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Orginal Article

Durability assessment of bio-based self-compacting sand concrete with recycled granite aggregate waste against chloride and sulphate attacks

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Abstract: The development of sustainable high-performance concrete with improved mechanical and durability properties while incorporating environmentally friendly components is a major concern today. This work investigates the feasibility of using granite industrial waste (GW) as a natural sand substitute by volume (10, 20, 30, and 40%) combined with seashell waste powder (SWP) as a cement substitute by weight (5, 10, and 15%) to improve the durability performance of self-compacting sand concrete (SCSC) against sulphate attack and chloride permeation. The obtained results showed the feasibility of developing eco-friendly SCSC by replacing up to 40% of sand with GW and 15% of cement with SWP, with a significant improvement in compressive strength and durability properties. However, SCSC containing 40% GW and 10% SWP showed the highest compressive strength (63 MPa), a 36.65% increase in electrical resistivity, and a 48.18% decrease in chloride-ion permeability. All SCSC mixes presented electrical resistivity greater than 20 kΩ·cm and chloride-ion passed charge below 2000 C, meeting the requirements for practical engineering applications. Furthermore, the response of the SCSC mix with GW and SWP against sulphate attack was considerably better than that of the control SCSC mix. Finally, the study results in the development of an encouraging and highly resistant concrete to extreme conditions without significant material damage, while reducing the demand for natural aggregates and conventional cement.

Keywords: chloride-ion permeability, durability, granite waste, seashell waste powder, self-compacting sand concrete, strength, sulphate attack

1. Introduction

Concrete is a construction material widely utilised for making strong and durable infrastructure elements. Along with building construction, it is also used in the construction of roads, bridges, etc. For the economic manufacturing of concrete, it should essentially be sustainable and durable. Concrete's service life and long-term resistance to aggressive environmental exposures are closely related to its durability [1-3]. Usually, concrete with low void content and minimal cracking, and high resistance, is less susceptible to chemical attacks that cause mechanical and durability damage. The primary impacts of all chemical attack mechanisms on the longevity of concrete are caused by gases and water, as well as hazardous substances that are transported through voids and cracks in the concrete's microstructure [4]. However, the transport of aggressive materials inside concrete and their interaction are important contributors to the evolution of its deterioration process [5].

The building and cement industries have emerged as major environmental protection challenges in recent years, considering that the building sector is one of the largest consumers of natural materials, a significant producer of waste, and a source of environmental pollution [6]. The cement and concrete industries are responsible for most of the sustainability and environmental pollution problems, such as raw material extraction, cement and aggregate production, and the transportation of these materials to the concrete building site [7]. Several environmental authorities worldwide are pushing the construction sector to reduce the amount of raw material consumption (cement and aggregates) used in concrete manufacturing in order to protect the environment. Additionally, they encourage the use of recycled industrial waste and by-product materials as aggregate and supplementary cementitious materials (SCMs) [8]. For this purpose, industrial products, by-products, mineral additives, and certain chemicals may also be used [9-14].

In recent decades, the high demand for infrastructure expansion has driven significant growth in cement production. To meet this demand, a substantial amount of cement or other supplementary materials is required. Cement consumption exceeded 4.1 billion tonnes in 2018, making it the second most consumed material after water. The cement industry is highly energy-intensive and environmentally polluting. Around 5% of the world's CO_2 emissions are currently produced by cement manufacturing [15]. In the coming years, it is anticipated that cement demand will rise by more than 8%, which is particularly high for a single industry [16]. Additionally, it has been demonstrated that replacing cement with supplementary cementitious materials (SCMs) can reduce energy consumption and CO_2 emissions [17]. Seashell waste accumulated in coastal areas (Fig. 1a) can be recovered and processed to be used as a partial cement replacement. Seashells contain a high percentage of calcium oxide (CaO), which can enhance the performance of concrete [18]. About 45,000 tonnes of seashell waste are produced annually worldwide [19]. The available literature indicates that several researchers have used seashell waste in concrete as a substitute for cement [20,21]. Tayeh et al. [19] studied the replacement of cement by 5%, 10%, 15%, and 20% seashell powder on the mechanical and durability properties of concrete. They observed an improvement in compressive strength and alkali attack resistance with 5% seashell powder. Lertwattanaruk et al. [22] also found that the partial substitution of cement with 5% seashell improved the 7- and 28-day compressive strengths of mortar compared to the control mix. Kong et al. [23] reported that using 0% to 40% seashell waste as a cement substitute can reduce CO_2 emissions by up to 52%. Adewuyi et al. [24] found a 7.89% improvement in the compressive strength of concrete when substituting cement with seashell. Furthermore, Abdelouahed et al. [25] studied the effect of partially replacing cement with 5% to 20% seashell waste on concrete durability; the results showed a reduction in chloride ion penetration for concrete with 10% seashell waste.

The global demand for natural aggregates for concrete manufacturing is expected to grow to 47 billion tonnes per year by 2025 [26]. The main negative impacts of aggregate mining on the ecosystem include the depletion of natural resources, changes in regional landscapes, and desertification [27,28]. The replacement of natural aggregates with recycled industrial waste has proven to be an extremely effective solution for environmental protection [29-35]. Granite is one of the most widely used materials in the construction industry. During the crushing and cutting processes of granite, about 30% of waste (GW) is generated and disposed of in landfills (Fig. 1b) [36,37]. According to the available literature, several studies have been conducted on the possibility of using GW to partially replace fine aggregates in the manufacturing of cementitious materials [38-42]. Joel [43] observed an improvement in concrete compressive strength when up to 20% of fine aggregate was substituted with crushed GW. Vijayalakshmi et al. [44] examined the effect of partially replacing fine aggregate with up to 25% GW on the mechanical and durability properties of concrete. The results showed a significant reduction in concrete workability with increased GW content. However, the compressive and flexural strengths, chloride ion permeability, and carbonation resistance of concrete containing 5% to 15% GW were comparable to those of concrete made with natural aggregates. Divakar et al. [45] found that substituting 35% of fine aggregate with GW increased compressive strength by 22%. Similarly, Singh et al. [46] observed an improvement in compressive strength and a decrease in concrete permeability when GW partially replaced 25% of fine aggregate. According to Singh et al. [47], replacing 30% of natural sand with GW in concrete was found to be optimal based on improved durability and mechanical strength characteristics.

It appears from the above research that using SWP as a cementitious material and GW as a fine aggregate can contribute to the development of durable and sustainable building materials. However, the durability performance of concrete based on GW aggregates combined with SWP as a cement substitute has not yet been studied. Therefore, the present experimental study aims to examine the strength and durability behaviour under adverse exposure conditions of SCSC incorporating GW as a natural sand replacement, combined with SWP as an SCM, in order to reduce natural resource consumption and CO_2 emissions, and to understand the long-term performance of SCSC made with GW and SWP when exposed to harmful and aggressive substances. The properties of SCSC made with GW as sand, supplemented with SWP, were analysed in terms of compressive strength, electrical resistivity (ER), rapid chloride-ion permeability (RCIP), and resistance to sulphate attack. Furthermore, SEM analysis was also conducted to examine the microstructure of selected SCSC mixes.

Fig. 1. (a) Raw seashells and (b) industrial granite waste

2. Materials and methods

2.1. Raw materials

The natural sand used in this study is river sand (NRS) from the Oued Souf quarry, with a nominal maximum size of 3.15 mm. Granite waste (GW) particles with a maximum nominal size of 4 mm, obtained after crushing by a Los Angeles machine and sieving granite cutting debris, were used as recycled aggregates. The physical properties, chemical composition, and sieve analyses of NRS and GW particles are given in Table 1 and Fig. 2, respectively. The scanning electron microscopy (SEM) images, presented in Fig. 3, clearly show that GW particles are more angular and rougher than NRS particles.

Ordinary Portland Cement (OPC) grade 43 MPa, complying with the NF EN 197-1 standard [48], was used to produce all SCSC mixes. Marble powder (MWP), obtained from the marble plate cutting and polishing industry, was used as filler in the SCSC mixes. The seashell waste used was collected from local beaches. After being cleaned by immersion in water for 24 hours to remove any traces of salt, it was heated at 105 °C for 24 hours to achieve a fully dry state, then crushed, sieved (< 80 µm), and burnt in a muffle furnace for 2 hours at 650 °C to produce seashell waste powder (SWP). The chemical and physical characteristics of OPC, MWP, and SWP are shown in Table 1, and their particle size distributions are shown in Fig. 4. The XRD analysis results of SWP, depicted in Fig. 5, showed that the mineralogical composition of calcined SWP is 98% calcium hydroxide ($Ca(OH)_2$) and calcium oxide (CaO).

To achieve satisfactory fluidity for the SCSC mixtures, a high-water-reducing polycarboxylate from the GRANITEX factory, with a solids content of 30% and a density of 1.08, was used as a superplasticiser. Tap water complying with the NF EN 1008 standard [49] was used to mix all SCSC mixtures and to store the prepared samples.

Table 1. Physical characteristics and chemical composition of cement, MWP, and SWP

Chemical Constituent(%)	Cement	MWP	SWP	NRS	GW
CaO	56.35	94.31	95.06	1.70	11.30
SiO_2	23.83	0.27	0.11	90.50	48.90
Al_2O_3	6.05	4.39	4.07	4.60	19.50
Fe_2O_3	4.66	0.12	0.10	0.50	12.00
MgO	2.44	0.56	0.22	0.20	5.30
K_2O	0.83	-	-	1.90	1.40
SO_3	2.37	0.06	0.11	0.70	0.30
Cl	-	0.10	0.10	-	-
Loss on ignition	1.72	41.90	-		
Physical properties					
Density (g/cm^3)	3.11	2.73	2.88	2.63	2.51
Blaine's specific surface area (cm^2/g)	3420	2700	8000		-
Fineness modulus	-	-	-	2.33	2.68
Water absorption (%)	-	-	-	0.96	4.34

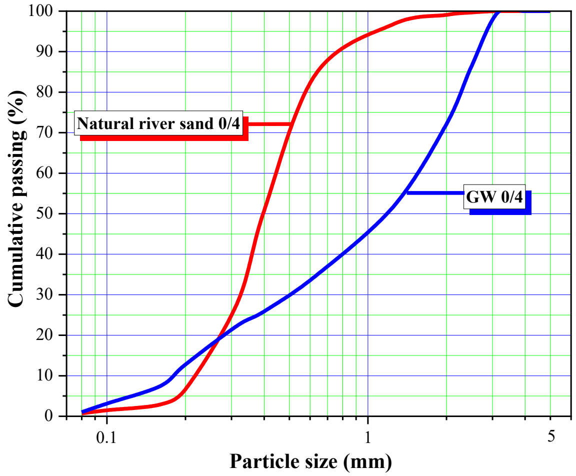


Fig. 2. Particle size distribution of natural river sand and GW

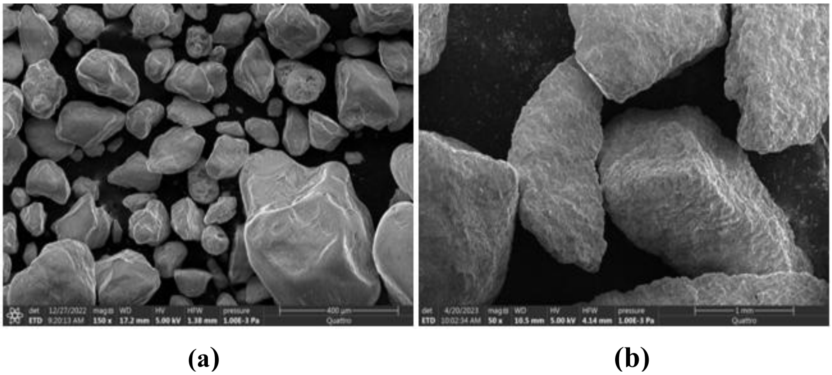


Fig. 3. SEM image of (a) NRS and (b) GW particle

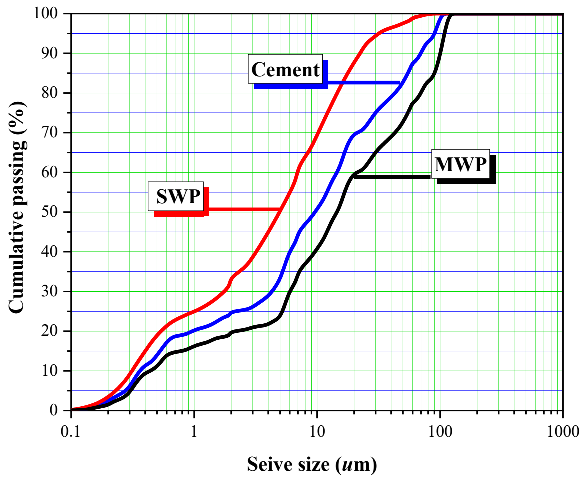


Fig. 4. Particle size distribution of cement, MWP, and SWP

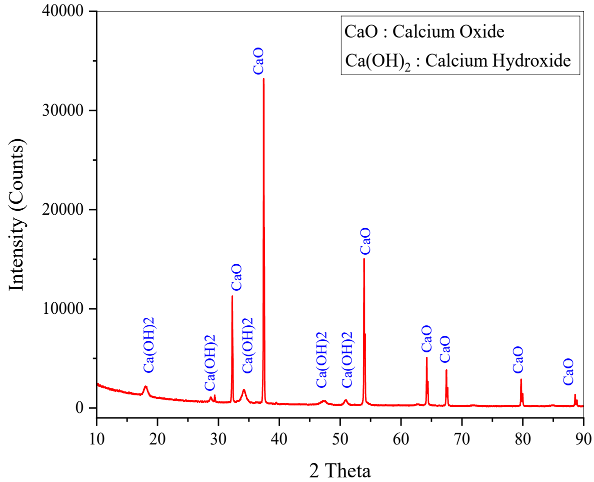


Fig. 5. XRD result of seashell waste powder

2.2. Preparation of mixtures and samples

In this study, the theoretical method presented by the SABLOCRETE project [50] was used to formulate all self-compacting sand concrete (SCSC) mixes, with a fixed water/binder ratio of 0.44. Sixteen SCSC mixes were produced: one control mix with 100% cement and 100% NRS, and fifteen other mixes with 5%, 10%, and 15% replacement of cement by SWP, and 10%, 20%, 30%, and 40% replacement of NRS by GW, according to the weights presented in Table 2. To achieve satisfactory workability, the amount of superplasticiser (SP) was adjusted for each SCSC mix by measuring the mini slump flow, as recommended by Edamatsu and Ouchi [51]. Superplasticiser was incorporated as a percentage of the binder mass. In this study, the target slump flow diameter was set at 270 ± 10 mm.

Table 2. Mix proportions of different SCSC mixes

Mix. ID	Binder			Fine aggregate		W/B ratio	SP (%)
	OPC (kg/m^3)	MWP (kg/m^3)	SWP (kg/m^3)	River sand (kg/m^3)	GW (kg/m^3)		
Control	403.86	201.93	0	1400	0	0.44	0.80
SWP_5+GW_0	380.82	201.93	20.04	1400	0	0.44	0.75
$SWP_{10}+GW_0$	360.78	201.93	40.08	1400	0	0.44	0.75
$SWP_{15}+GW_0$	340.74	201.93	60.12	1400	0	0.44	0.75
SWP_5+GW_{10}	380.82	201.93	20.04	1266.4	133.6	0.44	0.80
SWP_5+GW_{20}	380.82	201.93	20.04	1132.8	267.2	0.44	0.80
SWP_5+GW_{30}	380.82	201.93	20.04	999.2	400.8	0.44	0.80
SWP_5+GW_{40}	380.82	201.93	20.04	865.6	534.4	0.44	0.80
$SWP_{10}+GW_{10}$	360.78	201.93	40.08	1266.4	133.6	0.44	0.80
$SWP_{10}+GW_{20}$	360.78	201.93	40.08	1132.8	267.2	0.44	0.80
$SWP_{10}+GW_{30}$	360.78	201.93	40.08	999.2	400.8	0.44	0.80
$SWP_{10}+GW_{40}$	360.78	201.93	40.08	865.6	534.4	0.44	0.80
$SWP_{15}+GW_{10}$	340.74	201.93	60.12	1266.4	133.6	0.44	0.80

Mix. ID	Binder			Fine aggregate		W/B ratio	SP (%)
	OPC (kg/m^3)	MWP (kg/m^3)	SWP (kg/m^3)	River sand (kg/m^3)	GW (kg/m^3)		
SWP_{15}+GW_{20}	340.74	201.93	60.12	1132.8	267.2	0.44	0.80
SWP_{15}+GW_{30}	340.74	201.93	60.12	999.2	400.8	0.44	0.80
SWP_{15}+GW_{40}	340.74	201.93	60.12	865.6	534.4	0.44	0.80

2.3. Tests procedures

2.3.1. Compressive strength test

For each SCSC mixture, nine prismatic samples of 4 × 4 × 16 cm were produced to examine the compressive strength at 28, 90, and 180 days (three samples for each age group), according to the NF EN 196-1 standard [52], using a 250 kN compression testing machine with an applied load rate of 140 kg/cm²/min.

2.3.2. Electrical resistivity test (ER)

The electrical resistivity (ER) of SCSC was tested using an electrical resistivity meter (CERM) supplied by AIMIL Ltd. ER was first measured using the two-point uniaxial method, employing a handheld resistance measuring device with a frequency range of 0.5 to 10 kHz and external metal plates (Fig. 6). The test was performed in accordance with the ASTM C1760 standard [53] on 90-day-old SCSC samples with a diameter of 100 mm and a thickness of 50 mm. Based on Ohm's Law, the current passing through the samples as a result of the applied potential difference was measured. The following formula was used to determine the electrical resistivity:

Electrical resistivity (kΩ.cm), $y = R(A/l)$

where: R – the electrical resistance, A – the surface area of the samples, and l – the samples height.

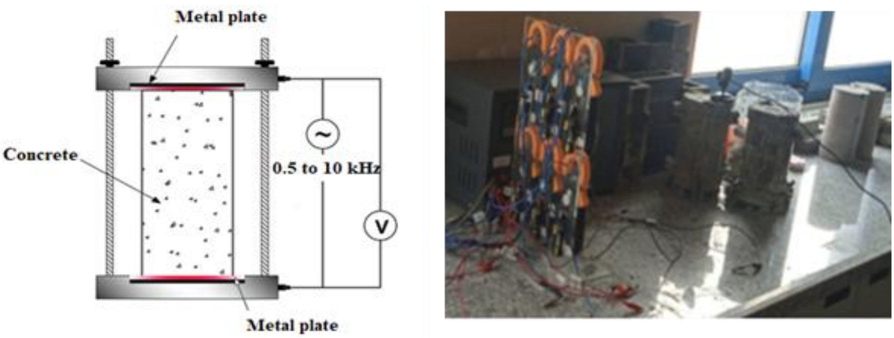


Fig. 6. Electrical resistivity test

2.3.3. Rapid chloride-ion permeability test (RCIP)

The permeability to chloride ions is an important characteristic in determining concrete durability. The test was carried out at 90 days of age according to the ASTM C1202 standard

[54], on samples measuring 50 mm in thickness and 100 mm in diameter. Sixteen samples were immersed in a solution containing 0.3% sodium hydroxide (NaOH) and 3% sodium chloride (NaCl). The results of the RCIP test were recorded every 30 minutes, from 0 to 360 minutes. The following formula was used to calculate the quantity of charge passed through SCSC samples subjected to 60 V for 6 hours (Fig. 7):

$$Q(Coulombs) = 900\left(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + 2I_{360}\right)$$

where: Q – charge passed in coulombs and I – current passed in amperes at time intervals 0, 30, 60, 90…, and 360 minutes.

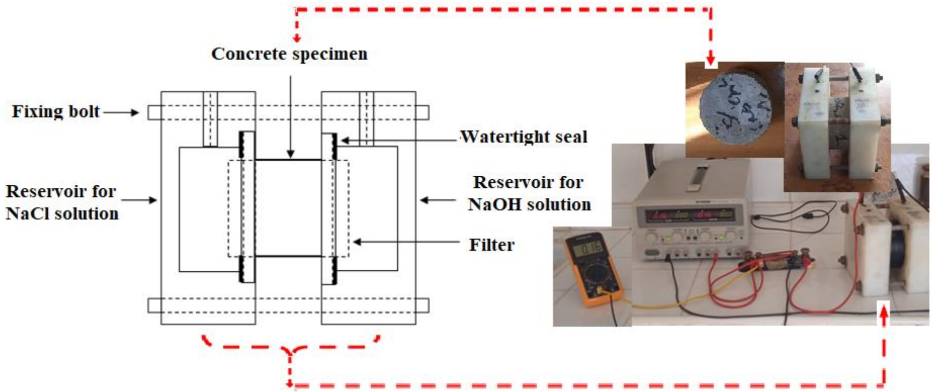


Fig. 7. Rapid chloride-ion permeability test

2.3.4. Sulphate attack test

Concrete's pH is greater than 12, making it highly alkaline. Thus, the reaction of the sulphate solution with cement pastes produces calcium sulphate and a highly soluble salt, resulting in a loss of concrete strength. The resistance of the studied SCSC mixtures against sulphate attack (ASR) was tested on 40 × 40 × 160 mm prismatic specimens aged 90 days, according to the ASTM C1012 standard [55]. For this test, all samples were weighed; half were immersed in lime-saturated water, and the others were immersed in a 5% concentration magnesium sulphate ($MgSO_4$) solution (Fig. 8). After being submerged for 180 days, the specimens were dried at 105 °C for 24 hours, then weighed and crushed to determine their losses in mass and compressive strength. The losses in weight and compressive strength were evaluated using the following formulas:

$$\text{Loss in weight (\%)} = \frac{W(t_{day}\,water) - W(t_{day}\,\text{sulfate})}{W(t_{day}\,water)} \times 100$$

$$\text{Compressive strength loss (\%)} = \frac{fc(t_{day}\,water) - fc(t_{day}\,\text{sulfate})}{fc(t_{day}\,water)} \times 100$$

where: $W(t_{day}\ water)$ – initial weight of the concrete specimens before t days of immersion in lime-saturated water, and $W(t_{day}$ sulphate$)$ – final weight of the concrete specimens after t days of immersion in sulphate solution; *fc*(t_{day} *water)* – compressive strength of concrete after t days of immersion in lime-saturated water, and *fc*(t_{day} *sulphate)* – compressive strength of concrete after t days of immersion in sulphate solution.

Fig. 8. SCSC specimens exposed to sulphate attack ($MgSO_4$)

2.3.5. SEM analysis

To determine the morphology of some SCSC mixes, microstructural analysis using scanning electron microscopy (SEM) was performed and compared with the control SCSC mix. For this analysis, 10 × 10 × 10 mm cubic samples aged 180 days were taken for each examined SCSC. The samples for this test were dried for 24 hours at a temperature of 105 ± 5 °C and then polished using a diamond paste on their surfaces. The morphology of the control SCSC and mixes containing SWP and GW was analysed using a VEGA3-TESCAN SEM with a 25 kV accelerating voltage.

3. Results and discussion

3.1. Compressive strength

Figure 9 displays the compressive strength results for different SCSC mixes at 28, 90, and 180 days. All SCSC mixes were found to have compressive strengths superior to that of the control mix. The mixes with 40% GW and 5%, 10%, or 15% SWP showed the highest 180-day compressive strengths, measuring 60.44 MPa, 63.4 MPa, and 57.43 MPa, respectively, compared to 48 MPa for the control SCSC, with improvement rates of 20.58%, 24.29%, and 16.41%. This increase in compressive strength may be attributed to the rough surface of GW particles (Fig. 3b) and the addition of SWP, which fills the pores and enhances the ITZ between the aggregates and cement paste [56,57]. According to Ostrowski et al. [57], irregular aggregates provide greater compressive strength due to lower axial and transverse deformations under load [58]. Similarly, Chen et al. [39] and Cheah et al. [59] found higher concrete compressive strength when replacing up to 60% of natural sand (NS) with GW. In geopolymer concrete, using 50% granite waste as fine particles, Nuaklong et al. [60] observed increases of around 27% and 40% in 7- and 28-day compressive strengths, respectively. Ahmadi et al. [61] also discovered that foamed concrete using sand from granite waste had an 8% improvement in compressive strength. In addition, the pozzolanic reaction of SWP with calcium hydroxide ($Ca(OH)_2$) contributes to this improvement in compressive strength at later ages (90 and 180 days), consistent with observations made by other authors [18,62].

Beyond 10% SWP, the compressive strength would be reduced due to the decreasing amount of clinker, as well as the high concentration of CaO caused by the increasing amount of SWP, which affects the dilution potential of cementitious materials [63,64]. Similarly, Okoro and Oyebisi [65] found that 10% substitution of cement with seashells gave the highest compressive strength of geopolymer concrete at early and later ages.

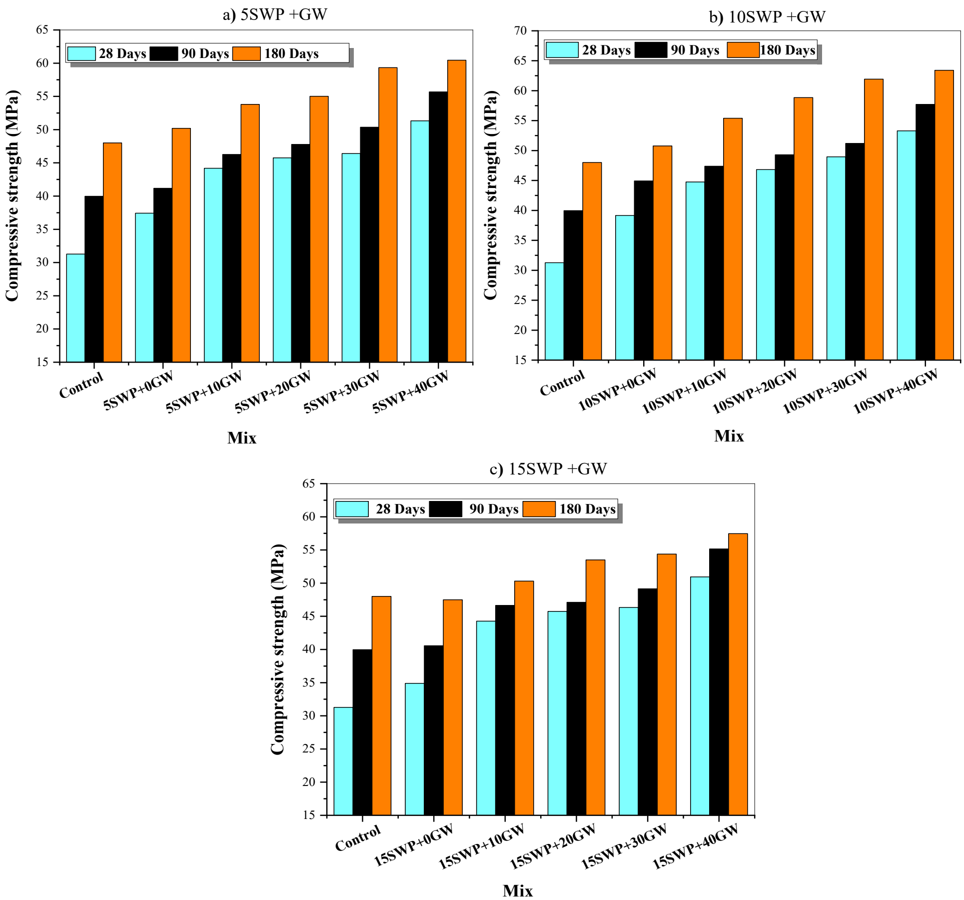


Fig. 9. Compressive strength of SCSC mixtures

3.2. Electrical resistivity

Electrical resistivity (ER), a measure closely correlated with the material's porous structure, can be used to assess the durability of concrete. Higher ER may translate into increased corrosion resistance caused by chemical ion penetration [66]. According to Shamsad et al. [67], corrosion cannot occur at ER values higher than 20 kΩ·cm. Based on the ER values (>20 kΩ·cm) presented in Fig. 10, all SCSC mixes exhibited low corrosion tendency compared to the electrical resistivity thresholds for depassivated steel. An increase in ER values is observed with increasing substitution of natural sand with GW. The ER values improved to 39.16 kΩ·cm, 44.31 kΩ·cm, and 37.57 kΩ·cm for mixtures with 40% GW and 5%, 10%, and 15% SWP, respectively, compared to 27.65 kΩ·cm for the control SCSC mixture, with improvement rates of 28.31%, 36.65%, and 25.28%, respectively. This development may be explained by the fact that increasing GW results in a reduction of voids, leading to a rise in ER, which is advantageous for structural concrete. Additionally, adding SWP benefits the ER values of the GW-based SCSC compared to the control SCSC. However, mixes with 10% SWP show the greatest improvement in ER.

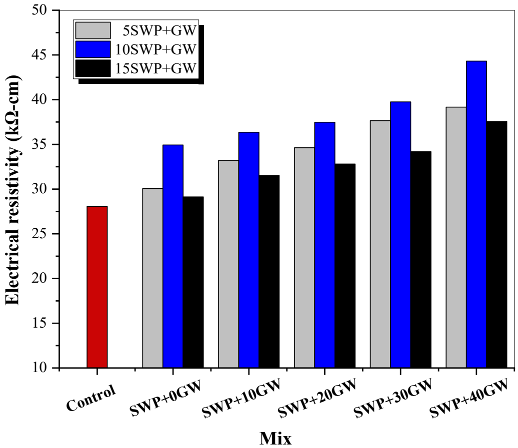


Fig. 10. Electrical resistivity test of SCSC mixtures

3.3. Rapid chloride-ion permeability

Chloride permeability, defined as the ability of a material to be penetrated by chloride ions, is an important parameter for assessing the durability of reinforced structural concrete [68]. Figure 11 shows the results of the 90-day rapid chloride-ion permeability of SCSC mixtures based on SWP and GW. The passed charge was 1594 C for the control SCSC mixture and decreased to 904 C, 826 C, and 1015 C for SCSC mixtures made with 5% SWP + 40% GW, 10% SWP + 40% GW, and 15% SWP + 40% GW, respectively, representing a reduction rate of 43.28%, 48.18%, and 36.32% compared to the control SCSC. This indicates the positive impact of SWP and GW on the reduction of chloride-ion permeability. These findings are consistent with those observed by Balasubramaniam et al. [69] and Li et al. [70] for replacement levels of natural sand by GW less than 40%. According to Jain et al. [71], a 44% reduction in the concrete passing charge was found at the 30% replacement level of NS by GW.

In addition, for all GW contents, the lowest chloride-ion permeability results were obtained by SCSC mixtures prepared with 10% SWP. Therefore, the best SCSC against chloride-ion permeability was with 10% SWP and 40% GW, with the lowest passed charge (826 C). This reduction in chloride-ion permeability can be attributed to the high fineness of SWP (8000 cm²/g) and the production of supplementary C-S-H gel through the pozzolanic reaction of $Ca(OH)_2$ with SWP, which filled the pores and compacted the microstructure. Based on their passed charge values between 1000 and 2000 C and according to the chloride-ion permeability classifications indicated by the ASTM C1202-12 standard [54], all studied SCSC mixtures can be classified in the category of low chloride-ion permeability and can be used in marine environments (Fig. 11).

The SCSC mixes' chloride-ion permeability results (passed charge) and electrical resistivity are correlated, as shown in Fig. 12. The figure illustrates a strong correlation

($R^2 > 0.9$) between the two parameters for SCSC mixes with SWP and GW, suggesting that chloride-ion permeability tends to decline as electrical resistivity increases. Therefore, the ER measurement can be used as an effective in-situ non-destructive technique for predicting concrete damage caused by chloride-induced steel corrosion.

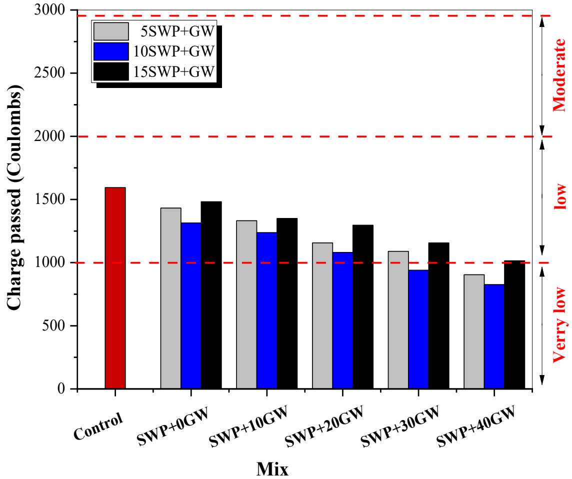


Fig. 11. Passed charge of chloride-ion permeability test of SCSC mixtures

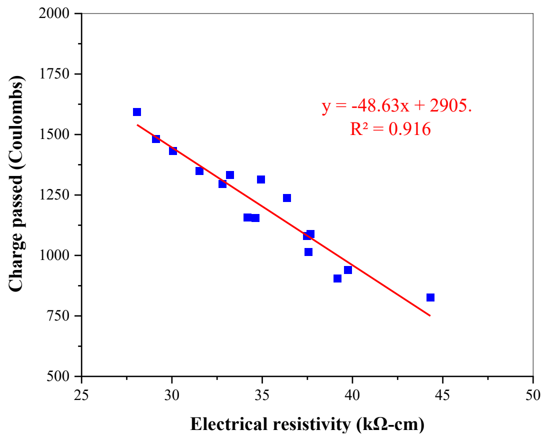


Fig. 12. Correlation between electrical resistivity and chloride-ion passed charge of SCSC mixtures

3.4. Resistance to sulphate attack

The assessment of sulphate attack resistance of concrete is imperative, especially for reinforced concrete exposed to chemical agents. The results of compressive strength and mass losses due to sulphate attack in SCSC based on GW and SWP are shown in Fig. 13. The mass and compressive strength losses of the 5% SWP + 40% GW, 10% SWP + 40% GW, and 15% SWP + 40% GW mixtures were lower than those of the control SCSC. This may be due to the finer granite particles packing the concrete more densely than natural sand. In addition, the inclusion of SWP as a cement substitute enhanced the concrete's resistance to chemical attacks. For the control SCSC, the losses in mass and compressive strength were

5.25% and 20.09%, respectively, and decreased to 2.93%, 2.04%, and 3.33% for mass loss, and 11.79%, 9.46%, and 12.11% for compressive strength loss, for the 5% SWP + 40% GW, 10% SWP + 40% GW, and 15% SWP + 40% GW mixtures, respectively. According to the literature, most studies showed that including GW might preserve or improve concrete sulphate resistance [5,44,72]. Zafar et al. [41] found a reduction of about 65.8% and 54.3% in strength and weight losses, respectively, in H_2SO_4 solution for concrete with 20% GW as natural sand. Furthermore, it is clearly shown from Fig. 13 that SCSC with 10% SWP has higher sulphate resistance compared to mixtures with 5% and 15% SWP; this is justified by the lower percentage of pores in the mixtures, which prevents the penetration of sulphate into SCSC mixtures [73,74].

As reported by Melara et al. [75], electrical resistivity, which is closely linked to ionic mobility in the material, can serve as an indicator of concrete's durability against sulphate attack. Figure 14 shows the linear relationship between compressive strength loss due to sulphate attacks and electrical resistivity for all SCSC mixtures. As shown in this figure, there is a good correlation coefficient (R^2 = 0.81), which could be explained by the fact that sulphate attack depends directly on the total porosity of the material.

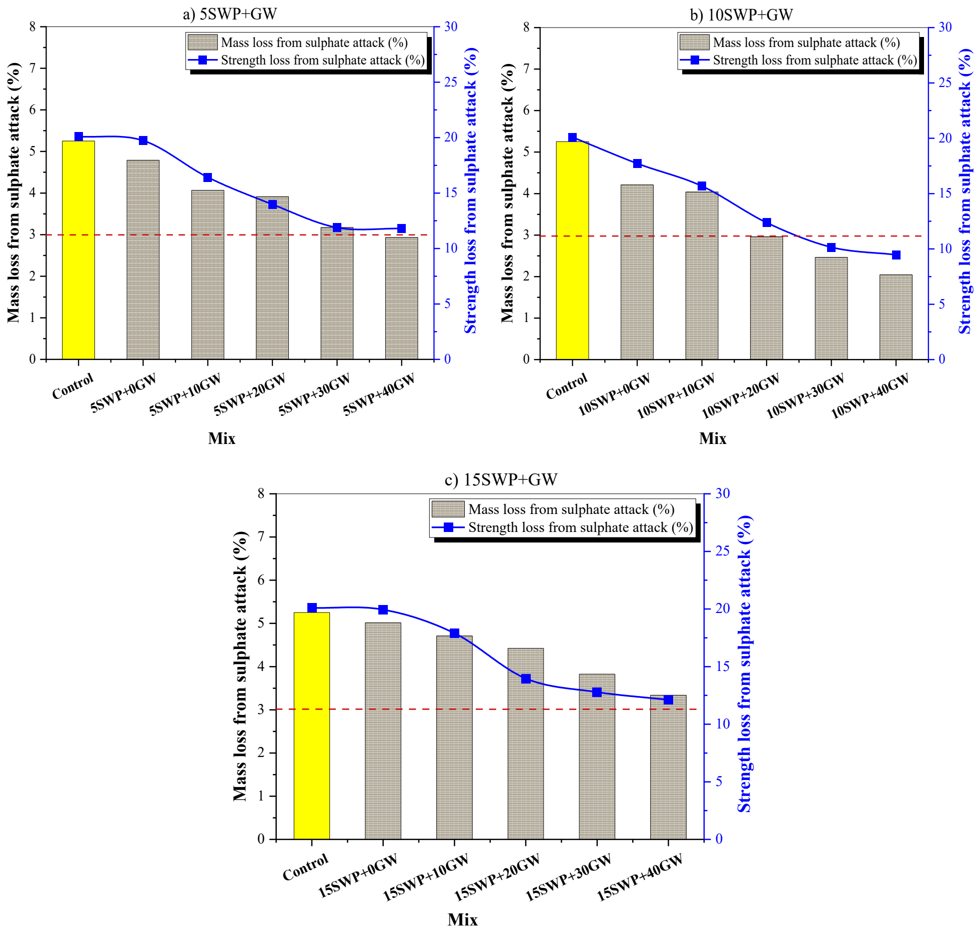


Fig. 13. Loss in mass and compressive strength of SCSC mixtures due to sulphate attack

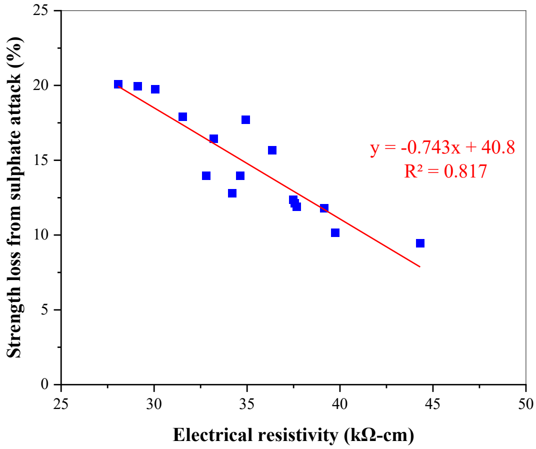
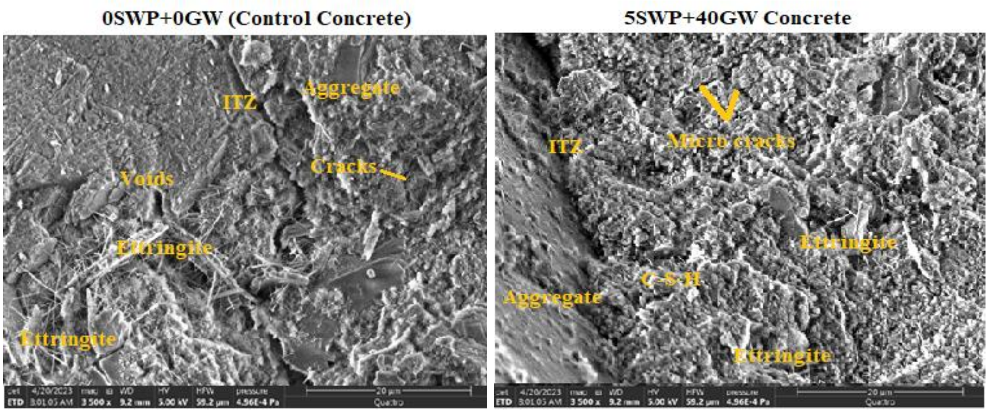


Fig. 14. Correlation between electrical resistivity and compressive strength loss of SCSC mixtures from sulphate attack

3.5. Microstructural analyses (SEM)

Figure 15 illustrates the SEM images of the control SCSC, 5% SWP + 40% GW, 10% SWP + 40% GW, and 15% SWP + 40% GW mixes. This figure indicates that the mixtures containing SWP and GW are more compact and have a stronger ITZ between the cement paste and aggregates than the control SCSC. This can be explained by the fact that the pozzolanic processes are responsible for consuming most of the portlandite ($Ca(OH)_2$). Additionally, the increased number of irregularly shaped GW particles contributes to improving the ITZ properties and supports the increase in strength for these mixtures [76]. In addition, SCSC samples with 5% and 10% SWP showed fewer pores and better packing at the ITZ compared to SCSC samples with 15% SWP, which displayed enlarged voids and higher porosity between the aggregate and cement paste. This may be due to the lack of CH hydrate, whereby the SWP would act as an inert phase in the cement paste and would not contribute to the synthesis of new C-S-H hydrates [77]. It can be concluded that the 10% SWP + 40% GW mix has the densest microstructure and strongest ITZ between the cement paste and aggregates compared to the other mixes.



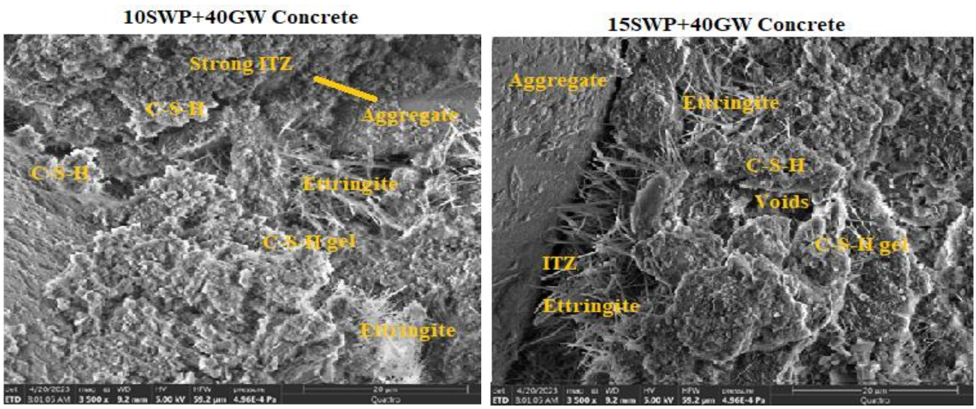


Fig. 15. SEM analysis images of some SCSC mixtures

5. Conclusions

The current study was conducted to investigate the feasibility of using SWP as a cement substitute combined with GW as fine aggregates to improve SCSC durability in several aggressive environments. Based on the experimental results obtained, the following conclusions can be drawn:

- The combined use of SWP and GW showed excellent mechanical and durability properties of SCSC, compensating for the adverse environmental and economic effects of using 100% cement and natural sand.
- The 180-day compressive strength increased from 48 MPa for control SCSC to 60, 63, and 57 MPa for mixtures with 40% GW and 5%, 10%, or 15% SWP, respectively, with improvement rates of 20.58%, 24.29%, and 16.41%.
- The addition of SWP gives an advantage in improving the electrical resistivity values of the GW-based SCSC; there was an approximately 36.65% increase for the SCSC mixture with 10% SWP and 40% GW compared to the control SCSC. However, all manufactured SCSC mixtures have electrical resistivity values greater than 20 kΩ·cm, indicating good corrosion resistance of structural concrete against chemical ion penetration.
- The permeability to chloride ions is 48.18% lower for SCSC mixtures based on SWP and GW. The best SCSC against chloride-ion permeability was achieved with 10% SWP and 40% GW, with the lowest passed charge (826 C). All SCSC mixtures are classified as having low chloride-ion permeability based on their passed charge being below 2000 C and can be used in marine environments.
- The chemical resistance of SCSC mixtures against sulphate attack was improved with the incorporation of SWP and GW at all substitution rates, enhancing concrete durability against aggressive environments. The 10% SWP-based SCSC mixtures with 40% GW showed the best sulphate resistance, with the lowest mass and strength losses.

This experimental study showed that SWP and GW have a significant positive effect as cement and fine aggregate replacements, improving the durability properties of SCSC under chloride and sulphate ingress. Given the abundance of SWP and GW in Algeria, it is logical to employ them to create concrete mixtures that are more environmentally friendly, more economically viable, and more durable.

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