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Developing High-strength, Flowable Sand Concrete by Adding Combined Industrial Ceramic and Granite Waste with Seashell Bio-waste as Fine Aggregates

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Abstract

Due to its large consumption of raw materials and high construction work rates, the building industry presents one of the most effective potentials for the use of recycled materials. In an attempt to maximize landfill waste valorization and enhance concrete properties, this study investigates the combined use of industrial ceramic waste (CW) and granite waste (GW) with seashell bio-waste (SW) and their effect on the physical and mechanical properties of flowable sand concrete (FSC). For this, seven FSC mixtures were manufactured by partially replacing natural sand with different amounts of CW, GW, and SW combinations (0, 5, 10, 15, 20, 25, and 30 wt%). The results showed that up to 30% recycled aggregates could be utilized while maintaining the fresh properties of all FSC mixes. Compressive and flexural strengths as well as ultrasonic pulse velocity were significantly improved by 40%, 90%, and 6%, respectively. Both water absorption and porosity were reduced by 20% with the simultaneous addition of 30% recycled aggregates, compared to the reference concrete. Furthermore, the scanning electron microscopy analysis of some FSC mixes showed that the microstructure of FSC was enhanced with a stronger bond between the cement paste and aggregates when the three recycled aggregates were included in amounts of up to 30%. Finally, the results are encouraging when CW and GW are used simultaneously with SW in developing high-strength FSC, allowing the replacement of up to 30% of fine aggregates for sustainable construction.

Keywords

ceramic, flowable sand concrete, granite, physical-mechanical properties, seashell, waste

1 Introduction

Concrete is a widely used construction material all over the world. It is an agglomerated composite material composed of dense particles of varying sizes linked together by a binder [1–3]. With current designs growing more complex, the production of fluid concrete has become a serious challenge for the concrete construction industry [4, 5]. Flowable sand concrete (FSC) is a novel type of concrete that is low in rough aggregates (gravel) and rich in fine aggregates. It is distinguished by its simplicity of installation and lack of compaction [6, 7]. Given the high demand for natural aggregates such as sand and the difficulties in opening new quarries, the use of industrial waste and by-products in the construction industry has emerged as an effective solution for conserving natural resources and reducing waste storage in landfills and along coastlines [8–16]. Additionally, owing to its lower cost and to legal requirements, this approach also addresses the economic and environmental challenges that many countries face [17].

The construction materials industry generates a significant rate of waste. The valorization of these wastes in concrete manufacturing is an important step toward environmentally friendly and economically viable construction methods. Researchers have demonstrated that industrial mineral wastes such as ceramic and granite waste (GW) can serve as components for construction concrete [18–20]. For instance, Gautam et al. [21] studied the incorporation of 0 to 40% bone china ceramic waste (BCCW) as a partial substitution for cement in self-compacting concrete (SCC). They found acceptable fresh properties, improved compressive and flexural strengths, increased ultrasonic pulse velocity (UPV), and enhanced resistance to water absorption, with up to 10% BCCW. In another study, Guendouz et al. [6] looked into substituting up to 60% of fine aggregate with floor slab waste

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to make flowable sand concrete. They found a drop in the workability and bulk density of mixtures as floor tile waste increased, while the compressive and flexural strengths were improved by 48% and 24%, respectively. El-Dieb and Kanaan [22] demonstrated that adding 20% ceramic tile waste (CW) to cement increased strength due to its pozzolanic properties. Similarly, Subaşı et al. [23] found that SCC mixes incorporating up to 20% CW as a cement substitute had excellent fresh characteristics. According to Bommisetty et al. [3], the concrete compressive strength increased to a 20% replacement before declining when replacing up to 25% of natural coarse aggregate with ceramic tile waste. Zegardło et al. [24] observed that using sanitary ceramic waste instead of gravel-basalt for ultra-high-strength concrete improved its compressive and tensile strength and decreased its bulk density. Guendouz and Boukhelkhal [19] looked at the impact of recycling ceramic tile and ceramic sanitary ware waste on FSC properties. They found a decrease in flowable sand concrete workability. However, adding up to 50% and 60% of ceramic sanitary ware and ceramic tile waste, respectively, improves the mechanical strengths.

Granite waste is often available in large quantities during the processes of cutting and polishing granite stone or on building and demolition sites; it has been extensively researched by several authors as an aggregate substitute in mortars or concrete. Zafar et al. [25] found a 42% increase in compressive strength for the mix having up to 20% granite dust as a natural sand (NS) substitute. Jain et al. [26] discovered that SCC with granite dust had negative fresh qualities but positive hardened properties. Ghannam et al. [27] investigated the use of up to 20% granite powder as a substitute for NS in concrete. They found that a 10% granite powder content increased the compressive strength by 30% compared to conventional concrete. According to Jain et al. [28, 29], substituting up to 40% of fine aggregates with GW could be beneficial in SCC manufacturing, with an improvement in mechanical performance at 25% GW replacement. Patil and Patil [30] observed an increase in compressive and abrasion strengths of SCC with up to 60% substitution of NS with GW. Similarly, Singh et al. [31] found that the addition of GW to concrete increased its compressive and flexural strengths while decreasing its permeability. Vijayalakshmi et al. [32] investigated the effects of GW as a partial river sand replacement. Their results showed that using up to 15% of GW might preserve concrete's mechanical performance and durability. Binici and Aksogan [33] found that using GW as a fine aggregate improves the condensed matrix and makes the concrete less permeable and more durable than ordinary concrete. According to Cordeiro et al. [34], using GW in place of river sand had a detrimental impact on the rheological properties of concrete mixtures. However, increasing the amount of superplasticizer (SP) can lessen this negative impact. Nuaklong et al. [35] looked at the characteristics of geopolymer concrete by substituting 25 and 50% of the natural river sand with granite debris. They discovered that the slump flow increased with higher GW content and that early compressive strength improved when 50% of the natural sand was replaced by GW. Amin et al. [36] found an improvement in compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity by replacing some of the cement with granite powder and all of the sand with crushed granite in ultra-high-performance concrete. Recently, Gautam et al. [37] studied the effect of up to 40% granite waste and 0, 10, 20, and 30% bone china powder waste (BCPW) as cement and fine aggregate, respectively, on self-compacting concrete properties. They achieved positive results in the fresh state, and SCC with 10% BCPW and 30% GW presented the greatest strength with a 15% enhancement in compressive strength [37, 38].

On the other hand, seashell waste (SW) that accumulates along the coast can be crushed, processed, and used as raw material for concrete. Several studies have been conducted to explore the impact of integrating crushed seashells into concrete mixtures. Goushik and Ramasamy [39] replaced between 10 and 25% of fine aggregates with crushed shells and discovered that the crushed shells negatively affected the concrete's fresh and hardened properties. Boudjellal et al. [40] studied the use of SW as sand at percentages ranging from 20% to 50%. According to their results, the concrete's tensile and compressive strengths improved significantly and showed their optimum for a substitution rate of 40%, with an increase of 24.12% and 30.05% in tensile and compressive strengths, respectively. Cuadrado-Rica et al. [41] studied the integration of crushed shells in standard concrete at percentages of 20%, 40%, and 60%. They discovered that the inclusion of shells reduced workability, density, and mechanical strength. Similarly, Bamigboye et al. [42] discovered that adding seashell to concrete mixes reduced both workability and strength.

From the above-mentioned studies, extensive research has been conducted on the valorization of industrial CW and GW, as well as seashell bio-waste (SW) as a marine by-product in concrete manufacturing. However, only one kind of waste has been valued so far. Therefore, the benefits for the economy and environment remain relatively small, especially in countries where waste generation is significant. The aim of this research is to create a locally derived, eco-friendly construction material with enhanced physical-mechanical properties, as well as maximum waste and low raw material consumption. Hence, the novelty of this study is to determine the feasibility of simultaneous use of industrial mineral waste from stone cutting and polishing processes (CW, GW) with marine biowaste (SW) as an alternative to natural fine aggregates in flowable sand concrete production. For this, the natural sand was replaced by combined recycled fine aggregates (CW, GW, and SW) at 0, 5, 10, 15, 20, 25, and 30 wt%. The impact of these wastes on the fresh and hardened properties of the FSC was examined using mini-slump flow diameter, V-funnel flow time, compressive and flexural strength, dry density, ultrasonic pulse velocity, water absorption, porosity accessible to water, and scanning electron microscopy (SEM) analysis.

2 Experimental

2.1 Materials

2.1.1 Cement and marble powder

An ordinary Portland cement (OPC) CEMI 42.5 N and marble powder (MP) obtained by grinding the white tiles were used as cement and filler, respectively. The chemical composition determined by the XRD analysis and the physical properties of cement and MP are listed in Table 1.

2.1.2 Natural and recycled aggregates

Siliceous sand with grain size varying between 0.08 and 5 mm was used as natural sand (Fig. 1). The off-cuts of floor tiles and granite from the industry landfill are crushed and ground to create the ceramic and granite waste aggregates,

Table 1 Chemical composition and physical properties of cement and MP

Chemical components (wt%)	OPC	MP
SiO_2	23.83	0.27
Al_2O_3	6.05	4.39
Fe_2O_3	4.66	0.12
CaO	56.35	94.31
MgO	2.44	0.56
K_2O	0.83	–
Na_2O	0.58	–
SO_3	2.37	0.06
CaO_{Free}	0.66	0.19
LOI*	2.23	–
Physical properties		
Specific density (g/cm^3)	3.1	2.73
Specific surface area (cm^2/g)	3420	2700

* Loss on ignition

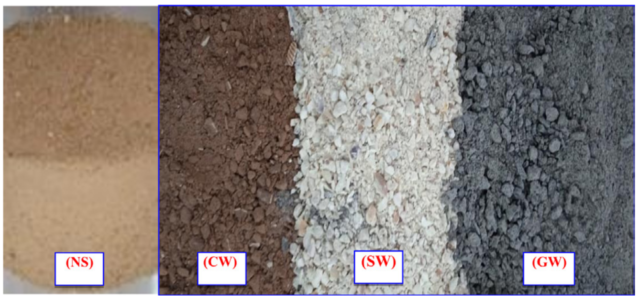

Fig. 1 Appearance of natural sand (NS), ceramic waste (CW), seashell waste (SW), and granite waste (GW)

which are then sieved through a 5 mm sieve to create a 0/5 class sand (Fig. 1). Seashells collected from the sea oyster family that were rejected in the littorals were used as a sand substitute in this study. After they were immersed in water for 24 h and thoroughly scrubbed with a brush to remove salt and contaminants, especially organic ones, they were dried for an hour at 40 ± 5 °C for a constant weight [31], then crushed, powdered, and sieved through a 5 mm sieve to produce the recycled sands as shown in Fig. 1. The SEM images of NS and recycled aggregates shown in Fig. 2 demonstrate the rounded shape and smooth texture for NS particles and the angular shape and rough surface of recycled grains. The particle size distributions of NS, CW, GW, and SW, as well as their physical properties and chemical composition, are shown in Fig. 3 and Table 2, respectively.

2.1.3 Water and admixture

Drinking water with a pH between 6.5 and 8, confirming the NF EN 1008 standard [43], was used in this study for mixing the mixtures and preserving the samples. The admixture used is a third-generation, high-water-reducing

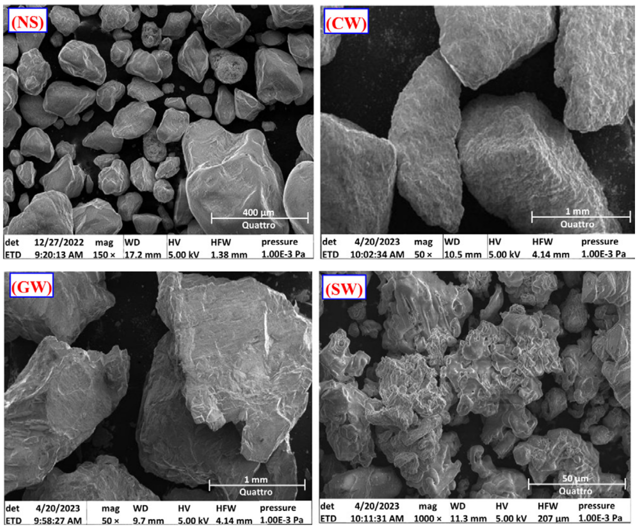

Fig. 2 SEM micrographs of natural sand (NS), ceramic waste (CW), seashell waste (SW), and granite waste (GW)

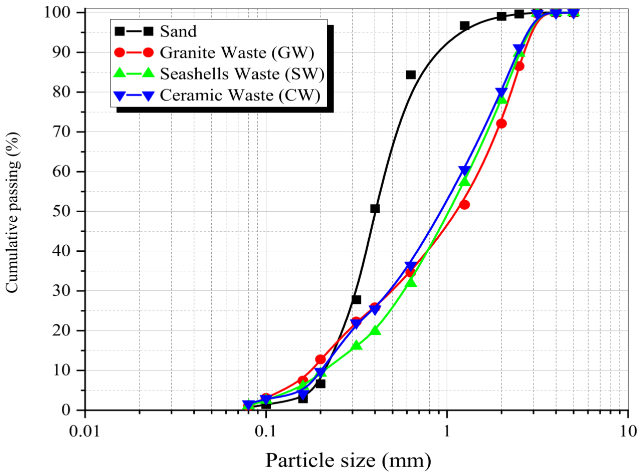

Fig. 3 Particle size distribution of natural sand, ceramic waste, seashell waste, and granite waste

Table 2 Chemical composition and physical properties of NS, CW, GW, and SW

Chemical components (wt%)	NS	CW	GW	SW
SiO_2	90.35	62.5	51.29	0.11
Al_2O_3	4.56	16.4	20.47	17.6
Fe_2O_3	0.51	5.7	12.58	0.10
CaO	1.67	9.2	11.88	81.5
MgO	0.15	2.2	5.51	0.22
K_2O	1.92	3.9	1.47	–
Na_2O	–	–	1.36	–
SO_3	0.7	0.2	0.27	0.11
Physical properties				
Specific density (g/cm^3)	2.63	2.50	2.51	2.82
Fineness modulus	2.33	2.66	2.68	2.79
Water absorption (wt%)	0.96	3.83	0.34	2.93

superplasticizer based on polycarboxylate. It is sold in liquid form under the brand name "MEDAFLOW30" and characterized by a yellowish color with a solids content of 30 wt%, a specific gravity of 1.08 g/cm^3, a pH equal to 6.25, and a chlorine content of less than 1 g/L.

2.2 Concrete mix design

The theoretical method suggested by Sablocrete [44] was used to determine the composition of all FSC mixes, the cement and filler contents of 404 kg/m^3 and 202 kg/m^3, respectively. The water-to-powder ratio (W/P) and the sand-to-powder ratio (S/P) were maintained constant at 0.44, and 2.31, respectively. The superplasticizer-to-cement ratio was selected for each mix to improve the fresh FSC flowability and homogeneity. A control mix (CFSC) with 100% natural sand and six other mixes containing 5, 10, 15, 20, 25, or 30% CW, GW, and SW in place of fine aggregate were made in this study (Table 3). The mix proportions for each 1 m^3 of FSC mixture (by mass) are given in Table 4.

To produce the different FSC mixes, the mixing procedure can be divided into three parts. For the first half-minute, the cement and aggregate were mixed together. 70% of the mixing water was then added, and the mixing was continued for 1 min. After that the superplasticizer mixed with the remaining 30% water was added and mixed for 1 min. The mixing was paused for 2 min to rest. Finally, before discharging the product, the FSC was mixed again for 1 min to guarantee the homogeneity of the FSC mix [45].

2.3 Casting and testing

All FSC mixes were manufactured in the laboratory at 20 °C and 50% relative humidity, using a 5L rotary mixer. Following the completion of the mixing procedure, many experiments were performed on the FSC mixes to evaluate their fresh and hardened properties. Fig. 4 illustrates the various tests done on the FSC mixes.

2.3.1 Fresh concrete tests

According to The European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) [46], the mini-slump flow diameter and V-funnel flow time produced by MATEST were used to evaluate the workability of the FSC mixture. Based on the results of these tests, the ideal superplasticizer dosage that produces no bleeding with high fluidity and filling capacity of the FSC mix was determined.

2.3.2 Hardened concrete tests

After 24 h of casting of the FSC mixes in different molds without vibration and compaction, the specimens were removed from the molds and stored in a lime-saturated water tank at 20 °C until the test age. Different tests in the hardened state were carried out on three specimens for all FSC mixes, and the average values are reported.

Table 3 Proportions of waste in FSC mixes (wt%)

Mix	GW	CW	SW
CFSC	0	0	0
FSC5W	5	5	5
FSC10W	10	10	10
FSC15W	15	15	15
FSC20W	20	20	20
FSC25W	25	25	25
FSC30W	30	30	30

Table 4 Mix design for 1 m³ of FSC mixes

	Mixes						
Constituent	CFSC	FSC5W	FSC10W	FSC15W	FSC20W	FSC25W	FSC30W
Cement (kg/m³)	404	404	404	404	404	404	404
Marble powder (kg/m³)	202	202	202	202	202	202	202
Sand (kg/m³)	1400	1190	980	770	560	350	140
Ceramic waste (kg/m³)	0	66.80	133.10	199.60	266.20	332.70	392.20
Granite waste (kg/m³)	0	66.80	133.60	200.40	267.20	334	400.80
Seashell waste (kg/m³)	0	75.30	150.60	225.90	301.30	376.60	451.90
Water (L/m³)	267.52	267.52	267.52	267.52	267.52	267.52	267.52
Superplasticizer (wt%)	0.8	0.85	0.85	0.9	0.95	1	1.2

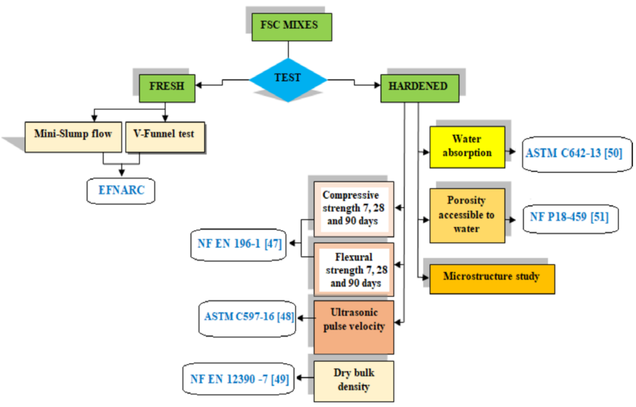

Fig. 4 Tests carried out on the FSC mixtures in the fresh and hardened state

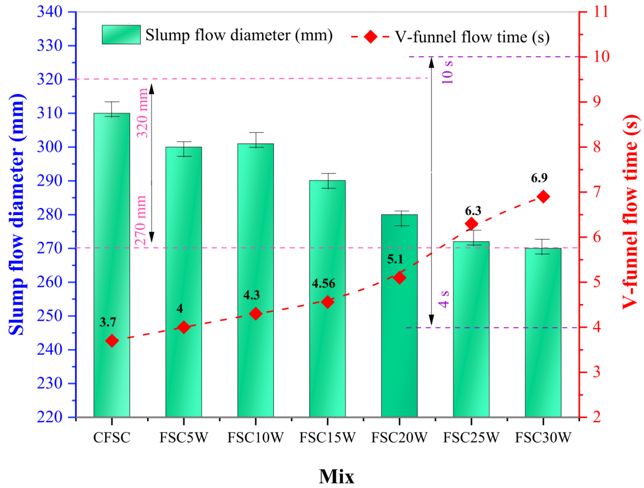

Fig. 5 Influence of CW, GW, and SW on the slump-flow diameter and the flow times of FSC mixes

The compressive and flexural strength were tested on 40 × 40 × 160 mm prismatic specimens at 7, 28, and 90 days of age, using a hydraulic crushing machine (ELE) with a capacity of 250 kN according to NF EN 196-1 [47]. A nondestructive ultrasonic pulse velocity (UPV) test using a Pundit apparatus (Proceq), that gives an idea of the homogeneity and porosity of the specimens was performed on 100 × 100 × 100 mm cubic specimens aged 28 days in accordance with ASTM C597-16 [48] and NF EN 12390-7 [49] standards. The dry density, porosity, and water absorption by immersion tests were carried out on 40 × 40 × 160 mm prismatic specimens at 28 days of age in accordance with ASTM C642-13 [50] and NF P18-459 [51], respectively. Finally, a VEGA3-TES CAN SEM (TESCAN Orsay Holding, Brno, Czech Republic) with an accelerating voltage of 25 kV was used to understand the microstructure of some FSC mixes.

3 Result and discussion

3.1 Workability

The characterization of fresh concrete workability is an important parameter that determines its ease of implementation. Fig. 5 presents the slump flow diameter and V-funnel flow time results for all FSC mixes. It was discovered from Table 4 that the SP demand increases as the content of recycled aggregates increases, with a dosage varying from 0.8% to 1.2%. The SP content in all mixtures with recycled aggregates was higher than that in the control mixture. It should be noted that each percentage of CW, GW, and SW required the necessary amount of SP to achieve the target workability of FSC blends without segregation and bleeding. As can be seen from Fig. 5, for all FSC mixtures, the flow diameter was found to be in a range of 270 ± 50 mm and 320 ± 50 mm, and the flow times were steady and varied between 2 and 10 s, indicating good workability that meets the EFNARC recommendations [46].

Fig. 5 shows that the spread diameter of the FSC has decreased and the flow time has significantly increased with the increasing substitution of sand by CW, GW, and SW. The better flow time results were observed for the FSC5W and FSC10W mixes as compared to the control one. At higher substitution levels (30%), an increase of up to 32% in the V-Funnel flow time was observed when compared to the CFSC. Similarly, Gautam et al. [52] found satisfactory fresh properties as per the EFNARC standard limit for SCC with bone china ceramic waste powder (BCCWP) and GW. However, for a mix with 30% BCCWP and 40% GCW, a decline in workability was observed. Mohammadsalehi and Mostofinejad [53] also showed a reduction in SCC workability by adding more than 10% granite sludge as a natural sand replacement.

This decrease in workability was caused by the rough surface and high angularity of the recycled particles (Fig. 2), which favored the frictional resistance between these recycled aggregates and cement particles and may have resulted in an increase in mix flowability [29, 37, 54, 55]. Additionally, the presence of voids at the surface of recycled grains results in their increased water absorption characteristics (Table 2) [6, 29, 56]. As a result, the combination of CW and GW with SW had a negative effect on the flow of FSC, and it is in agreement with several researchers, who noticed a decrease in the workability of concrete when using CW, GW, and SW as fine aggregate in the concrete mix design [33, 57–59].

3.2 Compressive and flexural strength

Fig. 6 shows the compressive and flexural strength results of the various FSC mixtures at 7, 28, and 90 days of hardening. As shown in Fig. 6, for all test periods, all FSC mixtures with combined recycled aggregates gave higher mechanical strengths compared to the control mixture, with an improvement in compressive and flexural strength by the increasing content of CW, GW, and SW. For instance, increases of about 67%, 31%, and 38% for the compressive strength and 150%, 148%, and 92% for the flexural strength were observed at 7, 28, and 90 days, respectively, for the mixture with 30% recycled aggregates compared to control FSC. This improvement in compressive and flexural strength is due to the higher hardness of CW, GW, and SW aggregates compared to natural sand, as well as their irregular shape and rough surface (Fig. 2), which provides a larger surface area resulting in strong bonding, interfacial transition zone (ITZ), between the cement paste and recycled aggregate particles [60–63].

Compared to the control FSC, it is clear that the increase in compressive strength at 90 days is significantly greater than the increases at 7 and 28 days. This may be due to the more excellent water absorption of ceramic and seashell aggregates compared to natural sand (Table 2), which provides a suitable environment for additional hydration of cement and an increase in mechanical strength [64].

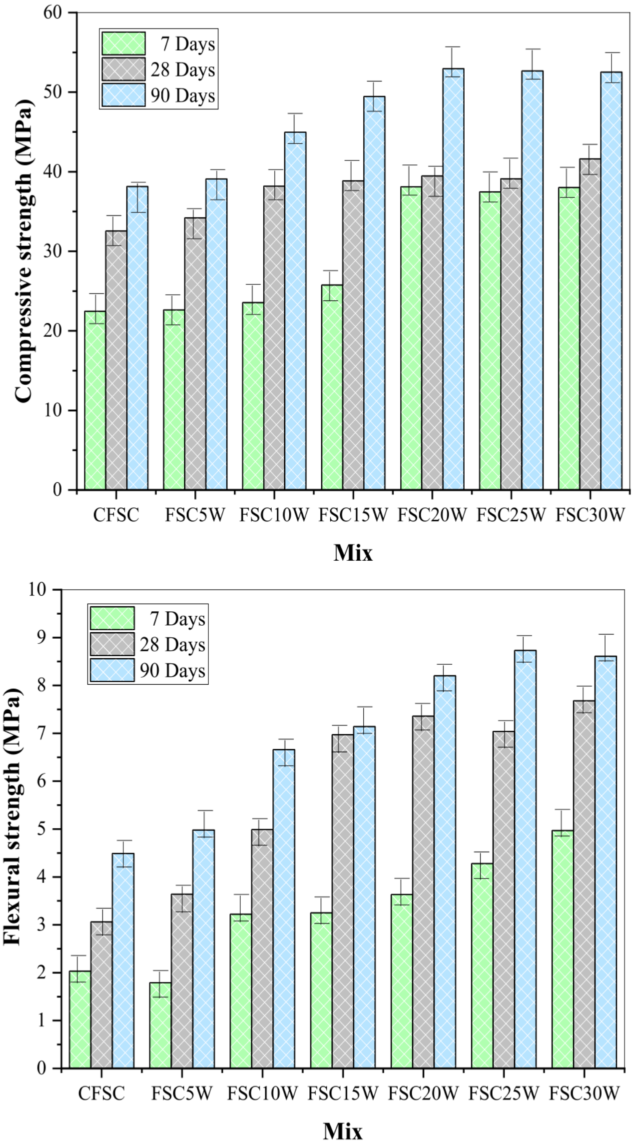

Fig. 6 Compressive and flexural strength of FSC mixes with different percentages of CW, GW and SW

Additionally, in the humid curing environment, the cement paste is hydrated more effectively, minimizing endogenous shrinkage, which eventually increases strength [65]. The improvement in mechanical strength with the integration of CW, GW, and SW was in accordance with those observed in several research studies [19, 55, 58, 66–71]. Jain et al. [72] found an increase of about 20% in compressive strength of SCC with up to 40% GW incorporation as fine aggregates. Mohammadsalehi and Mostofinejad [53] also found up to a 5.9% increase in SCC compressive strength by adding 20% granite sludge as a natural sand replacement. According to Wang et al. [73], the presence of WG facilitates the generation of calcium silicate hydrate (C–S–H), enhancing the interfacial transition zone, and improving aggregate strength. Vilas Meena et al. [74] found that replacing 30% of natural sand with ceramic waste tile (CWT) exhibited the highest compressive strength in the SCC.

3.3 Bulk density and ultrasonic pulse velocity (UPV)

The effect of CW, GW, and SW on the dry bulk density and UPV results at 28 days of age is depicted in Fig. 7. These results show an increase in bulk density and UPV values as the percentage of CW, GW, and SW increases. For instance, the UPV values increased by 0.01, 0.40, 0.75, 1.77, 3.34, and 5.51% for FSC5W, FSC10W, FSC15W, FSC20W, FSC25W, and FSC25W mixes, respectively, compared to the control mixture. This increase in dry density may be due to the higher density of SW compared to natural sand, as well as to the greater filling of CW and GW grains (Fig. 3), which minimize the interconnected voids and increase compactness of mixes, thus improving the density of the concrete matrix as reported by other authors [4, 38]. Additionally, the good intergranular continuity between particles due to the angular shape of CW, GW, and SW grains could decrease the pore size in the mixes, which consequently increases the UPV [75].

3.4 Porosity and water absorption by immersion

Fig. 8 shows the effect of CW, GW, and SW on the porosity and water absorption results of the FSC mixes after 28 days of hardening. It is clearly shown in Fig. 8 that the porosity and water absorption decreased proportionally with the increasing rate of CW, GW, and SW, and the mixture with 30% waste replacement has the lowest porosity and water absorption values. For instance, the porosity of the control FSC was 11% and fell to 10% and 9% for FSC15W and

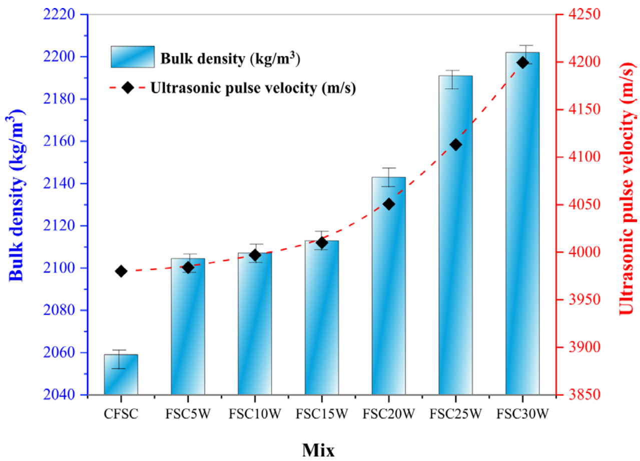

Fig. 7 Dry bulk density and ultrasonic pulse velocity of different FSC mixes

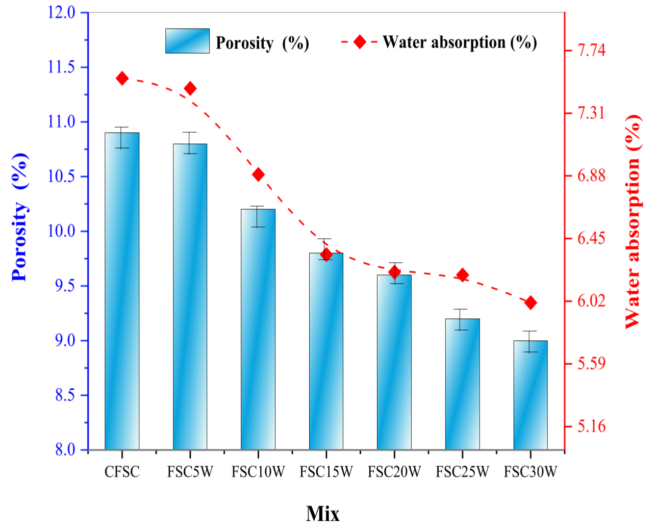

Fig. 8 Porosity and water absorption by immersion of different FSC mixtures

FSC30W, respectively. This decrease in porosity and water absorption may be justified by the high amount of fine particles, rough morphology, and angular shape of CW, GW, and SW (Figs. 1 and 2), which led to refilling the concrete's pores and densifying the microstructure of FSC mixtures, as well as improving the interlocking between the cement paste and aggregate in ITZ [76]. This porosity and water absorption decrease tendency with the use of CW, GW, and SW as fine aggregate has also been noted by other researchers [38, 77–79]. According to Binici and Aksogan [33], concrete with 10% granite aggregates had a capillary absorption coefficient that was 32% lower than the control concrete. In contrast, Vijayalakshmi et al. [32] found an increase in water absorption in concrete by adding granite powder. Jain et al. [72] showed that the replacement of natural fine aggregates with up to 50% GW exhibited reductions by around 53%, 15%, and 24% in water permeability, water absorption, and sorptivity of SCC, respectively.

Moreover, the results of the porosity confirm those for compressive strength and ultrasonic pulse velocity, as can be seen from Fig. 9. According to Fig. 9, the hardened properties of FSC containing CW, GW, and SW are strongly related to each other, with high coefficients of determination ($R^2 > 0.93$), indicating a decrease in compressive strength and UPV as the porosity increases.

In addition, it is clearly shown from Fig. 9 that both compressive strength and ultrasonic pulse velocity show a breaking point at around 9.6–9.7 porosity, which is corresponding to FSC with 15% of mixed wastes (FSC15W) indicating that the UPV significantly increased for mixed containing more than 15% of waste, with a porosity less than 9.7%. This can

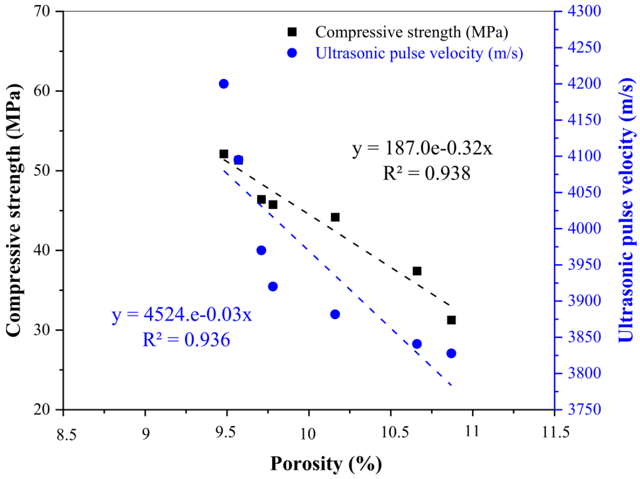

Fig. 9 Relationship between porosity, compressive strength and UPV of FSC mixtures

be related to an increased density of the mixtures with the incorporation of waste materials, particularly SW. However, the compressive strength values appear to have been growing slowly for mixes with above 15% of mixed wastes.

3.5 Microstructural analysis

A SEM analysis was used to look at the internal behavior of some FSC mixes that contained combined CW, GW, and SW. The SEM images of CFSC, FSC5W, FSC20W, and FSC30W mixtures are presented in Fig. 10. As shown in Fig. 10, the SEM images indicate voids, cracks, and ITZ and calcium silicate hydrate (C–S–H) gel of the examined FSC mixtures. It is clearly shown that FSC20W and FSC30W

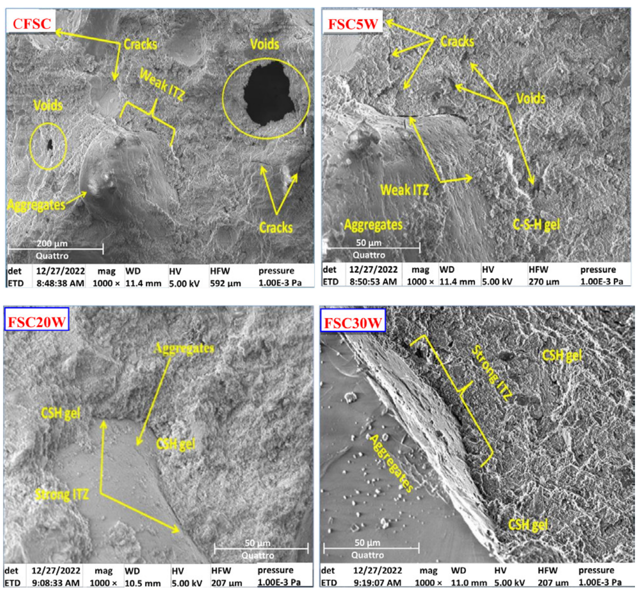

Fig. 10 SEM images of CFSC, FSC5W, FSC20W, and FSC30W mixtures

mixtures have a more consistent and denser microstructure between the paste and aggregates than FSC5W and CFSC, which have more pores and cracks and may negatively impact the cohesion between the matrix and aggregates. FSC30W was the mix with the best mechanical properties, as was previously mentioned. It was shown to exhibit maximum values for all studied properties thanks to the formation of an additional C–S–H gel, thus improving filling ability and providing a better cement matrix to the aggregate interface (ITZ) and forevermore enhancing the strength and other mechanical properties of the concrete [27, 38, 80]. Jain et al. [72] showed a denser microstructure in SCC containing up to 50% granite waste aggregate (GWA) as fine aggregates. Gautam et al. [21] also showed a dense microstructure and higher hydration products and lesser permeable voids with the use of 10% BCCW and 30% GW in SCC. According to Gautam et al. [38], this improvement in performance of FSC was mainly due to the pozzolanic behavior and finer particle size of CW and SW and the better filling property of GW.

4 Conclusions

The present study examined the combined use of CW, GW, and SW as fine aggregates to develop an ecofriendly fluid sand concrete. This new building material is a good strategy to solve the problems of sustainable solid waste management while saving landfills, preserving natural resources, and conserving the ecosystem. From the obtained finding, the following conclusions can be drawn:

- The addition of up to 30% of CW, GW, and SW in a combined manner is feasible in terms of fresh FSC characteristics since all mixtures exhibit flow characteristics within an acceptable range according to EFNARC recommendations with a minimum dosage of superplasticizer.
- For all ages, the combined use of CW, GW, and SW instead of natural sand in FSC has improved the compressive and flexural strengths. The 90-day compressive and flexural strengths were improved by 38% and 92%, respectively, for FSCs with 30% use of CW, GW, and SW.
- For all curing ages, UPV and bulk density increase as the amount of CW, GW, and SW increases in FSC.
- With up to 30% CW, GW, and SW, both porosity and water absorption were decreased by 20%, confirming the excellent durability of FSC mixtures with these recycled aggregates.

- According to SEM analysis, the addition of up to 30% of CW, GW, and SW as sand substitution improved the microstructure of FSC and developed a stronger bond between cement paste and aggregates.

Based on their improved physical-mechanical properties and environmental advantages, FSC mixes with 30% recycled waste showed the most balanced performance overall, making them perfect for application in heavily reinforced structural parts. Moreover, owing to its lower cost and to legal requirements, this study also addresses the economic and environmental challenges faced by several countries.

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