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Orginal Article

Enhancing the mechanical and durability properties of bio self-compacting sand concrete containing granite industrial waste as a fine aggregate: an experimental study

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Abstract: Self-compacting sand concrete (SCSC) is a highly fluid concrete widely used as a building material. The present investigation examined the impact of using seashell powder (SSP) and granite waste (GW) as supplementary cementitious material and fine aggregate, respectively, on the mechanical properties and elevated temperature durability of SCSC. For this purpose, SSP and GW were used to substitute 5, 10, and 15% by weight of cement and 10, 20, 30, and 40% by volume of natural sand, respectively. The fresh and hardened properties of SCSC mixtures were studied through a variety of tests, including setting time, slump flow, compressive strength, flexural strength, compactness, abrasion resistance, and elevated temperature resistance. SEM analysis was also carried out to investigate the developing microstructural properties of hardened SCSC mixtures. The results indicated acceptable fresh properties with low superplasticiser dosages in SCSC mixtures for up to 40% GW replacement. The compressive and flexural strengths improved by 30.61% and 35.82%, respectively, after 90 days of curing for SCSC mixtures with 10% SSP and 40% GW compared with the control mixture. Moreover, the incorporation of SSP in SCSC mixtures with varying levels of GW resulted in the best durability, while 40% GW improved their abrasion and elevated temperature resistance. The study demonstrates that the combined use of SSP and GW in the production of green self-compacting sand concrete is feasible in terms of both mechanical and durability properties.

Keywords: durability, elevated temperatures, granite waste, mechanical properties, seashells, self-compacting sand concrete

1. Introduction

The increasing demand for building materials observed in recent years has had major negative impacts on the environment due to increased pollution of water, air, and soil [1,2]. The manufacture of concrete requires large quantities of cement and aggregates, which are essential for construction [3]. Over the past few decades, the world has experienced rapid urbanisation. According to the United Nations Department of Economic and Social Affairs, over 55% of the world's population resides in urban areas, a figure projected to rise to 68% by 2050 [4]. Concrete production continues to increase to meet the demands of the construction market. In addition, population growth necessitates the development of new projects requiring large volumes of concrete. In recent decades, the use of self-compacting sand concrete (SCSC), a type of concrete, has increased in the construction industry due to its flowing nature and low segregation without the need for vibration [5-8]. These properties help to ensure that structures are strong, durable, and economical [9].

Cement manufacturing generally involves the grinding and calcination of natural resources such as limestone and clay and is responsible for around 7% of total CO_2 emissions worldwide [10-12]. The production of 1000 kg of cement generates about 900 kg of CO_2, which has a harmful effect on the ozone layer and the global environment [13-16]. Furthermore, cement production is extremely energy-intensive due to the high temperatures required for calcination (1450°C), which increases the overall manufacturing cost [17,18].

Seashells constitute a readily available waste material, especially in coastal areas, with about 16 million tonnes collected annually [19]. Seashell waste can be recycled into seashell powder (SSP) and treated for use in concrete as a supplementary cementitious material. In general, the use of SSP as a supplementary cementitious addition, owing to its high calcium oxide (CaO) content, improves the performance of concrete (rheological, mechanical, and durability), while also offering economic and environmental benefits [20]. Recent research by Kong et al. [21] demonstrated that the utilisation of waste oyster shells as a cement replacement at levels of 0, 20, and 40% can reduce CO_2 emissions by 26–52%. Tayeh et al. [22] examined the impact of using seashell powder as a partial replacement for cement at levels of 0%, 5%, 10%, 15%, and 20%. The results showed that replacing 5% of cement with seashell powder improved workability, mechanical performance, and durability against alkali and sulphate attacks. Abdelouahed et al. [23] investigated the influence of using 5%, 10%, 15%, and 20% seashell powder (SSP) as a cement replacement. The results showed that 5% replacement improved mechanical resistance, while 10% provided the best durability against chloride ion penetration. Furthermore, Adewuyi et al. [24] studied the effect of up to 30% periwinkle seashell (PSA) powder as a cement replacement in concrete. They found that 10% PSA provided optimal compressive strength, and that cement concrete mixed with shell ash under sulphate attack exhibited the lowest compressive strength loss. Othman et al. [25] reported a compressive strength of 45 MPa for the control concrete, which decreased to 36 MPa when cockle shells were used as a partial cement replacement. Lertwattanaruk et al. [26] utilised 5% seashell powder as a supplementary cementitious material and observed that the compressive strength of cement mortar was lower than that of the control mortar at 7 and 28 days of curing.

In the context of increasing industrial development, the accumulation of waste in landfills has led to environmental and health problems due to the pollution of air, water, and soil [27]. Granite waste (GW) is a type of solid waste generated in the stone industry during the cutting of granite stone [28]. Several researchers have examined the potential of this waste in concrete manufacturing. Vijayalakshmi et al. [29] studied the impact of GW as a substitute for river sand on the mechanical and durability properties of concrete and concluded that up to 15% GW can be utilised in concrete without any loss of mechanical and durability performance. Cordeiro et al. [30] reported that the use of GW as a partial substitute for fine aggregates had a negative effect on the rheological properties of concrete. Ghannam et al. [31] investigated the influence of GW as a partial replacement for sand on the mechanical performance of concrete and observed a positive effect. Vijayalakshmi et al. [29] studied the effect of GW as a replacement for fine aggregate on the abrasion resistance and sorptivity of self-compacting concrete (SCC). The results showed that the abrasion resistance and sorptivity of SCC mixtures improved with substitutions of up to 40% GW.

In an effort to reduce aggregate extraction and CO_2 emissions while extending the lifespan of currently saturated landfills from both ecological and economic perspectives, the present study explores the recycling and reuse of waste in the construction industry. According to the literature, several studies have investigated the effects of substituting GW for fine or coarse aggregates and SSP for cement on the properties of ordinary concrete. Their results were encouraging in terms of durability and technical performance. However, no research has yet been conducted on their simultaneous use to replace both cement and aggregate components in flowable sand concrete. The novelty of this study therefore lies in examining the mechanical performance and elevated-temperature durability of SCSC mixtures incorporating industrial granite waste (GW) as a partial replacement for natural sand, combined with seashell biowaste powder (SSP) as a cementitious material, to develop a new economical SCSC with high durability and physico-mechanical properties. GW was used as a natural sand replacement in amounts of 10, 20, 30, and 40 wt%, while SSP was used to replace OPC in amounts of 5, 10, and 15 wt%. Tests on initial and final setting time, slump flow diameter, compressive and flexural strength, abrasion resistance, compactness, and resistance to elevated temperatures were carried out to investigate the combined effects of SSP and GW on the fresh, physical-mechanical, and durability properties of SCSC mixtures. Scanning electron microscopy (SEM) analysis was also performed to assess the microstructure of selected SCSC mixtures.

2. Materials and methods

2.1. Materials

In this study, ordinary Portland cement (OPC) type CEM I 42.5 with a Blaine fineness of 342 m^2/kg and a specific density of 3110 kg/m^3, conforming to the NF EN 197-1 standard [32], was used as a binder. Marble powder (MP), with a Blaine fineness of 270 m^2/kg and a specific density of 2730 kg/m^3, obtained from the cutting and polishing of white marble plates, was utilised as a filler. Seashell powder (SSP), shown in Fig. 1(a), was produced from seashell waste after grinding and calcining in an oven for two hours at 650°C to decompose the calcium carbonate phases ($CaCO_3$) into CaO, and was used as a cement substitute.

Natural sand aggregate and granite waste (GW), with a maximum size of 4.75 mm, were used as fine aggregates in all the SCSC mixtures prepared in this study. A general image of GW is shown in Fig. 1(b). Details of the chemical composition and physical properties of all the materials used are presented in Table 1. SEM images of SSP and GW are illustrated in Fig. 2(a) and (b), respectively, showing the angular shape and rough surface of GW particles. The sieve analyses of cement, SSP, and fine aggregates are shown in Figs. 3(a) and (b), respectively. Figure 4 presents the mineralogical composition of SSP by X-ray diffraction analysis.

The superplasticiser used to improve the fluidity of SCSC mixtures was a high-range water-reducing polycarboxylic ether type.

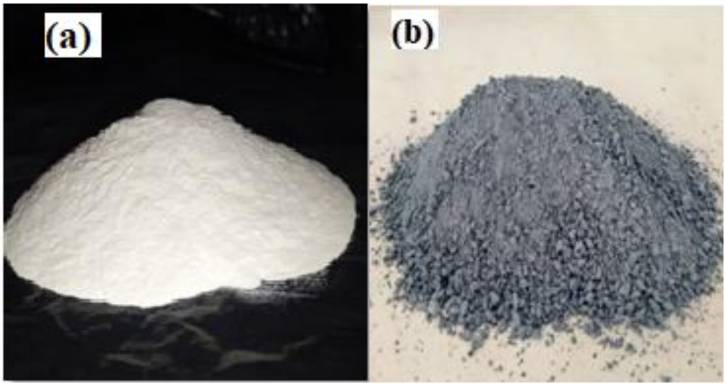


Fig. 1. General images of seashell powder (a) and GW (b) *Source*: own study

Table 1. Chemical composition and physical properties of all materials. *Source*: own study

Chemical composition (%)	Cement	MP	SSP	Sand	GW
SiO_2	23.80	0.26	0.10	90.35	51.29
Al_2O_3	6.05	4.39	4.07	4.56	20.47
Fe_2O_3	4.66	0.12	0. 1	0.51	12.58
CaO	56.35	94.31	95.06	1.67	11.88
MgO	2.44	0.56	0.22	0.15	5.51
K_2O	0.83	-	-	1.92	1.47
Na_2O	0.58	-	-	-	1.36
SO_3	2.37	0.06	0.11	0.7	0.27
L.I	2.22	-	-	-	-
Cl	-	0.11	0.11	-	-
Physical properties					
Specific density (kg/m^3)	3112	2731	2883	2630	2510
Blaine fineness (m^2/kg)	342	270	800	-	-
Fineness modulus	-	-	-	2.33	2.68
Water absorption (%)	-	-	-	0.96	4.34

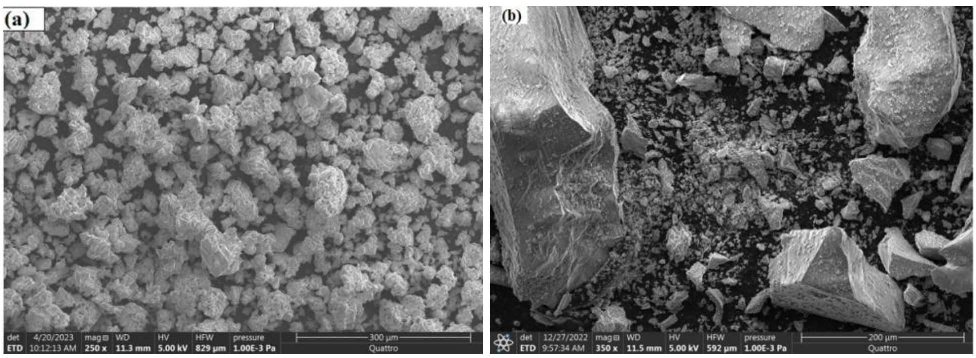


Fig. 2. SEM images of SSP (a) and GW (b). *Source*: own study

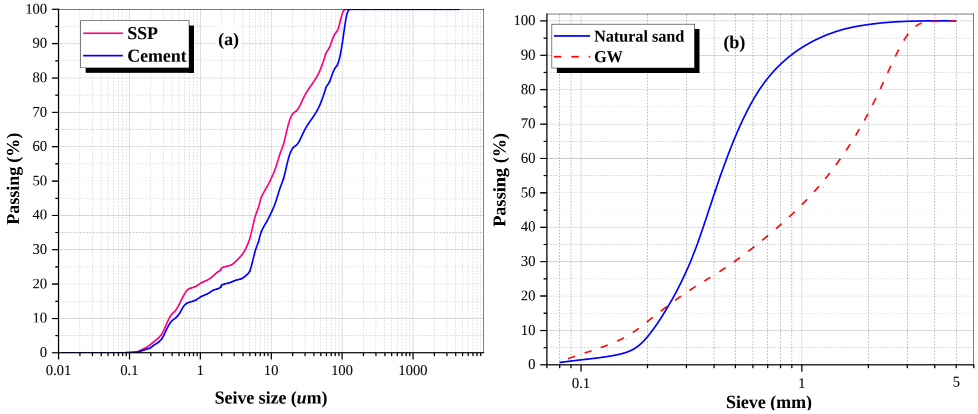


Fig. 3. Particle size distribution of cement and SSP (a), and fine aggregates (b). *Source*: own study

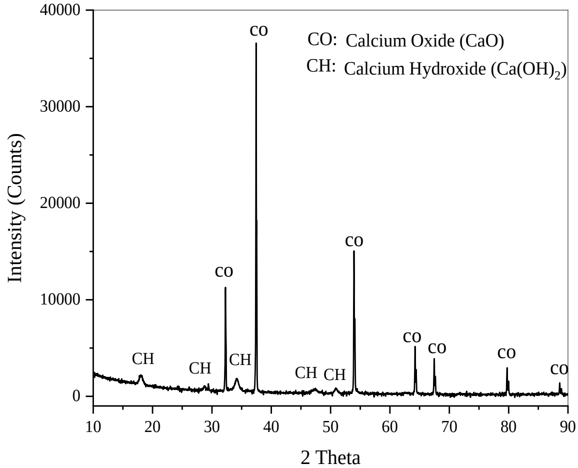


Fig. 4. X-ray diffraction analysis of SSP. *Source*: own study

2.2. Mixture proportions

For the purpose of evaluating how the combination of SSP as a cementitious material and GW as a fine aggregate affects the mechanical and durability characteristics of SCSC, sixteen mixtures were prepared and tested in this study. In all SCSC mixtures, SSP was used as a partial cement replacement at 0%, 5%, 10%, and 15% by weight, while natural fine aggregate was replaced with GW at 0%, 10%, 20%, 30%, and 40% by weight. A fixed water-to-binder ratio (w/b) of 0.44 by mass was used for all mixtures. Details of the mixture proportions of different SCSC mixes with SSP and GW are presented in Table 2.

2.3. Testing procedure

The slump flow test was performed for all fresh SCSC mixtures in accordance with EFNARC recommendations [33] to assess their filling and passing capacity. To determine the setting time properties of SCSC mixtures, initial and final setting time tests were conducted according to the ASTM C191-21 standard [34].

For hardened concrete, compressive and flexural strengths were evaluated on 40×40×40 mm cubic and 40×40×160 mm prismatic specimens, respectively, at 7, 28, and 90 days of curing, in accordance with the NF EN 196-1 standard [35]. Compactness was measured according to the ASTM C642-13 standard [36] on three 40×40×160 mm prismatic specimens after 28 days of curing. The abrasion resistance test (Fig. 5) was carried out on 70×70×70 mm cubic specimens in accordance with the ASTM C779/C779M-12 standard [37]. Finally, SEM analysis, using a VEGA3-TESCAN SEM with an accelerating voltage of 25 kV, was performed after 90 days to determine the morphology and microstructure of SCSC samples with 40% GW combined with 5%, 10%, and 15% SSP.

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

Mix. ID	Binders			Fine aggregates		w/b ratio	SP (%)
	OPC (kg/m^3)	MP (kg/m^3)	SSP (kg/m^3)	Sand (kg/m^3)	GW (kg/m^3)		
Control	400	200	0	1400	0	0.44	0.80
SSP_5+GW_0	380	200	20	1400	0	0.44	0.75
$SSP_{10}+GW_0$	360	200	40	1400	0	0.44	0.75
$SSP_{15}+GW_0$	340	200	60	1400	0	0.44	0.75
SSP_5+GW_{10}	380	200	20	1266.4	133.6	0.44	0.80
SSP_5+GW_{20}	380	200	20	1132.8	267.2	0.44	0.80
SSP_5+GW_{30}	380	200	20	999.2	400.8	0.44	0.80
SSP_5+GW_{40}	380	200	20	865.6	534.4	0.44	0.80
$SSP_{10}+GW_{10}$	360	200	40	1266.4	133.6	0.44	0.80
$SSP_{10}+GW_{20}$	360	200	40	1132.8	267.2	0.44	0.80
$SSP_{10}+GW_{30}$	360	200	40	999.2	400.8	0.44	0.80
$SSP_{10}+GW_{40}$	360	200	40	865.6	534.4	0.44	0.80
$SSP_{15}+GW_{10}$	340	200	60	1266.4	133.6	0.44	0.80
$SSP_{15}+GW_{20}$	340	200	60	1132.8	267.2	0.44	0.80
$SSP_{15}+GW_{30}$	340	200	60	999.2	400.8	0.44	0.80
$SSP_{15}+GW_{40}$	340	200	60	865.6	534.4	0.44	0.80

Fig. 5. Abrasion testes. *Source*: own study

Fig. 6. Heating of specimens. *Source*: own study

According to ISO 834-1:2025 [38], the high-temperature resistance (fire resistance) of SCSC specimens was tested at 28 days on half of the 40×40×160 mm prismatic samples placed in a muffle furnace (Fig. 6). These were exposed to high-temperature cycles of 200°C, 400°C, 600°C, and 800°C for 1 hour to ensure a uniform distribution of heat in the furnace (Fig. 7).

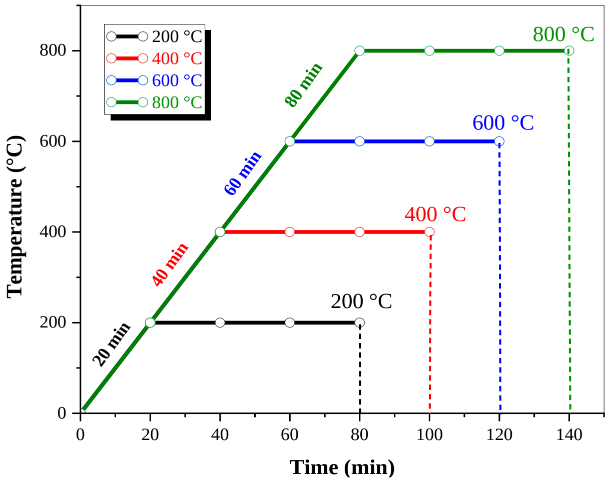


Fig. 7. Time–temperature curve of the electrically controlled furnace. *Source*: own study

3. Results and discussion

3.1. Fresh properties of SCSC mixtures

3.1.1. Setting time

Figure 8 presents the setting time results (initial and final) for the SCSC mixtures containing 0%, 5%, 10%, and 15% SSP. It can be seen that all mixtures have initial and final setting times between 30 min and 600 min, meeting the ASTM C595-08a and NF EN 197-1 standards [39,40]. Furthermore, the setting times were extended with increasing levels of cement replacement by SSP. This extension in the setting times of SCSC mixes can be attributed to the delayed reaction of SSP with water. It is well known that the high proportion of calcium oxide (CaO) in seashells (their main component), due to the dilution effect of SSP in the cement matrix, may delay the setting process [26]. The SCSC mix containing 15% SSP recorded initial and final setting times of 157 min and 197 min, respectively, which were the longest of all the mixes. Therefore, SSP can potentially be used as a set retarder in hot climates, which is advantageous for transported concrete. Adewuyi et al. [24] also observed that both the initial and final setting times of blended cement pastes increased as the level of cement replacement with seashell ash increased.

3.1.2. Workability

The slump flow diameter results of all the SCSC mixtures are shown in Fig. 9. The results indicate that the slump flow diameter of SCSC mixtures falls within the range of 270–320 mm, demonstrating acceptable deformability according to EFNARC recommendations

[33]. The slump flow diameter increased in mixes containing 5%, 10%, and 15% SSP. This increase is likely due to the fact that the hydration of SSP takes longer than that of cement, which may extend the initial setting time and leave more free water available. Conversely, mixtures with GW showed a decrease in slump flow diameter compared with those containing natural aggregate, particularly at 40% GW replacement. This reduction in slump flow diameter was attributed to the angular shape (Fig. 2b) and high water absorption of GW compared with natural aggregate (Table 1). Therefore, the use of SSP can help to reduce the need for superplasticisers in achieving the same level of workability as the control mix. These findings are consistent with previous research on the use of GW aggregates [41-43]. According to Lin et al. [44], GW with a large surface area and high water absorption takes up part of the mixing water, consequently reducing the flowability of mortar.

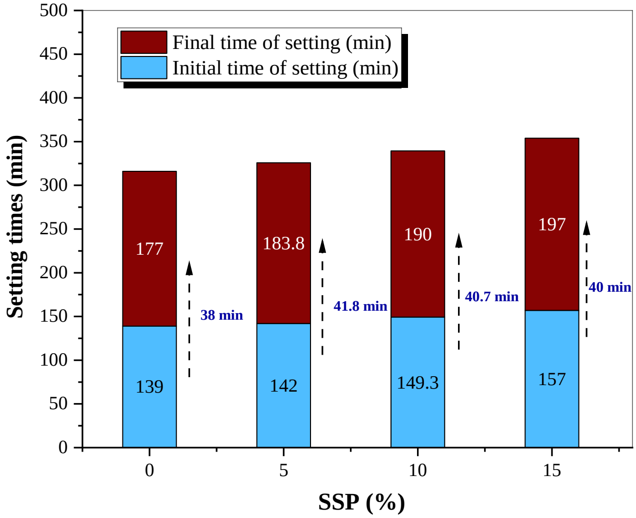


Fig. 8. Influence of SSP on initial and final setting times. *Source*: own study

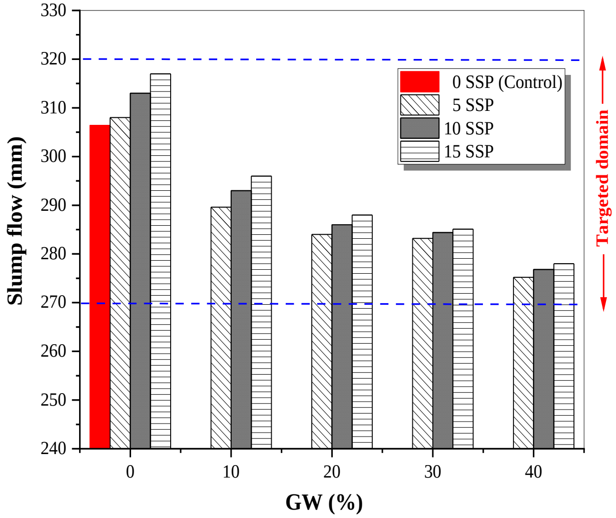


Fig. 9. Slump flow of SCSC mixtures. *Source*: own study

3.2. Hardened properties of SCSC mixtures

3.2.1. Compressive strength

The evolution of the compressive strength of the various SCSC mixtures at 7, 28, and 90 days of curing is illustrated in Fig. 10. As shown, compressive strength increased with the incorporation of SSP. However, the SCSC mixture with 15% SSP showed a reduction in compressive strength compared with mixtures containing 5% and 10% SSP. The results indicate that compressive strength values were affected differently by the various SSP substitutions. The increase in strength is attributed to the formation of calcite during the hydration reaction. By contrast, the reduction at 15% SSP is due to the formation of more voids within the microstructure of SCSC mixtures, resulting from the higher CaO content in SSP, which may react with Al_2O_3 and gypsum, thereby reducing the potential for alite hydration [45,46]. Furthermore, Fig. 10 shows that the addition of GW increased the compressive strength of SCSC mixtures at all curing ages. The 90-day compressive strength of the control SCSC mixture (without SSP and GW) was 39.97 MPa, increasing to 56.68 MPa, 57.71 MPa, and 55.16 MPa for mixtures prepared with 5%, 10%, and 15% SSP combined with 40% GW (5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW), respectively. This improvement in compressive strength may be explained by the angular shape and rough surface of GW particles, which enhance the interfacial transition zone between paste and aggregates, as well as the higher hardness of GW compared with natural sand.

3.2.2. Flexural strength

The flexural strength of SCSC mixtures after 7, 28, and 90 days of curing, with various SSP and GW substitutions, is presented in Fig. 11. The results show that flexural strength increased as the substitution of GW increased. Flexural strength values improved to 5.59 MPa, 6.03 MPa, and 5.31 MPa for 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW mixtures, respectively, compared with mixtures without GW. The variation in flexural strength with GW and SSP incorporation was similar to that observed for compressive strength. The results also show that GW had a greater effect on the development of flexural strength than SSP. The highest improvement was observed in SCSC mixtures with 10% SSP, which may be attributed to the strong interface between paste and aggregates, likely due to the high CaO content in SSP, which consequently enhanced flexural strength [47]. Additionally, the presence of GW improved the flexural strength of SCSC mixtures compared with the control (0 SSP + 0 GW). Flexural strength values of mixes with 40% GW were higher than those of the control SCSC by 36.49%, 41.12%, and 33.14% with 5%, 10%, and 15% SSP incorporation, respectively. This improvement is explained by the angular shape and rough surface of GW particles (Fig. 2b), which helped to develop a stronger transition zone between the cement paste and GW.

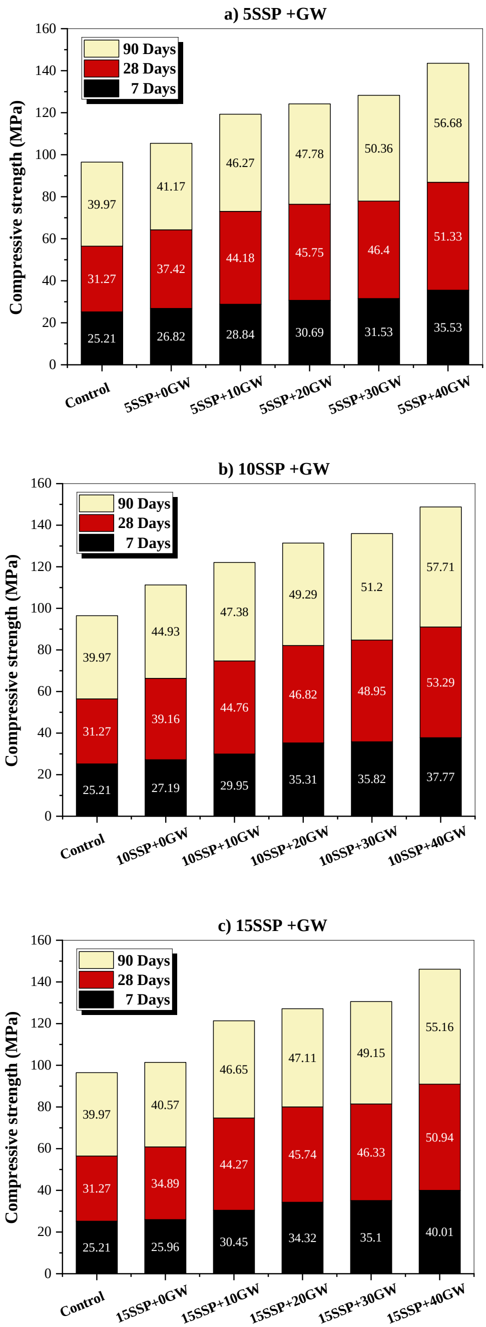


Fig. 10. Compressive strength of SCSC mixtures

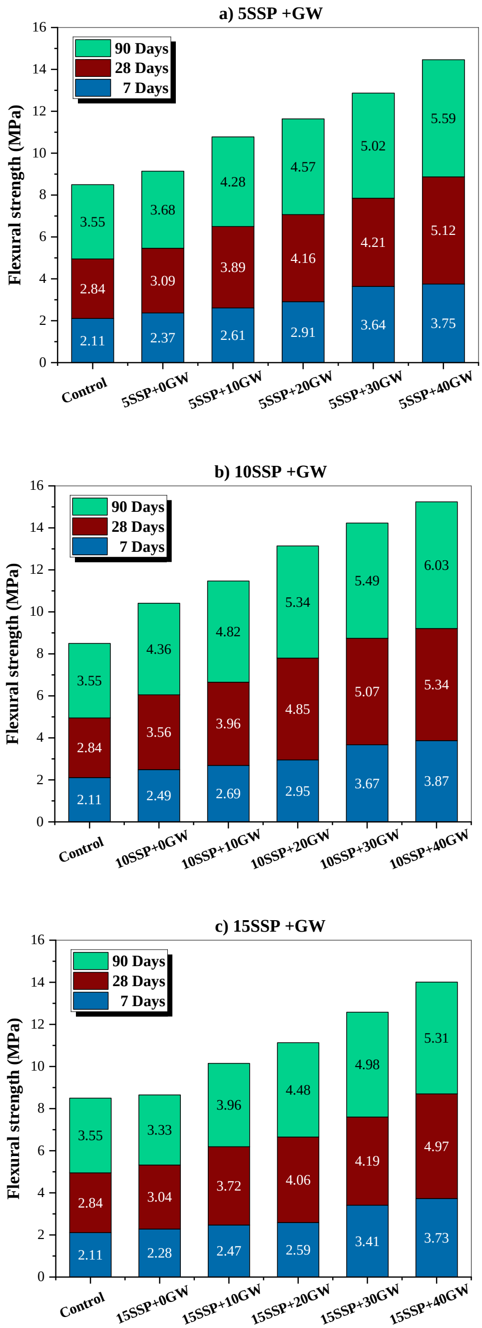


Fig. 11. Flexural strength of SCSC mixtures

3.2.3. Compactness

Figure 12 shows the compactness results of SCSC mixes at 28 days of curing. With the individual incorporation of SSP without GW (5SSP + 0GW, 10SSP + 0GW, and 15SSP +

0GW), the compactness of the SCSC mixes increased compared with the control mix. The maximum compactness was observed in SCSC mixtures containing 10% SSP. This improvement is attributed to the reduction in porosity, which can be explained by the reduced water demand of the binder as well as the fineness of SSP (8000 cm²/g), which can fill micro-pores and increase the compactness of the SCSC microstructure. It is also evident from Fig. 12 that the addition of GW increases the compactness of SCSC mixtures. The compactness values of 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW mixtures were 95.93%, 96.87%, and 95.7%, respectively, representing increases of 1.35%, 2.31%, and 1.11% compared with the control SCSC. This indicates that the presence of GW particles enhances the compactness of SCSC mixtures, resulting in denser mixes. The increase in compactness is further attributed to the rough surface of GW, which provides better adhesion with the binder. The inclusion of GW as a sand replacement reduces voids, thereby improving compactness [48].

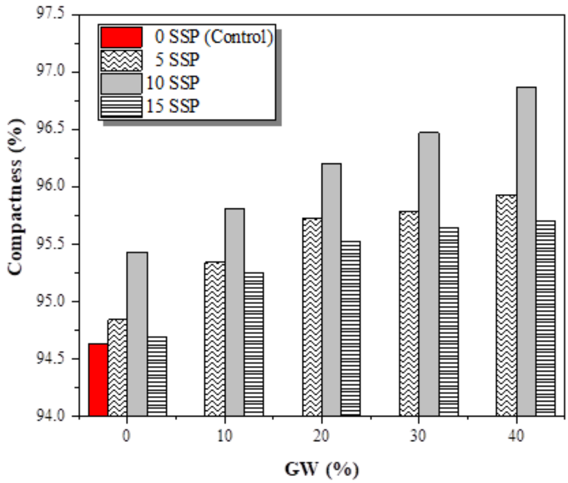


Fig. 12. Compactness of SCSC mixtures. *Source*: own study

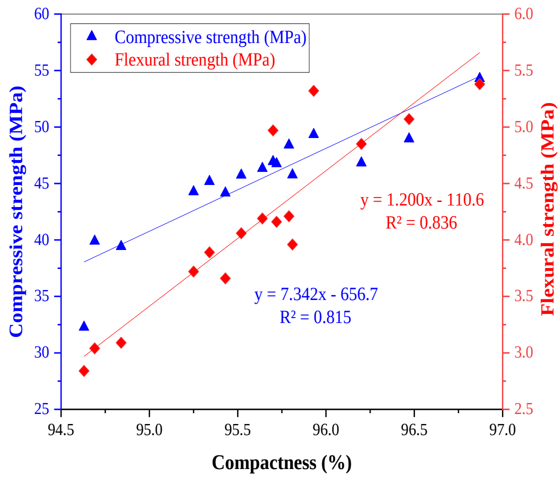


Fig. 13. Relationship between compressive and flexural strengths and compactness of SCSC mixtures. *Source*: own study

The relationship between compressive and flexural strengths and the compactness of all SCSC mixtures at 28 days is shown in Fig. 13. It can be seen that the increase in compactness is associated with an increase in mechanical strength, with high correlation coefficients ($R^2 > 0.8$).

3.2.4. Abrasion resistance

Figure 14 shows the abrasion resistance results in terms of the abrasion coefficient (mass loss) of SCSC mixes at 28 days of curing. The results reveal that the abrasion coefficient decreased with the addition of SSP and GW. For the control mixture, the abrasion coefficient was 3.87 kg/m², which decreased to 2.16 kg/m², 2.06 kg/m², and 2.52 kg/m² for SCSC mixtures prepared with 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW, respectively. The results also indicate that the optimum abrasion resistance was achieved in the SCSC mixture containing 10% SSP and 40% GW. This decrease in abrasion coefficient is attributed to the development of a denser microstructure associated with the good gradation of GW particles. Moreover, the rough surface and angular morphology of GW particles, combined with the pozzolanic reaction of SSP, provided strong bonding with the binder, reducing the likelihood of particle separation and thereby enhancing compressive strength, which in turn improves abrasion resistance [28].

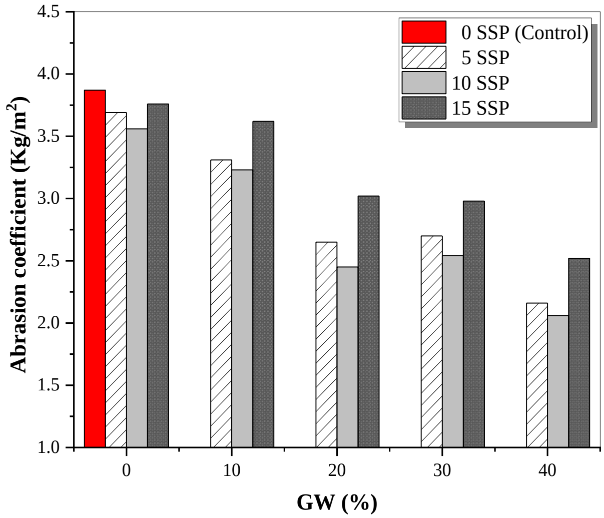


Fig. 14. Abrasion resistance of SCSC mixtures. *Source*: own study

Figure 15 shows the relationship between abrasion resistance (abrasion coefficient) and compressive strength of SCSC mixes at 28 days. A strong correlation was observed between abrasion resistance and compressive strength, with a high correlation coefficient ($R^2 \geq 0.8$), indicating that improvements in abrasion resistance are highly dependent on improvements in compressive strength.

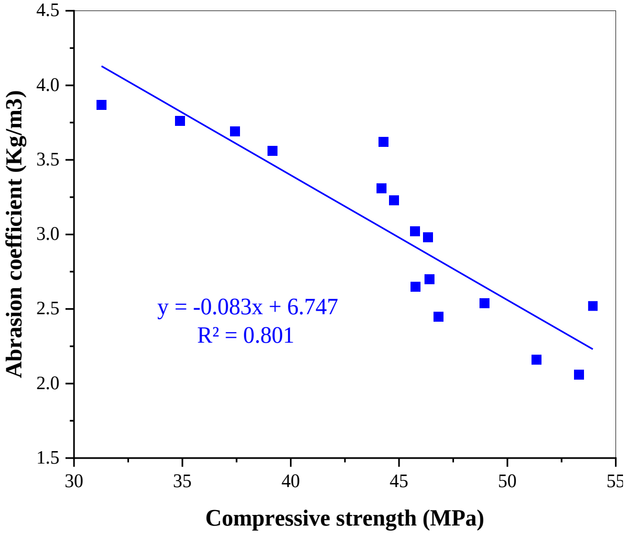


Fig. 15. Relationship between compressive strength and abrasion resistance of SCSC mixtures. *Source*: own study

3.3. Elevated temperature resistance

3.3.1. Mass loss

Figure 16 shows the impact of high temperature on mass loss in SCSC specimens. The results clearly reveal that increasing temperature led to higher mass loss in all SCSC mixtures. This increase in mass loss at elevated temperatures can be explained by the evaporation of capillary water and the decomposition of C-S-H gel and $CaCO_3$ [49]. The heat generated within the SCSC causes pore pressure, which directly induces spalling, especially at 800°C, as shown in Fig. 18. It was observed that the mass loss values of SCSC mixtures containing 5%, 10%, and 15% SSP without GW (5SSP + 0GW, 10SSP + 0GW, and 15SSP + 0GW) were higher than those of the control SCSC mixture in the temperature range of 200–800°C. This is attributed to the decomposition of seashells at high temperatures, which creates pores in the matrix. These pores contribute to crack patterns and facilitate heat dissipation [50]. In addition, 5SSP + 0GW had fewer pores than 10SSP + 0GW and 15SSP + 0GW and was unable to dissipate pore pressure effectively, which led to spalling at 800°C (Fig. 18).

Furthermore, the addition of GW decreased the mass loss of SCSC mixtures, from 7.95% for the control SCSC to 5.77%, 6.52%, and 7.02% for 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW mixtures, respectively. These values are 27.42%, 17.98%, and 11.69% lower than the control SCSC mixture at 800°C. This reduction can be attributed to improved bonding between GW aggregates and cement paste in the interfacial transition zone (ITZ), due to the angular shape and rough surface of GW particles (Fig. 2b), as confirmed by the flexural strength results (3.2.2). This stronger bonding limits water expulsion and reduces the thermal deterioration of the concrete structure [51,52]. Jain et al. [53] also reported about 6% weight loss when substituting around 60% of fine aggregate with GW in SCC exposed to fire up to 800°C.

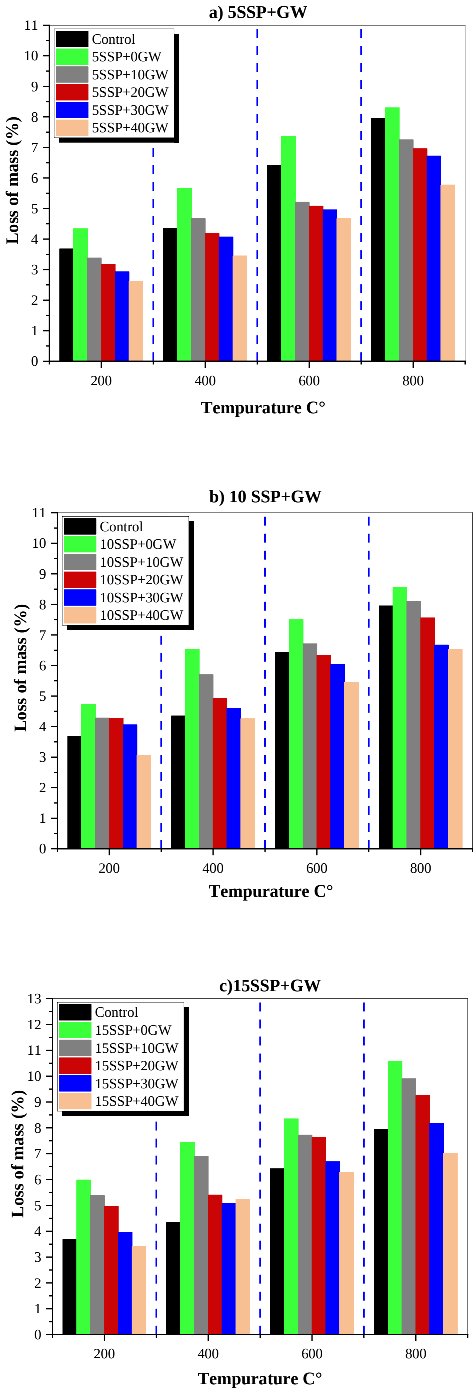


Fig. 16. Mass loss of SCSC mixtures exposed to elevated temperatures

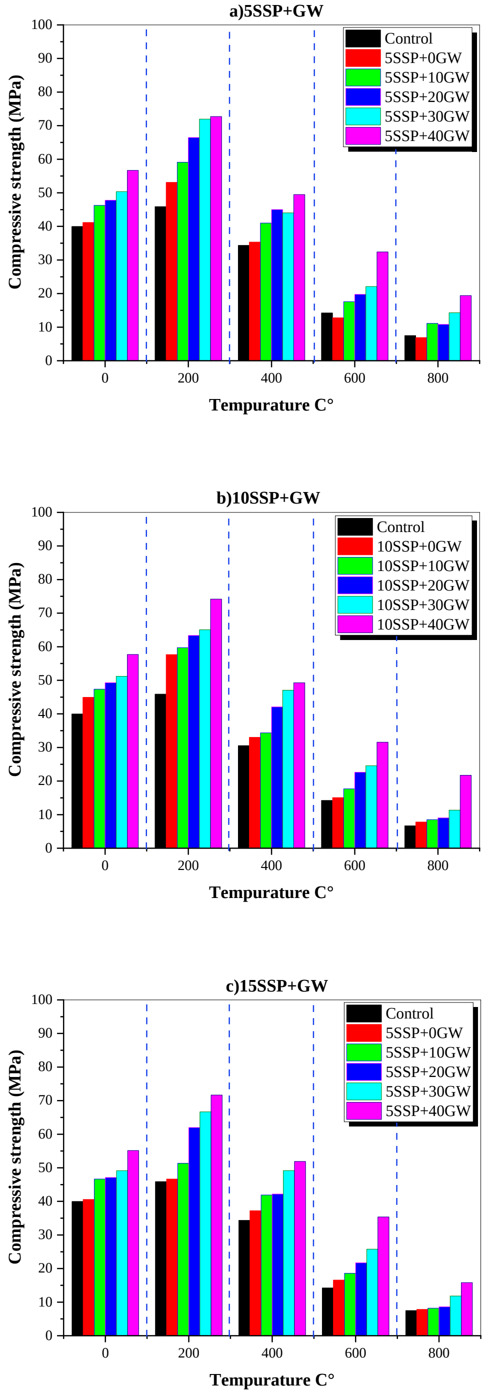


Fig. 17. Compressive strength loss of SCSC mixtures exposed to elevated temperatures

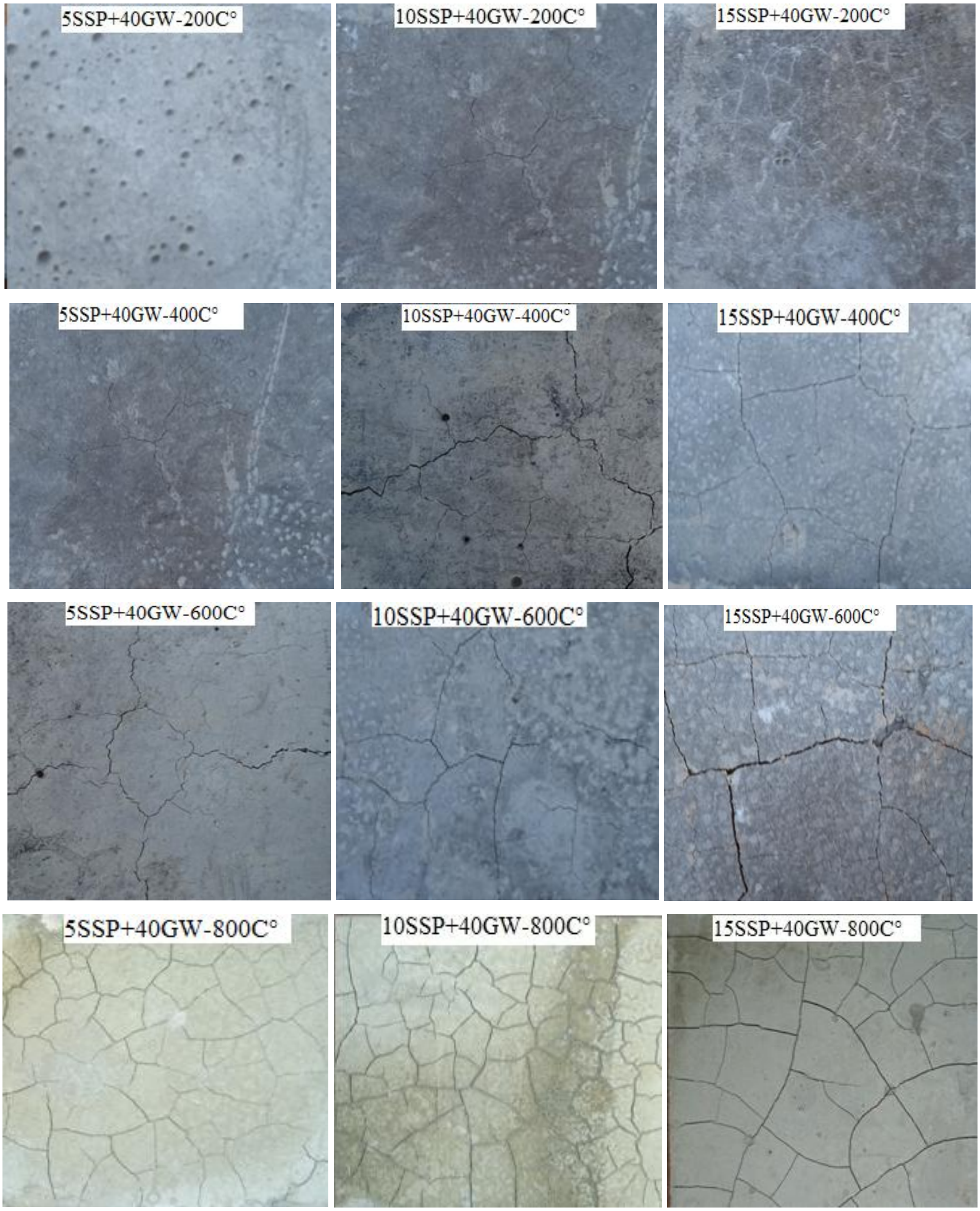


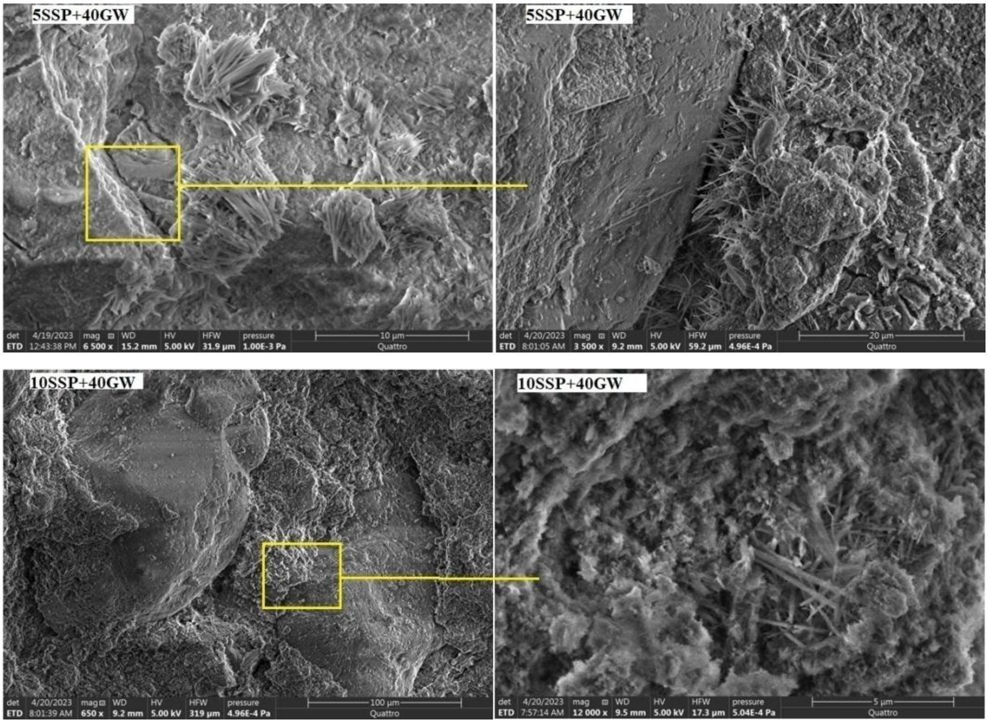
Fig. 18. Surface texture of SCSC specimens after exposure to elevated temperatures. *Source*: own study

3.3.2. Residual compressive strength

Figure 17 shows the effect of elevated temperatures of 200°C, 400°C, 600°C, and 800°C on the residual compressive strength of SCSC specimens. Three distinct stages were observed in the variation of compressive strength with temperature. Initially, as the temperature increased to 200°C, the compressive strength of all SCSC mixtures containing SSP and GW also increased, reaching a peak around this temperature. This may be due to the evaporation of chemically bound water in the hydrates, which generates strong internal pressures (Van der Waals forces) and improves compressive strength. Beyond 400°C, a linear decrease in compressive strength was observed for all SCSC mixtures with increasing temperature. At 800°C, reductions in compressive strength of 19.51 MPa, 21.14 MPa, and 15.81 MPa were recorded for 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW mixtures, respectively, compared with the control. This reduction can be explained by the loss of $Ca(OH)_2$, which increases porosity and promotes the formation of cracks and surface spalling, as shown in Fig. 18. Furthermore, the main cause of degradation at 600°C is the thermal instability of aggregates, resulting from the decarbonation of calcium carbonate ($CaCO_3$) between 600°C and 800°C. Compared with the control SCSC, the GW-based SCSC samples showed significantly improved strength retention. At all elevated temperatures, mixes with maximum GW replacement (40%) exhibited higher strength retention than other mixes. This improved performance of SCSC with GW is due to the pores generated in the matrix at higher temperatures, which reduce spalling, as well as the higher hardness of GW compared with natural sand. These findings suggest that the use of GW as a fine aggregate is highly effective in enhancing fire resistance.

3.4. Microstructure analysis

Figure 19 shows SEM images of the 5SSP + 40GW, 10SSP + 40GW, and 15SSP + 40GW mixtures after more than 90 days of curing. It is evident that the 10SSP + 40GW mixture has a denser microstructure and a stronger interfacial transition zone (ITZ) between cement paste and aggregates than the 5SSP + 40GW and 15SSP + 40GW mixtures, which exhibited more cracks. This may explain the reduction in strength in the latter. Moreover, the denser ITZ in the 10SSP + 40GW mixture is attributed to the efficient pozzolanic reaction and the generation of C-S-H hydrates provided by 10% SSP.



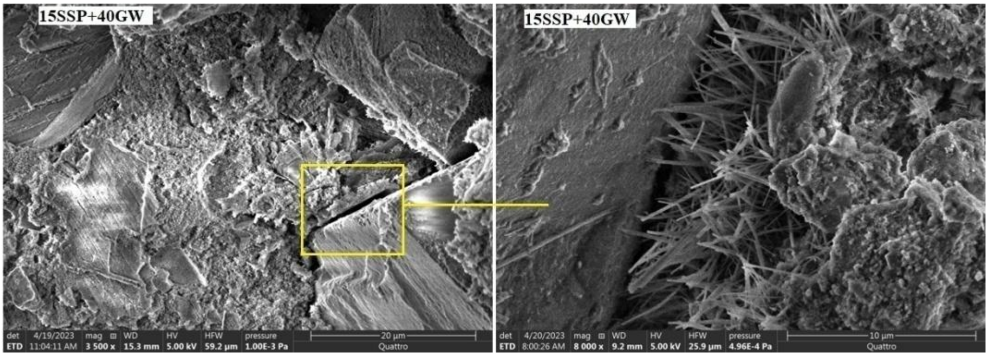


Fig. 19. SEM images of SCSC mixtures. *Source*: own study

4. Conclusions

This research examined the effect of SSP and GW as supplementary cementitious material and fine aggregate, respectively, on the behaviour of SCSC exposed to various high temperatures. Based on the results obtained, the following conclusions can be drawn:

- Replacing cement with up to 15% SSP extends the initial and final setting times of SCSC mixtures. It is therefore recommended for use as a set retarder in hot climate zones. This can also be advantageous for extending the setting time of transported concrete.
- Using up to 40% GW as a partial replacement for fine aggregate reduces the flow of SCSC, although it remains within the acceptable limits prescribed by EFNARC recommendations. However, with a low dosage of superplasticiser, the addition of SSP compensates for this negative effect and improves the flowability of GW-based SCSC. SSP can therefore be used as a water-reducing additive.
- The combined use of up to 40% GW as fine aggregate and 15% SSP as cement improves the mechanical strength, compactness, and abrasion resistance of SCSC, owing to the angular shape and rough surface of GW particles together with the filling and pozzolanic effects of SSP.
- SCSC with 10% SSP and 40% GW is considered the optimal mixture, achieving the highest compressive and flexural strengths (58 MPa and 6 MPa, respectively), compactness (97%), and the lowest abrasion coefficient (2.06 kg/m^2). This resulted in improved resistance to surface wear, potentially enhancing durability and extending service life.
- The mass loss of all SCSC specimens increased significantly, while compressive strength decreased with exposure to elevated temperatures. Replacing natural sand with up to 40% GW was found to be highly effective in increasing strength and reducing spalling and mass loss under high temperatures.
- The use of up to 10% SSP improved the microstructure and ITZ between aggregate and cement paste in GW-based SCSC mixtures. As a result, a denser microstructure, enhanced mechanical performance, and improved durability were achieved.

Based on these findings – covering fresh and hardened properties, mechanical and durability indices, and microstructural analyses – it can be concluded that the use of industrial GW and SSP waste as by-products in self-compacting sand concrete is a novel approach. This not only offers significant economic and environmental benefits but also enhances the durability and sustainability of concrete structures. The combined use of up to 40% GW as fine aggregate and 10% SSP as cement in SCSC provides superior post-fire properties, with optimum mechanical and durability performance, and is highly recommended for use in many structural applications.

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