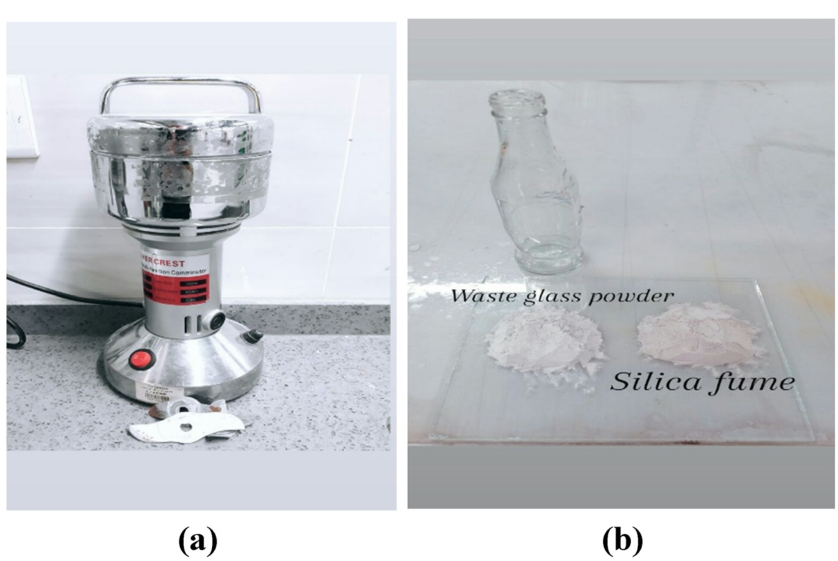
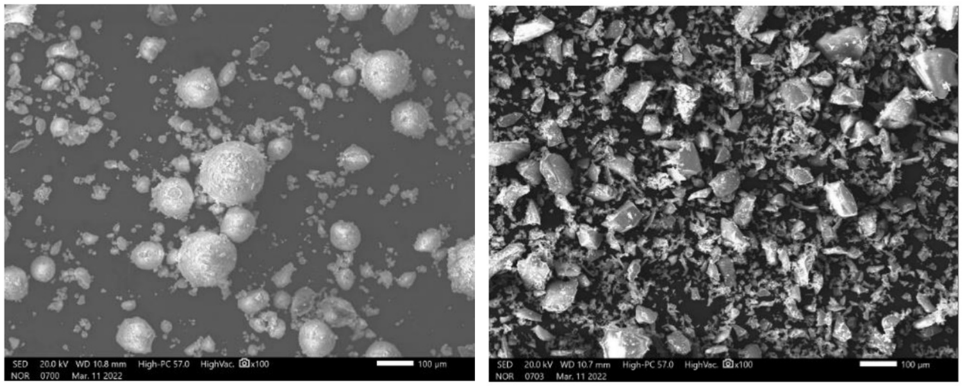



**Figure 3:** (a) Small mill and (b) WGP and SF.



(a) (b)

**Figure 4:** SEM images for (a) SF and (b) glass powder waste.

**Table 4:** Chemical composition of WGP

| Composition | Glass powder (%) |
|---|---|
| $SiO_2$ | 73.6 |
| CaO | 8.04 |
| $SO_3$ | 0.23 |
| $Na_2O$ | 12.6 |
| MgO | 2.78 |
| $K_2O$ | 0.3 |
| $Fe_2O_3$ | 0.7 |
| $Cr_2O_3$ | 0.04 |
| $TiO_2$ | 0.025 |
| $AL_2O_3$ | 1.4 |

crushed with a tamping rod to release any trapped air. The samples were covered with nylon sheets to stop water evaporation for 1 day after the concrete surface had been troweled into a smooth finish. On the second day, the samples were opened and placed in a water tank for curing to the day of testing after 7 and 28 days. In total, 18 cubes were examined for compressive strength and density at 7 and 28 days, while ultrasonic pulse velocity (UPV) was tested at 28 days. The information on the concrete mix types and designations is presented in Table 6 and Figure 5.

# 3 Testing of concrete specimens

## 3.1 Compressive strength test

The compressive strength test has been performed depending on B.S: 1881 [47]. It used a machine of 2,000 kN maximum capacity, as demonstrated in Figure 6.

## 3.2 UPV

The UPV was measured using Pundit Lab+ according to BS:12504 [36] requirements for HSC. It had a bandwidth

**Table 5:** Typical properties of EU NIFLOW 612i

| Properties* | Value |
|---|---|
| Addition rate range | 1 – 3 L per 100 kg cement (1.0–3%) v/w by weight of cement |
| Appearance | Light brown |
| Specific gravity | 1.09 ± 0.02 at 20®C |

*From the catalog of manufacture.

**Table 6:** Proportion of mixtures

| Mix symbol | Cement ($kg/m^3$) | SF ($kg/m^3$) | WGP ($kg/m^3$) | Sand ($kg/m^3$) | Gravel ($kg/m^3$) | Water ($kg/m^3$) | HRWR ($L/m^3$) | HRWR (wt% of cementitious) | W/C + p |
|---|---|---|---|---|---|---|---|---|---|
| A | 442 | 78 (15%) | | 665.6 | 1,144 | 130.0 | 10.30 | 1.5 | 0.25 |
| B | 468 | 52 (10%) | | 665.6 | 1,144 | 182.8 | 2.29 | 0.4 | 0.35 |
| C | 494 | 26 (5%) | | 665.6 | 1,144 | 234.0 | 0.57 | 0.1 | 0.45 |
| A1 | 442 | | 78 (15%) | 665.6 | 1,144 | 130.0 | 10.30 | 1.8 | 0.25 |
| B1 | 468 | | 52 (10%) | 665.6 | 1,144 | 182.8 | 2.29 | 0.4 | 0.35 |
| C1 | 494 | | 26 (5%) | 665.6 | 1,144 | 234.0 | 0.57 | 0.1 | 0.45 |

Where (A, B, and C) concrete is prepared by mix cement replaced with SF (A1, B1, and C1). Concrete is prepared by WGP.


**Figure 5:** EUNIFLOW 612i.

between 24 and 500 Hz [48]. The UPV (Pundit Lab+) is demonstrated in Figure 7.

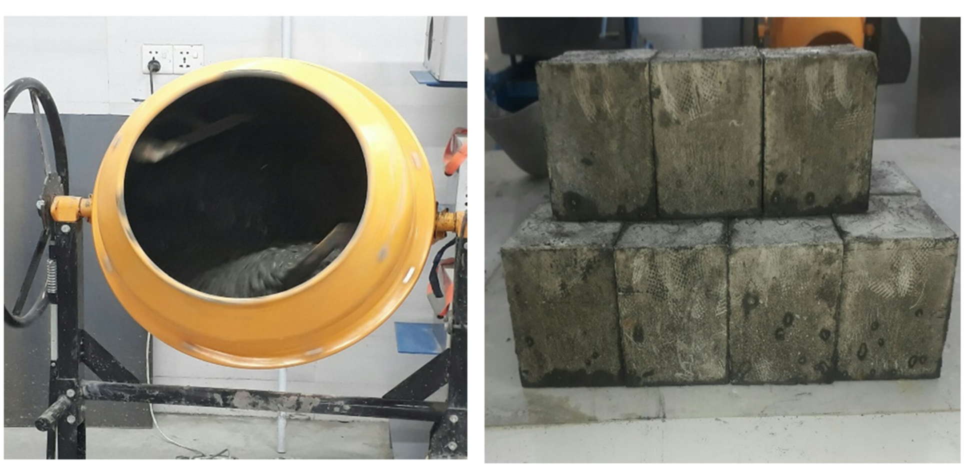
## 4 Results and discussion

The influence of SF and WGP on features of concrete, including compressive strength, UPV, and density, are demonstrated in Figures 8–11.

Figure 8 shows that compressive strength increased with different cement replacements by SF and WGP of 5, 10, and 15% by weight of cement. When there was a substitution of cement with SF with 5, 10, and 15%, the compressive strength was 43, 52, and 73.5 MPa after 7 days and was 52, 60, and 84 MPa, respectively, after 28 days. When

**Figure 7:** Compressive strength machine.

**Figure 8:** UPV (Pundit Lab+).



(a) (b)

**Figure 6:** (a) Portable cement mixer and (b) different specimen cubes.

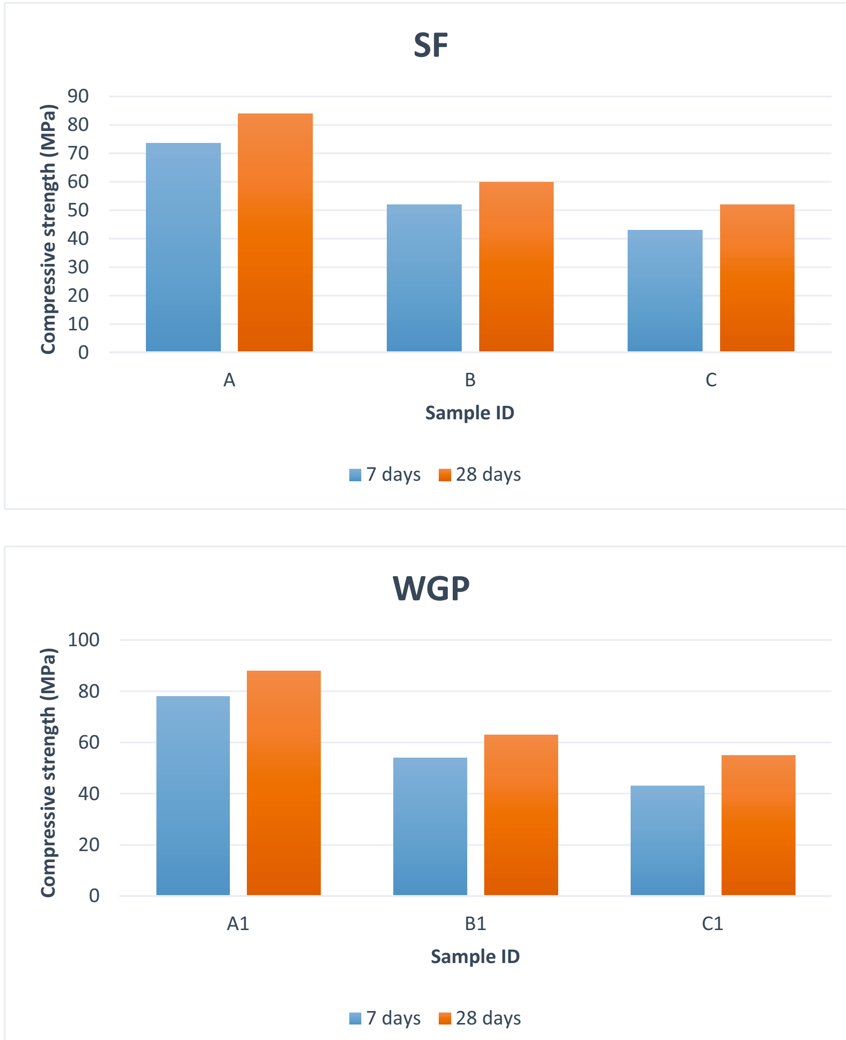



**Figure 9:** Compressive strength for various replacement materials and ratios.

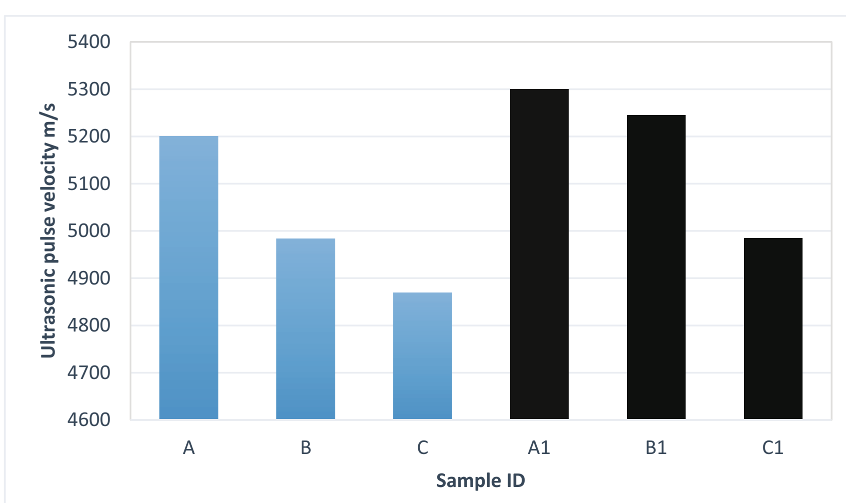



**Figure 10:** UPV for different replacement materials and ratios.

replacing SF with WGP with 5, 10, and 15%, the compressive strength was 43, 54, and 78 MPa after 7 days and 55, 63, and 88 MPa, respectively, after 28 days. The maximum magnitudes of compressive strength were found at 15% during the replacement of cement with WGP instead of SF. The WGP gave the higher values of compressive strength than the SF after 7 and 28 days, which might result from the WGP pozzolanic materials' high activity being the cause of the increased compressive strength of concrete. Additionally, the silica present in WGP reacted with calcium hydrate formed throughout the hydration process to form calcium silicate hydrate gel, which provides additional binding characteristics and contributes to the increased compressive strength of concrete [49].

The UPV in HSC was detected after 28 days of curing values in concrete samples having 5, 10, and 15% SF was 4,870, 4,984, and 5,200 m/s, respectively, while concrete specimens containing WGP (5, 10, and 15%) were 4,984, 5,245, and 5,300 m/s, as demonstrated in Figure 9. The UPV increased in concrete specimens containing 15% of WGP and SF, while 5% in concrete specimens containing WGP and SF caused UPV values to decrease.

Impact of replacing WGP and SF cement by on the density of concrete after replacement of SF with 5, 10, and 15%, the density values were found 2,395, 2,388, and 2,440 kg/m$^3$ at 7 days, while at 28 days, the density was 2,390, 2,432, and 2,456 kg/m$^3$ respectively; however, during the replacement of SF by WGP with 5, 10, and 15%, the density values were 2,375, 2,420, and 2,489 kg/m$^3$ after 7 days and 2,422, 2,455, and 2,481 kg/m$^3$ after 28 days, as demonstrated in Figure 10. Adesina and Das [50] discovered that the substitution of 25% fly ash with glass powder improved the performance of designed cementitious composite mixes using glass powder, reducing concrete voids and improving concrete density.


**Figure 11:** Density for different replacement materials and ratios.

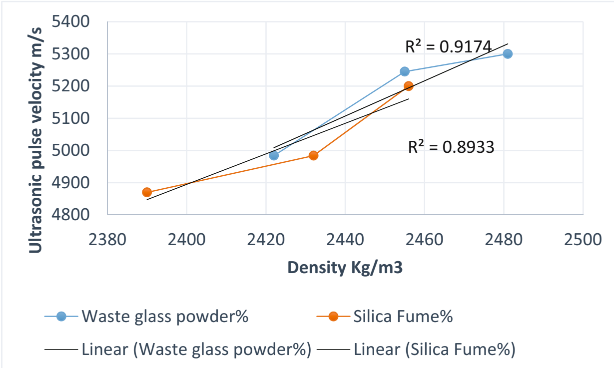



**Figure 12:** Relationship between UPV and density for different replacement materials and ratios.

When 15% cement was changed with WGP instead of SF, the density and UPV values rose. Nonetheless, the WGP provided greater values than the SF because the WGP was finer than the SF and had high activity led to fill the gaps, increasing both UPV and leading to denser concrete, as seen in Figure 10. Figure 11 demonstrates the relationship between UPV and density after using different replacement ratios of both SF and WGP; however, WGP gives higher density and UPV comparison with similar replacement ratios of SF. Based on Aldeeky and Al Hattamleh [51], there is a good coefficient of correlation (ranged 0.832 and 0.929) between UPV and dry density, where in current research the authors obtained similar coefficients of correlation range (Figure 12).

## 5 Conclusion

To enhance the development sustainability goals, most of industrial wastes have been reused or recycled based on the composite of the selected materials; in the current study, glass powder and SF waste were recycled to improve the concrete strength. Depending on the findings of the experimental work of this research, it has been reached:

The highest compressive strength values were discovered when cement was replaced with 15% SF and SF was replaced with WGP. After 7 and 28 days, the compressive strength was 78 and 88 MPa, respectively. UPV values in concrete specimens containing 15% powder glass, on the other hand, are higher than in specimens containing 15% SF. However, 5% WGP in the concrete mix reduced UPV readings.

The density values increased as the percentage of WGP in the mix increased, with up to 15% of the WGP instead of SF. The density level was 2,482 and 2,481 kg/m$^3$ after 7 and 28 days, respectively. Partial replacement of SF with WGP at a ratio of 15% was observed. Therefore, WGP gave higher mechanical (compressive strength) and physical properties (density and UPV) than SF with a ratio of 15% and lower properties with a ratio of 5%. WGP can be used instead of SF in HSC production.

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**Conflict of interest:** The authors state no conflict of interest.

**Data availability statement:** Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on a reasonable request from the corresponding author with the attached information.

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