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# Contribution to the reinforcement of cement composites using aggregates from industrial windshield waste

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**Abstract:**

The excessive extraction of raw materials for aggregate and cement production for developing sustainable concrete results in significant environmental issues. Automotive windshield waste (WGA) is increasing daily, contributing significantly to landfills due to a rapidly growing population and limited recycling options. This research investigates the use of WGA as a substitute for fine aggregates combined with blast furnace slag (BFS) as a filler to produce a new eco-friendly self-compacting sand concrete (SCSC). For this, eleven SCSC mixtures were prepared at a constant cement and BFS content of 400 kg/m$^3$ and 200 kg/m$^3$, respectively. The water-to-powder ratio was kept constant at 0.44. The superplasticizer-to-cement ratio was selected for each mix to improve the fresh SCSC flowability and homogeneity. The sand was substituted in volume with the WGA at a proportion of 10 to 100% with a step of 10%. The obtained results show the feasibility of producing high-performance SCSC by completely replacing natural sand with WGA, without impairing the concrete's workability, mechanical, and durability properties. SCSC with 20% WGA substitution was found to be optimum with compressive and flexural strength 80% and 50% higher than the reference concrete, respectively. Furthermore, the use of up to 100% WGA showed high-quality concrete with more than 80 MPa compressive strengths, a significant reduction in water absorption and porosity, a denser microstructure, and a stronger interfacial transition zone (ITZ).

**Keywords:**
self-compacting sand concrete, windshield waste, mechanical properties, durability

## 1. Introduction

As concrete production and usage expand, the demand for natural aggregates, constituting 70–80% of the total volume of concrete mix designs, is rapidly increasing. Preserving natural aggregates while producing concrete poses a significant challenge in this scenario. Furthermore, reducing reliance on natural resources for creating aggregates for construction and minimizing the space required for landfill disposal of solid waste necessitates exploring innovative solutions to address these concerns within structural frameworks [1-6]. Glass waste (WG) is a part of municipal solid waste that is available in significant quantities. It constitutes approximately 7% of the total global solid waste [7-9]. Furthermore, approximately 200 million tons of WG were produced annually, with a recycling rate less than 30% [7,10-13]. The United States Environmental Protection Agency (EPA) reports that 7.6 million tons of waste glass were dumped in landfills in 2018, accounting for 5.2% of all municipal solid waste that year [14]. As a non-biodegradable material, its accumulation poses significant environmental risks, leading to high landfill volumes. Hence, repurposing it into value-added products as a sustainable, partial replacement for cement or aggregate in concrete reduces the necessity for landfilling and enhances sustainability within the industrial sector.

Building materials researchers engage in recycling various types of waste glass (WGs), encompassing window glass, lamp glass, and cathode ray tube glass, as well as packaging and bottle glass [15-17]. Nonetheless, the recycling of WG from damaged or end-of-life vehicles (ELV) has received scant attention from researchers. Glass waste, commonly referred to as "windshield glass" in the automotive industry, remains largely untapped. Windshield glass comprises laminated glass composed of two or more flat glass layers bonded by polyvinyl butyral organic polymer (PVB). This construction renders it challenging to fully separate the glass from the PVB, severely limiting its recyclability post-useful life [18,19]. Consequently, vehicle glass waste often ends up in landfills, contributing to a more intricate disposal process than traditional waste glass [20]. However, landfilling poses increasing challenges due to dwindling sites and the non-biodegradable nature of waste glass, rendering it an unsustainable and environmentally unfavorable option. Glass takes millions of years to degrade naturally [21]. Additionally, there are currently 1.2 billion automobiles globally, a number projected to exceed 2 billion by 2040 as it continues to rise [22]. Hence, there is an urgent need to recycle and use this waste.

In several research studies, waste glass (WG) has been used as a cementitious material (SCM) or to partially replace fine aggregates in both concrete and mortar [17,18,23-26]. The previous investigations on the effect of WG aggregates on concrete properties have revealed two contrasting viewpoints regarding workability and mechanical strength. It is clear from various research that the smooth surface of WG decreases its cohesion with the cement paste, thus enhancing the concrete workability [21,23,27]. On the contrary, certain studies have indicated that WG reduced concrete workability. This decrease has been linked to the angular shape, sharp edges, and larger aspect ratio of glass particles, which impede the mobility of cementitious mixtures [28-30]. Arabi et al. [31] found that substituting recycled coarse aggregate (RCA) volume with recycled glass aggregate (RGA) in self-compacting concrete (SCC) reduced its flowability but still met acceptable performance parameters for practical applications. For the mechanical performance, Khan and Sarker [23] found that compressive strength decreased from 77 MPa to 73 MPa at 90 days of age by totally replacing (100%) natural sand with WG compared to reference mixes. However, the porosity increased from 1.5% to 13% for replacing ratios between 25% and 100% WG. Tan and Du [32] found that mortars incorporating 25–100% green glass fine aggregate exhibited approximately 20–25% higher compressive strength and 7–16% higher tensile strength. Consequently, mortars containing green glass displayed superior mechanical properties compared to those with clear glass, even when the percentages were the same. Benli [33] found a 71.4% increase in the compressive strength of alkali-activated foam concrete (AAFC) by replacing 50% of river sand with waste glass sand. Harrison et al. [34] found similar mechanical strength to reference concrete by using up to 20% waste glass as fine aggregate replacement. However, the GW tends to lose its surface adhesion with cement paste when used as coarse aggregate. According to Sahani et al. [28], the level of replacement of glass powders with fine aggregate was optimum at 20% replacement level, with an enhancement in compressive, split tensile, and flexural strengths by 10–25%. Park et al. [26] also found a decline in concrete's compressive and tensile strengths for a WG replacement level of up to 70%. However, they discovered that the strength development of concrete incorporating various colored glass fine particles was not significantly affected by the color of the glass. Similarly, Ling and Poon [27] found a decrease in mortar strength with an increasing amount of cathode ray tube glass replacement as fine aggregate. Lee et al. [35] discovered that the compressive strength of mortar improved at 28 days with the addition of very fine glass particles (glass sand). Ismail and Al-Hashmi [36] and Zaetang et al. [37] demonstrated that the ideal replacement of natural sand with fine recycled GW to achieve high concrete properties was 20% and 40%, respectively. Seeboo et al. [38] also proved that the use of GW as fine aggregates can be successfully used for up to 20% replacement for precast pedestrian slabs. On the other hand, it is shown that GW powder can serve as a siliceous raw material with excellent pozzolanic properties and can be substituted for cement in mortar or concrete to enhance durability and mechanical properties, typically between 10 to 25% [39-44]. Gebremichael et al. [45] discovered that it is practical to produce concrete with acceptable fresh, hardened, and durability properties by replacing cement, fine aggregate, and coarse aggregate with an optimum of 10%, 15%, and 20% of crushed and ground waste glass, respectively. According to Yan et al. [46], adding WG to UHPC increased its flowability and decreased its early-age mechanical characteristics while greatly enhancing its later-age mechanical characteristics. The 28-day compressive strength rises by 8.6% when the WG concentration is 20%.

Self-compacting sand concrete (SCSC) is a category of cement concrete that offers a solution to mitigate the financial challenges associated with using coarse aggregates [47-50]. This concrete provides innovative solutions for the construction industry due to its effectiveness and adaptability in different applications, such as deep foundation construction, soil grouting, and concrete restoration [51]. Typically, SCSC is composed of sand, cement, water, one or more admixtures, and additives. The ability of SCSC to self-compact offers significant advantages, especially when filling intricate forms in coatings and formworks. Fresh concrete must possess both high fluidity and adequate viscosity simultaneously to exhibit such behavior [52,53]. All components of SCSC must be carefully selected and proportioned to achieve these seemingly contradictory qualities. Due to their finer particles, SCSC requires more cement and water compared to other types of concrete. The increase in water content leads to weak interfaces between granular materials and negative outcomes like bleeding and segregation [54-56]. However, high cement contents can also result in significant creep and drying shrinkage [57,58]. Consequently, superplasticizer is a staple in SCSC blends to create high fluidity, while substantial fine materials are often employed to maintain the mix's stability and cohesion, minimizing bleeding, segregation, and settlement [59,60]. The nature of fine additions used in SCSC design significantly affects the material's qualities in fresh and hardened states [61].

In an effort to reduce $CO_2$ emissions and natural resource extraction while prolonging the life of landfills that are currently saturated, the current study is a part of the process of recycling and reusing waste in the construction industry, which is highly beneficial from an ecological and financial standpoint. From the aforementioned literature review, vehicle windshield glass waste increased day by day due to the fast-growing population and limited recycling options. However, incorporating these wastes into cement concrete significantly reduces their accumulation in landfills. Several studies have been conducted on the use of various industrial GWs as cement or fine or coarse aggregate in ordinary concrete; however, the recycling of windshield glass waste as an alternative construction material in SCSC has not been investigated. Therefore, the current study aims to experimentally assess the feasibility of using up to 100% WGA as a sand replacement for producing a novel eco-friendly SCSC. The purpose of this study was to evaluate the effects of WGA as a natural sand replacement and BFS as a cement addition on the workability, compressive and flexural strength, modulus of elasticity, ultrasonic pulse velocity, water absorption, and porosity of SCSC. Scanning electron microscopy (SEM) analysis has also been used to assess the microstructural characteristics of control SCSC and SCSC with 20% WGA.

## 2. Materials and methods

### *2.1. Materials*

#### *2.1.1. Cement and filler*

Cement CEM II/B-L 42.5 N-type from the MASCARA factory (Mascara city, Algeria), conforming to NF EN 197-1 standard specifications [62], was used in this study, with a density of 3100 kg/m³ and a fineness of 3300 cm²/g. It demonstrates an average compressive strength of 40 MPa after 28 days. The addition of fillers is essential in the production of self-compacting sand concrete [63]. The filler used in this study is blast furnace slag (BFS) from the EL HADJAR factory

(Annaba city, Algeria). The chemical composition and physical properties of cement and BFS are shown in Table 1. However, their particle size distributions are shown in Fig. 1.

### *2.1.2. Natural and recycled aggregates*

Siliceous sand from the Oued Souf quarry in the south of Algeria, with a maximum diameter of 3.75 mm, was employed as fine natural aggregate (Fig. 2a). Glass waste aggregate (WGA), derived from windshield glass waste, was used as recycled fine aggregate (Fig. 2b). The windshield glass consists of multiple layers separated by a PVB (polyvinyl butyral) interlayer to improve safety and sustainability (Fig. 3). The WGA was generated from discarded automotive windshields through a complex process using manual crushing tools and the Los Angeles machine. A significant challenge was the effective separation of the PVB film from the glass, requiring adequate fracture (Fig. 3). The detailed chemical compositions and physical properties of the aggregates used were presented in Table 1. Figure 2a-b revealed a rounded shape and smooth surface of natural sand particles, while the particles of WGA are irregularly shaped with a smooth surface, featuring faceted steps and conical edges. The particle size distributions of sand and WGA aggregate used are shown in Fig. 1.

### *2.1.3. Chemical admixture and water*

The chemical admixture used was a superplasticizer (Sika® ViscoCrete®-4037 RMX) commercially available in Algeria and complies with the NF EN 934-2 standard [64], with a density of 1.06 kg/m$^3$, a pH of 5, a chloride content less than 0.1% wt, an equivalent $Na_2O$ content less than 1.0% wt, and a dry solid content of 29.5% wt. Tap water complying with the NF EN 1008 standard [65] was used to mix all SCSC mixtures and to store the prepared samples.

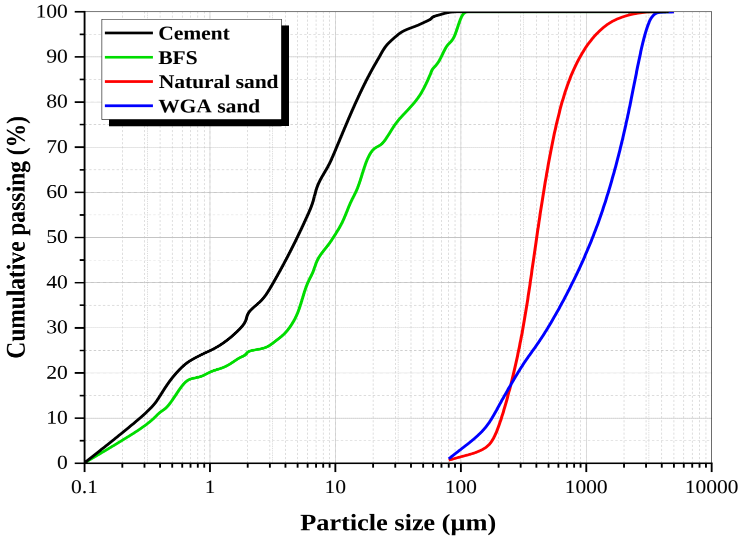


**Fig. 1.** Particle size distribution of cement, BFS, natural sand, and WGA. Source: own study

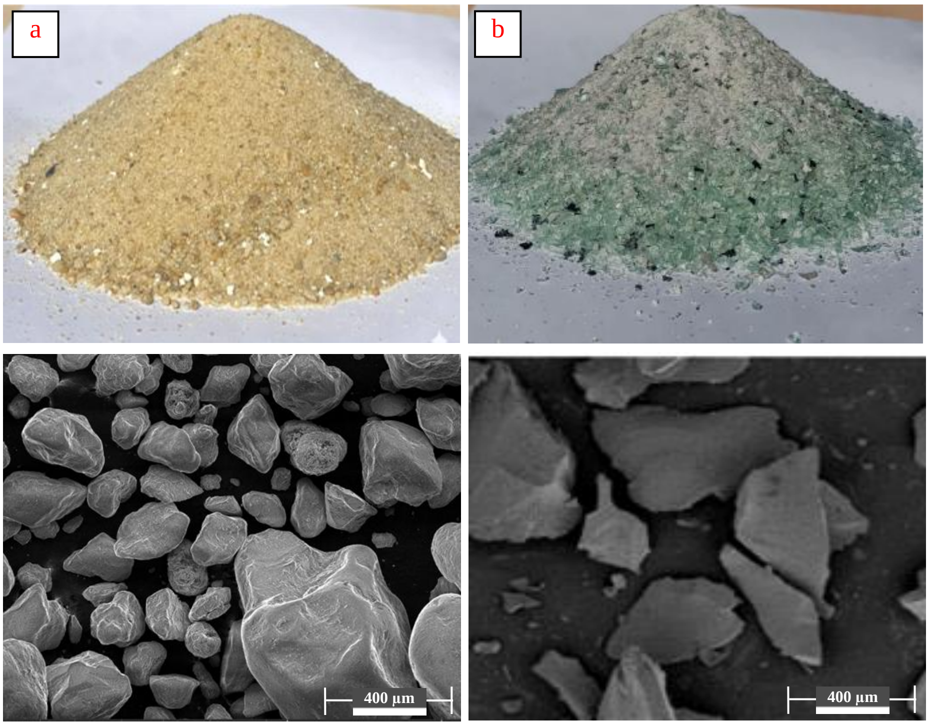


**Fig. 2.** General aspect and SEM images of (a) natural sand and (b) WG sand (b). Source: own study

**Table 1.** Chemical composition and physical properties of cement, BFS, natural sand, and GW sand. Source: own study

| Chemical composition (%) | Cement | BFS | NS | WGA |
|---|---|---|---|---|
| $SiO_2$ | 24.33 | 39.5 | 57.67 | 90.3 |
| $Al_2O_3$ | 6.18 | 10.9 | 6.10 | 4.6 |
| $Fe_2O_3$ | 4.76 | 0.4 | 0.51 | 0.5 |
| CaO | 57.54 | 45.4 | 5.6 | 1.7 |
| MgO | 2.49 | - | 0.3 | 0.2 |
| $K_2O$ | - | 2.5 | 1.92 | 0.9 |
| $Na_2O$ | - | - | 15.4 | 1.30 |
| $SO_3$ | 2.42 | 0.8 | 0.7 | 0.5 |
| LOI | 2.26 | - | 11.8 | - |
| Cl | | | - | - |
| Physical properties | | | | |
| Specific density (kg/m$^3$) | 3110 | 2730 | 2610 | 2460 |
| Specific surface area (m$^2$/kg) | 3420 | 2700 | - | - |
| Fineness modulus | - | - | 2.2 | 2.45 |
| Maximum size (mm) | - | - | 3.15 | 4.75 |
| Sand equivalent (%) | - | - | 81.78 | - |
| Water absorption (%) | - | - | 0.96 | 4.34 |

BFS – Blast furnace slag, NS – Natural sand, WGA- Windshields glass aggregate.

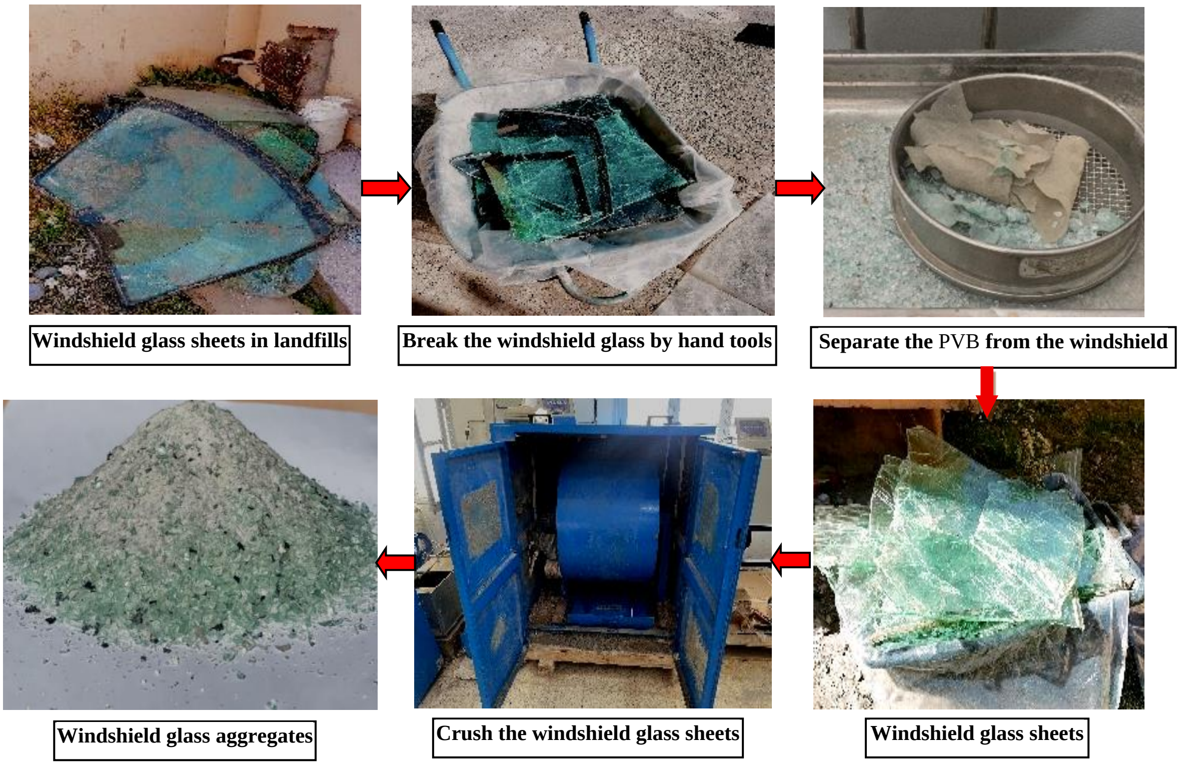


**Fig. 3.** Preparing steps of windshield glass aggregate (WGA). *Source*: own study

### *2.2. Mix proportions*

For the purpose of evaluating how the WGA affects the rheological, mechanical, and durability characteristics of SCSC, eleven different SCSC mixes were produced in this study, including a control mix with 100% NS and ten other mixes with WGA. The reference SCSC mixture was developed according to the method proposed by the Sablocrete project [63], with modifications made to the water-to-powder ratio (W/P) and the superplasticizer content to adapt local material requirements with optimal fresh SCSC mix characteristics. For SCSC with recycled sand, natural sand was partially replaced in volume by WGA at varying percentages from 10% to 100%, with incremental steps of 10%. In all mixes, the quantities of binder (cement and filler) and w/b ratio were kept constant at 600 kg/m$^3$ and 0.44, respectively. The superplasticizer-to-cement ratio was selected for each mix to keep a closer flow diameter than for the control one as well as to improve the fresh SCSC flowability and homogeneity, with a target slump flow diameter between 270 and 320 mm as recommended by the EFNARC recommendations [66]. It should be noted that each percentage of WGA required the necessary amount of SP to achieve the target workability of SCSC mixes without segregation and bleeding. The details of the mix proportions for each 1 m$^3$ of SCSC mixtures (by weight) and their mixture IDs are displayed in Table 2.

**Table 2.** Mix proportioning of different SCSC mixes. Source: own study

| Mix. ID | Binder | | Fine aggregate | | W/P ratio | SP (%) |
|---|---|---|---|---|---|---|
| | Cement (kg/m$^3$) | BFS (kg/m$^3$) | Sand (kg/m$^3$) | WGA (kg/m$^3$) | | |
| Control | 400 | 200 | 1400 | 0 | 0.44 | 1.00 |
| 10%G | 400 | 200 | 1268 | 132 | 0.44 | 0.60 |
| 20%G | 400 | 200 | 1136 | 264 | 0.44 | 0.50 |
| 30%G | 400 | 200 | 1004 | 396 | 0.44 | 0.50 |
| 40%G | 400 | 200 | 872 | 528 | 0.44 | 0.45 |
| 50%G | 400 | 200 | 740 | 660 | 0.44 | 0.45 |
| 60%G | 400 | 200 | 608 | 792 | 0.44 | 0.45 |
| 70%G | 400 | 200 | 476 | 924 | 0.44 | 0.50 |
| 80%G | 400 | 200 | 280 | 1120 | 0.44 | 0.55 |
| 90%G | 400 | 200 | 213 | 1188 | 0.44 | 0.55 |
| 100%G | 400 | 200 | 0 | 1320 | 0.44 | 0.65 |

BFS – Blast furnace slag, WGA – Windshields glass agreggate, W/P – water-to-powder ratio, SP – Superplasticizer.

### *2.3. Mixing process and testing*

For developing the different SCSC mixes, a specific mixing process was adopted based on self-compacting concrete guidelines described by the French association of civil engineering [66]. Ensuring good homogeneity is critical; therefore, the components of the SCSC were blended together using a mixer tank with a 5 L capacity, as described by the NF EN 196-1 standard [67]. The mixing process for SCSC comprised four distinct stages. Dry components were first added to the mixer tank, and the mixer was started at low speed. After 30 seconds of mixing, 2/3 of the water was added over the next 30 seconds, followed by the remaining 1/3 of water with the superplasticizer for an additional 30 seconds. The mixer was then set to high speed, continuing mixing for another 30 seconds. The mixer was stopped for 3 minutes. Finally, the mixing resumed at high speed for 60 seconds.

The characterization of fresh concrete workability is an important parameter that determines its ease of implementation. According to Edamatsu et al. [68], the spread by measuring the mini-slump flow diameter was used to assess the workability of the different SCSC mixtures immediately after mixing. Based on the results of these tests, the ideal superplasticizer dosage that produces no bleeding with high fluidity and filling capacity of the mix was determined.

To determine the different hardened properties of the studied mixes, prismatic molds (4×4×16 cm$^3$) were used to produce all SCSC specimens with no vibration or compaction. The SCSC mixture samples were prepared in a room with controlled conditions, maintaining a temperature of 20 ± 2°C and relative humidity of 50-60%. The specimens were demolded after 24 hours and kept in lime-saturated water at 20°C until the testing time.

Compressive and flexural tensile strengths were evaluated at 7, 28, 90, and 365 days according to the NF EN 196-1 standard [67]. The modulus of elasticity, ultrasonic pulse velocity, water absorption, and porosity were determined as physical characteristics at the age of 90 days according to ASTM C469-14 [69], ASTM C597-16 [70], and ASTM C642-21 [71] standards, respectively. Microstructural analysis (SEM) was evaluated on control SCSC and SCSC with 20% WGA mixes aged over 90 days.

## 3. Results and discussion

### *3.1. Slump flow diameter and superplasticizer need*

The characterization of fresh concrete workability is an important parameter that determines its ease of implementation. To allow a valid comparison of different SCSC results in the hardened state, the level of workability for all SCSC mixes was maintained the same and corresponded to a slump flow diameter between 270 and 320 mm, as recommended by the EFNARC recommendations [66]. For this, the water-to-binder ratio was kept constant for all SCSC mixes at a value of 0.44, and the superplasticizer content was adjusted for all mixes to keep the same flow diameter as the control one and to achieve satisfactory fluidity and viscosity.

Figure 4 shows the slump flow results and the amount of superplasticizer needed for the different fresh SCSC mixtures. It is clearly shown from this figure that for all SCSC mixtures, the flow diameter was found to be in a range of 270 ± 50 mm and 320 ± 50 mm, indicating good deformability that meets the EFNARC recommendations [66]. It was also discovered that the increased replacement of WGA with the addition of BFS as filler enhances the flowability of the fresh SCSC mixes and reduces the superplasticizer amount needed for their production compared to the control SCSC mixture. Similarly, Boukhelkhal et al. [58] and Sideris et al. [72] discovered that BFS enhanced the fresh properties of SCC by reducing the amount of superplasticizer required. Beyond 60% WGA replacement, Figure 4 shows a slight decrease in the flowability of mixtures with 70, 80, 90, and 100% WGA compared to mixtures with 40, 50, and 60% WGA. Nevertheless, all SCSC mixtures exhibit a higher slump flow diameter and less superplasticizer dosage needed than the control mixture and with no sign of segregation, indicating good deformability according to the EFNARC recommendations [66]. Park et al. [26] also found a decrease in slump of concrete when the content of WGA as fine aggregate increased to 70% by weight.

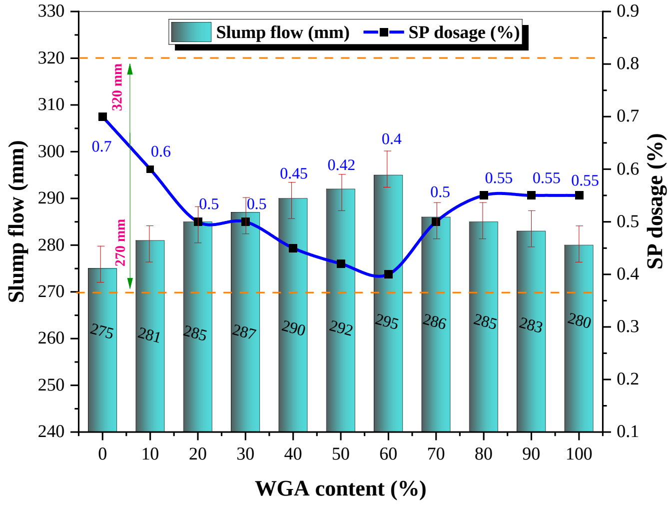


**Fig. 4.** Variation of superplasticizer dosage and slump flow of difference SCSC mixes. Source: own study

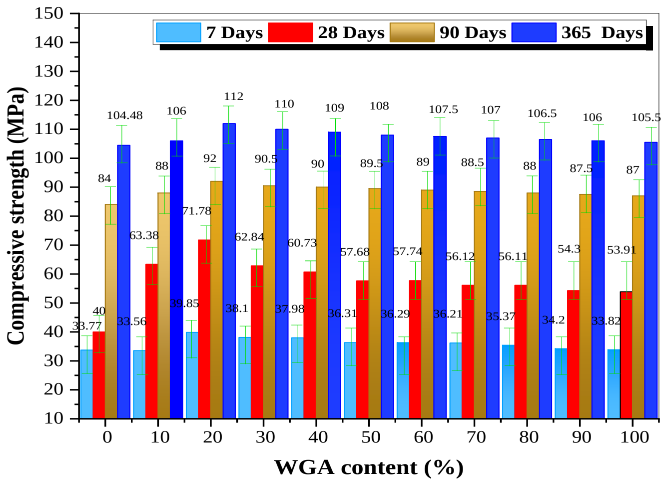


**Fig. 5.** Compressive strength of different SCSC mixtures. Source: own study

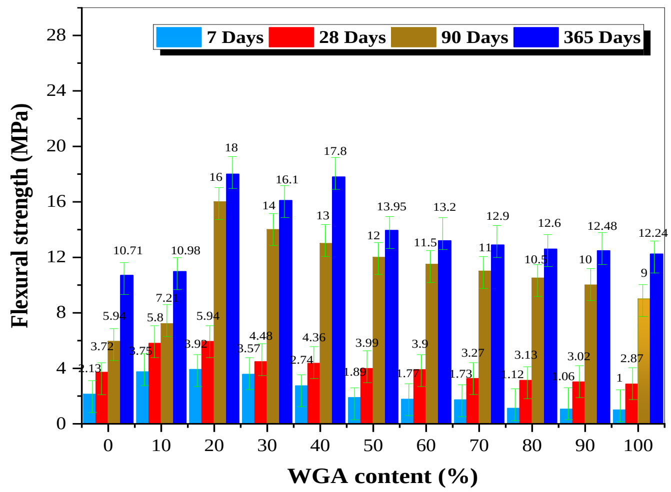


**Fig. 6.** Flexural strength of different SCSC mixtures. Source: own study

This improvement in the flowability of WGA-based SCSC may be due to the low water absorption and smooth surface of WGA compared to NS, which provided a weaker cohesion with the cement paste. However, for high replacement levels, SCSC-WGA mixtures do not flow easily due to their cubic shapes and sharp corners that do not move easily, as is the case with NS with spherical morphology (Fig. 1). In addition, the flow of WGA becomes difficult due to strong bonding between aggregates, making their separation extremely complicated. This advantageous improvement in the workability of SCSC with the use of WGA has been confirmed by several other researchers for other types of concrete [22,34,73-77]. Khan and Sarker [23] found a 4% to 15% increase in the flow of alkali-activated mortar when using between 25% and 100% WGA. On the contrary, Arabi et al. [31] found a negative impact of WGA on the flowability and passing ability of SCC and attributed this to the higher count of coarse aggregate particles by volume, mainly concentrated in the 3/8 mm size fraction (80%).

### *3.2. Compressive and flexural strengths*

Figures 5 and 6 illustrate the variation in the compressive and flexural strength results of different SCSC mixes at 7, 28, 90, and 365 days, respectively. It is clearly shown from these figures that the addition of up to 100% WGA as fine aggregate led to a significant increase in the mechanical strength of the SCSC mixture. However, all WGA-based SCSC have compressive and flexural strength higher than control SCSC. For all curing times, the optimum amount of compressive and flexural strength was developed for SCSC mixtures with 20% WGA. For instance, the compressive strength increases by 80% for SCSC with 20% WGA and 35% for SCSC with 100% WGA at 28 days, compared to reference SCSC. However, the flexural strength increases by 50% for SCSC with 20% WGA and remains almost the same for SCSC with 100% WGA at 28 days, compared to control SCSC. This increase in mechanical strength can be attributed to the higher hardness and irregular shape of WGA compared to NS (Fig. 1). Similar findings were reported by other researchers [78-82], who attributed this enhancement to the improved physical bond between the angular-shaped WGA particles and the paste. Similarly, Wang and Huang [83] found that 20% was the optimum level of sand replacement with glass self-compacting concrete. Islam et al. [40] also found that the optimum glass content is 20% considering mortar and concrete compressive strength at 90 days.

The pozzolanic reactions of WGA fine particles and BFS also help the improvement in mechanical strength at later ages (after 28 days), which is consistent with the observations of Ali et al. [84], Govardhan et al. [85], Okoro and Oyebisi [86], and Sideris et al. [72]. However, the decrease of strength when the WGA percentage is above 20% compared to that with 10% and 20% WGA may be due to (i) the cement paste and WGA particles not linking as well. At the ITZ, the cement mortar and glass particles may have a poorer connection if there are sharp edges and smooth particle surfaces; (ii) the increased water content in the WGA-based mixes is attributed to the limited capacity of WG to absorb water; and (iii) the cracks induced by the expansion stress generated due to the alkali-silica reaction initiated by the silica present in waste glass (WG). It should be noted that despite the reduction in strength for SCSC mixtures with more than 20% WGA compared to those with 10 and 20% WGA, it remained greater than that of the control mixture.

Some other researchers found that substituting fine aggregate with a substantial volume of waste glass notably diminished mortar/concrete strength [22,26,32,37,87]. Ling and Poon [27] demonstrated a 20% decrease in the 28-day strength of mortar when using 100% crushed cathode ray tubes as a fine aggregate replacement. Afshinnia and Rangaraju [88] attributed this to the poor bonding between glass aggregates and cement paste at the ITZ. However, our study revealed nearly no reduction in mechanical strength when using 100% WGA. This outcome was attributed to the superior strength of WGA compared to regular glass waste, aligning with the findings of Zaetang et al. [37] and Ling and Poon [27]. Thus, WGA presents itself as a promising eco-friendly alternative for replacing natural fine aggregate in concrete applications.

### *3.3. Modulus of elasticity*

The modulus of elasticity (MOE) is crucial in assessing structural deformation to meet service standards. The concrete's modulus of elasticity is affected by the aggregates' nature, the cement matrix, and their relative proportions in the mixture [89]. Previous studies have shown that incorporating WGA into concrete increases the modulus of elasticity [90,91]. The average dynamic modulus of elasticity values for different SCSC mixtures after 90 days of curing are presented in Fig. 7, demonstrating the positive effect of using WGA as fine aggregate. Indeed, SCSCs incorporating WGA exhibited higher values compared to the reference SCSC. The MOE increased from 38 GPa for control SCSC to 40 GPa for SCSC with 100% WGA at 90 days, with the optimum value found for the mixture with 40% WGA.

This improvement is attributed to multiple factors: the high strength and low density of WGA, the increased compressive strength caused by the WGA fine particles, and the addition of BFS that fills more of the pores and compacts the microstructure. Additionally, the development of a robust interfacial transition zone (ITZ) between the cement paste and the WG contributes to the observed enhancements in elastic properties. Steyn et al. [92] and Omoding et al. [93] also found an increase in MOE by replacing up to 30% and 50% of fine and coarse aggregate, respectively, with recycled WG. On the contrary, Ali and Al-Tersawy [94] have reported decreased MOE with WG incorporation. In conclusion, this study demonstrates that incorporating WGA can enhance the MOE of SCSC, which is beneficial for construction and structural repair applications.

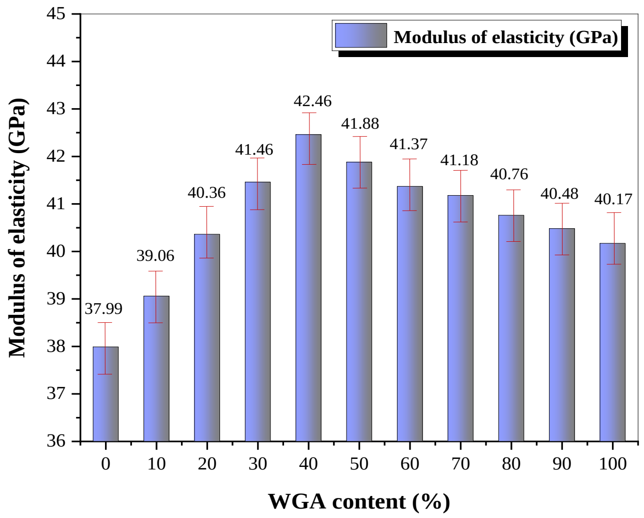


**Fig. 7.** Dynamic modulus of elasticity of different SCSC mixtures. Source: own study

### *3.4. Water absorption and porosity*

Water absorption and porosity are critical parameters in determining the performance and durability of concrete. Understanding and controlling these characteristics is essential for designing concrete structures that can withstand harsh environments and maintain their performance over time [95]. Figure 8 presents a decline in water absorption by immersion and porosity as the volume of WGA incorporated into SCSC increases. The decrease in water absorption and porosity was from 1% to 13% and 3.61% to 17.16%, respectively, for SCSC mixtures containing from 10% to 100% WGA, respectively, compared to SCSC with 100% NS. This observed decrease in porosity and water absorption can be attributed to three primary factors: (1) the inherently lower porosity of WGA compared to natural sand, (2) the lower water absorption capacity and impermeable nature of the WGA compared to NS, and (3) the long-term pozzolanic reaction of BFS and fine particles of WGA, which results in the progressive filling of voids within the SCSC samples. The same findings were observed in previous research using recycled glass as a substitute for sand [28,37,96,97]. According to Wright et al. [98], this decline in water absorption with integrating glass as aggregates is due to the augmentation of the water-resistant volume within the concrete matrix that bolsters its resistance to water infiltration.

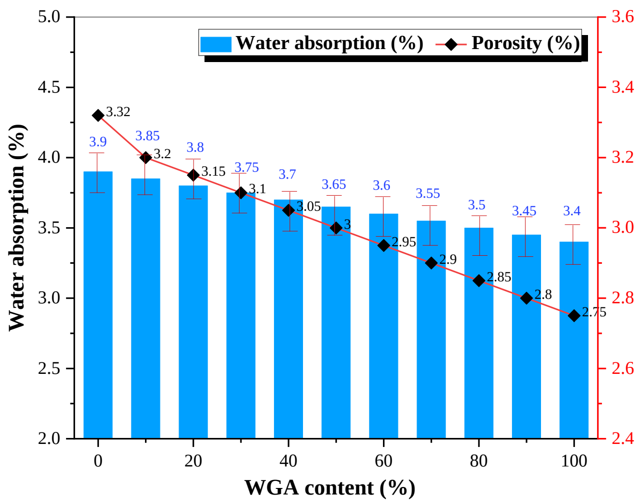


**Fig. 8.** The water absorption and porosity of different SCSC mixtures. Source: own study

### *3.5. Ultrasonic pulse velocity (UPV)*

The ultrasonic pulse velocity (UPV) method has been widely acknowledged as a nondestructive method for its efficacy in assessing concrete quality. According to Malhotra et al., concrete with a UPV value surpassing 3500 m/s is deemed to possess commendable durability [99]. The ultrasonic pulse velocity results for the different SCSC mixtures are depicted in Fig. 9. It is shown from this figure that the UPV value increases with the increasing replacement level of NS with WGA from 10% to 100%. For instance, the 90-day UPV values are 4300 m/s and 4341 m/s for SCSC with 50% and 100% WGA, respectively, compared to 4260 m/s for control SCSC without WGA. This improvement in UPV values brought about by the addition of WGA is very advantageous for structural concrete and can be attributed to several factors. First, the favorable density and reduced porosity of the produced SCSC mixtures and the hardness of WGA particles compared to natural sand (NS). Additionally, the incorporation of blast furnace slag combined with the fine particles of WGA contributes to filling voids and exhibits long-term pozzolanic reactions, resulting in the observed increase in UPV values. It is also shown from these findings that all SCSC mixtures exhibited UPV between 3500 and 4500 m/s, indicating a good quality of WGA-based SCSC according to Malhotra et al. [99]. Similarly, Bindumadhavan et al. [100] and Gür [101] observed a comparable improvement in UPV when WGA is used instead of sand.

The UPV can be directly related to the porosity and hardness of the material. The relationships between the 90-day UPV, porosity, and compressive strength results of the different SCSC mixtures are shown in Fig. 10. The observed increase in UPV with rising WGA content correlates with the enhancement in compressive strength and the reduction in porosity, with high coefficients of correlation (i.e., $R^2 > 0.7$). This outcome was also found by other researchers, who claimed that the UPV values of geopolymer and cement composites increased with the increase in compressive strength [37,102,103].

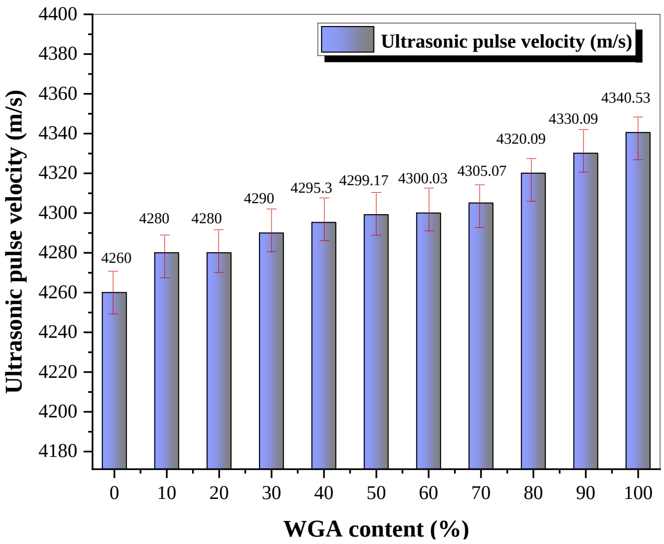


**Fig. 9.** UPV of different SCSC mixtures. Source: own study

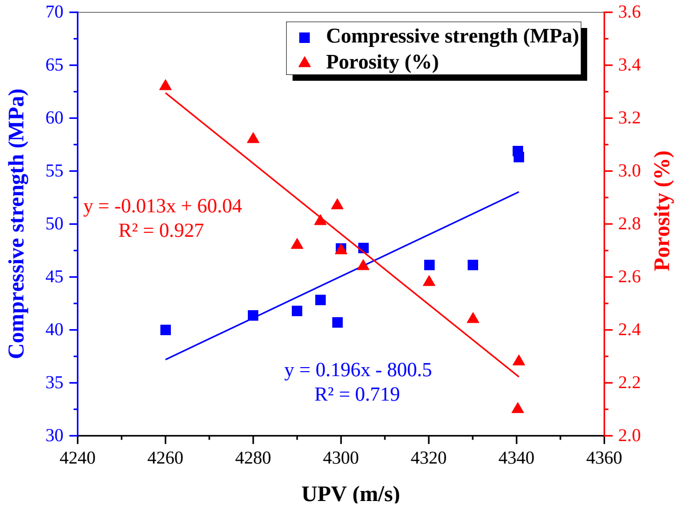


**Fig. 10.** Correlation between UPV, compressive strength, and porosity of SCSC-based WGA mixes. Source: own study

**Table 3.** Summary of experimental results and statical analyses. Source: own study

| Mix | slump flow | Compressive strength (MPa) | | | | Flexural strength (MPa) | | | | E (GP) | UPV (m/s) | Wabs (%) | P (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7 d | 28 d | 90 d | 360 d | 7 d | 28 d | 90 d | 360 d | | | | |
| 0 | 275 | 33.77 | 40 | 84 | 104.48 | 2.13 | 3.72 | 5.94 | 10.716 | 37.99 | 4260.00 | 3.9 | 3.32 |
| 10 | 281 | 33.56 | 63.38 | 88 | 106 | 3.75 | 5.8 | 7.21 | 10.98 | 39.06 | 4280.00 | 3.85 | 3.2 |
| 20 | 285 | 39.85 | 71.78 | 92 | 112 | 3.92 | 5.94 | 16 | 18 | 40.36 | 4290.00 | 3.8 | 3.15 |
| 30 | 287 | 38.1 | 62.84 | 90.5 | 110 | 3.57 | 4.48 | 14 | 16.1 | 41.46 | 4295.30 | 3.75 | 3.1 |
| 40 | 290 | 37.98 | 60.73 | 90 | 109 | 2.74 | 4.36 | 13 | 17.8 | 42.46 | 4299.17 | 3.7 | 3.05 |
| 50 | 292 | 36.31 | 57.68 | 89.5 | 108 | 1.89 | 3.99 | 12 | 13.95 | 41.88 | 4300.03 | 3.65 | 3 |
| 60 | 295 | 36.29 | 57.74 | 89 | 107.5 | 1.77 | 3.9 | 11.5 | 13.2 | 41.37 | 4305.07 | 3.6 | 2.95 |
| 70 | 286 | 36.21 | 56.12 | 88.5 | 107 | 1.73 | 3.27 | 11 | 12.9 | 41.18 | 4320.09 | 3.55 | 2.9 |
| 80 | 285 | 35.37 | 56.11 | 88 | 106.5 | 1.12 | 3.13 | 10.5 | 12.6 | 40.76 | 4330.09 | 3.5 | 2.85 |
| 90 | 283 | 34.2 | 54.3 | 87.5 | 106 | 1.06 | 3.02 | 10 | 12.48 | 40.48 | 4340.53 | 3.45 | 2.8 |
| 100 | 280 | 33.82 | 53.91 | 87 | 105.5 | 1 | 2.87 | 9 | 12.24 | 40.17 | 4260.00 | 3.4 | 2.75 |
| Max | 295 | 39.85 | 71.78 | 92 | 112 | 3.92 | 5.94 | 16 | 18 | 42.46 | 4340.53 | 3.90 | 3.32 |
| Min | 275 | 33.56 | 40 | 84 | 104.48 | 1.00 | 2.87 | 5.94 | 10.72 | 37.99 | 4260.00 | 3.40 | 2.75 |
| Mean | 285.36 | 35.95 | 57.69 | 88.54 | 107.45 | 2.24 | 4.04 | 10.92 | 13.72 | 40.65 | 4298.20 | 3.65 | 3.00 |
| SD | 4.215 | 1.643 | 5.095 | 1.504 | 1.679 | 0.910 | 0.801 | 2.175 | 1.992 | 0.945 | 19.225 | 0.136 | 0.143 |
| COV | 1.48 | 4.57 | 8.83 | 1.70 | 1.56 | 40.56 | 19.81 | 19.91 | 14.51 | 2.33 | 0.45 | 3.74 | 4.77 |

d – days, E – Modulus of elasticity, UPV – Ultrasonic pulse velocity, Wabs – Water absorption, P – Porosity, SD – standard deviation, COV - Coefficient of variation (%)

### *3.6. Statistical analysis*

In Table 3 are summarized all the experimental results and a comprehensive statistical analysis of these results for WGA-based SCSC mixes in terms of max and min values, mean values, sample standard deviations, and coefficients of variation (COV) for all studied fresh and hardened properties. Although absolute dispersion is measured using standard deviation values, the COV is the main focus of the discussion because it offers a consistent way to measure data variability and makes it possible to compare properties with different units and quantities, such as workability, strength, and porosity, in a meaningful way. With a COV value of 1.48%, the workability represented by the slump flow diameter showed very low variability, indicating excellent consistency and reproducibility of the mix production process for all WGA substitution rates. A low COV was also observed for compressive strengths at all ages and modulus of elasticity (E) with values ranging from 1.56% to 8.83% for compressive strengths and 2.33% for E, suggesting excellent mixture repeatability as well. However, a high COV was observed for flexural strength, with values ranging from 14.51 to 19.91 for samples older than 28 days of age. Despite this variability, all COV values were below 20%, indicating satisfactory reproducibility and acceptance. The only exception was flexural strength at 7 days, which showed a moderate COV with a maximum value of 40.56%. These levels of dispersion are typical for the flexural strength, which reflects the dominant influence of the smooth surfaces of glass aggregates on the bond adhesion between WGA and cement paste and therefore the reduction in the flexural strength, especially at an early age (7 days). Looking at the durability indices expressed by porosity and water absorption, as well as ultrasonic pulse velocity (UPV), a low COV was determined, with values of 4.77%, 3.74, and 0.45%, respectively. Confirming that the enhancement in mechanical performance is systematically related to the low matrix porosity, as shown with their high relationship presented in Fig. 10. In general, the statistical indicators in Table 3 demonstrate the reliability of the experimental program and support the analytical interpretation of the trends observed in the properties of fresh and hardened SCSC.

### *3.7. Microstructure analysis (SEM)*

In this study, scanning electron microscopy (SEM) was employed to visualize the microstructural evolution of selected SCSC mixtures. Samples for SEM analysis were obtained from the interior of the specimens. Figure 11 presents SEM micrographs of the control SCSC and SCSC with 20% WGA (optimal mix) for samples with more than 90 days of age. The micrographs presented in this figure show a dense and more continuous microstructure across all SCSC mixtures, exhibiting a strong interfacial transition zone (ITZ) between the cement paste and aggregates, which is attributed to the self-consolidation properties of SCSC, as well as to the increased hydration products, particularly C-S-H gel and CH crystals, which fill gaps and block capillary channel pathways. Furthermore, these improved results are also attributable to the filling effect that comes from the addition of BFS as filler, which resulted in a reduction of the void ratio. This observation is corroborated with the observed porosity test results and supports the enhanced strength characteristics of these SCSC mixtures that were presented in sections 3.2 and 3.4.

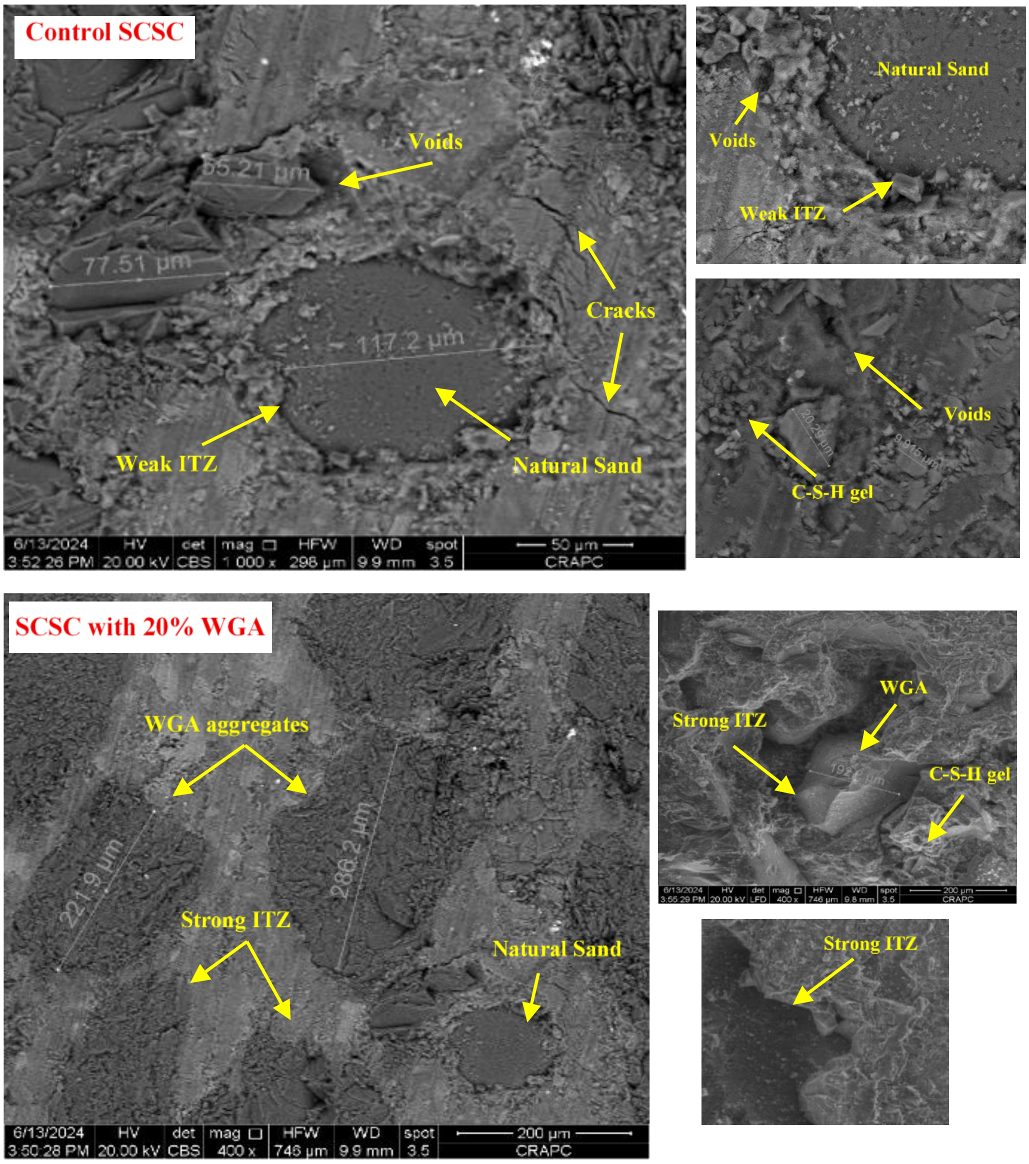


**Fig. 11.** SEM images of CSCSC and SCSC with 20% WGA. Source: own study

On the other hand, Figure 11 showed a strong ITZ between WGA aggregates and cement paste, with a denser surface and fewer cracks and voids for all WGA-based SCSC compared to control SCSC without WGA, which exhibits some voids, microcracks, and a poor ITZ. This enhancement in the microstructure of WGA-based SCSC may be due to the irregular and rough surface of WGA (Fig. 1). In addition, the fine particles of WGA can affect the hydration process and the degree of pozzolanic reaction in SCSC, resulting in hydration products with a more compact shape and encapsulated nucleation sites. Afshinnia and Rangaraju [88] stated that due to the low water absorption and smooth surface of WGA, the amount of free water in concrete increases significantly in concrete containing higher percentages.

## 4. Conclusion

In this research, an experimental study was conducted to examine the feasibility of valorizing automotive waste glass as fine aggregate combined with BFS by-product as filler in the development of a new sustainable self-compacting sand concrete and their impact on its fresh and hardened properties. The findings of the different experiments allowed us to draw the following conclusions.

- For a given W/P ratio (0.44), the use of up to 100% WGA as a natural sand replacement with BFS as a filler improves the fluidity of fresh SCSCs due to their low water absorption capacity and smooth surface texture, which ensures lower cohesion with cement paste.
- Using up to 100% WGA as sand combined with BFS as filler helps to improve both the compressive and flexural strength for all curing ages, the modulus of elasticity, and UPV of SCSC. All WGA-based SCSC can be classified as high-quality concrete with 90-day compressive and flexural strengths and UPV higher than 80 MPa, 6 MPa, and 3500 m/s, respectively.
- SCSC with 20% WGA substitution was found to be optimum, with compressive and flexural strength 80% and 50% higher than the reference concrete, respectively.
- The combined use of BFS and WGA results in reduced porosity and water absorption of SCSCs. SCSC with 100% WGA exhibited the lowest values, with decreases of approximately 13% and 17% in water absorption and porosity, respectively, compared to the control mix.
- The SEM analysis revealed an improvement in the microstructure of WGA-based SCSC with a denser structure and a stronger ITZ between cement paste and WGA governed by the pozzolanic reaction of BFS and fine WGA particles, as well as the irregular shape of WGA compared to NS.

Finally, it is encouraging to produce an eco-friendly, high-strength concrete by completely replacing natural sand with windshield glass waste. This will not only minimize the cost and environmental impact by reducing the significant proportion of this waste sent to landfill and the natural resources extraction but will also improve the physical and mechanical performance of SCSC and energy savings for future generations. This new ecological WGA-based SCSC is highly recommended in construction for many structural elements (structural concrete frames, foundations, large-scale concrete production, prefabricated panels, separation in buildings, etc.).

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