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Orginal Article

Mechanical strength and environmental impacts of eco-self-compacting mortar containing dune sand in the Oued-Souf region of Algeria as cementitious materials

Moussa Hadjadj[1], Youcef Toumi[2], Selma Lounis[3], Merouane Guettioui[4]

[1] *Department of Civil Engineering; Laboratory Materials and Environment (LME);*
Faculty of Technology; University of Médéa; Médéa 26000, Algeria;
hadjadj1204@gmail.com; ORCID: 0009-0007-2304-2712
[2] *Department of Civil Engineering; Laboratory Materials and Environment (LME);*
Faculty of Technology; University of Médéa; Médéa 26000, Algeria;
youceftoumi20188@gmail.com; ORCID: 0009-0004-3050-3642
[3] *Department of Process Engineering; Laboratory Materials and Environment (LME);*
Faculty of Technology; University Saad Dahlab of Blida, Algeria;
lounisselma82@gmail.com; ORCID: 0009-0004-8872-8633
[4] *Department of Civil Engineering; Laboratory Materials and Environment (LME);*
Faculty of Technology; University of Médéa; Médéa 26000, Algeria;
guettioui.merouane@gmail.com; ORCID: 0009-0002-3720-8342

Abstract: Desertification is a major global problem, while the scarcity of renewable energy sources continues to be a growing concern. Due to the abundance of dune sand in the southern regions of the Algerian Sahara, known as dry zones, and despite the beauty of the dune sand and its scenic appearance, it has become a threat to surrounding vegetation through the desertification of agricultural lands. To address these challenges, the use of dune sand as a cementitious material in sustainable concrete has been studied. In this work, the effect of using dune sand powder (DSP) as a partial replacement for Ordinary Portland Cement (OPC) on the workability, mechanical, and microstructural properties of self-compacting mortars (SCM) was investigated. In this study, OPC was replaced by 5%, 10%, 15%, and 20% DSP by weight. The fresh properties of SCM mixtures were evaluated using the mini-slump flow and V-funnel flow time tests. The mechanical performance of SCM was assessed through compressive strength and flexural strength tests. SEM analysis was also conducted to examine the microstructural development of the hardened SCM. The results show that the use of DSP improved the workability of SCM mixtures. The study revealed that the compressive strength and flexural strength increased to 63.03 MPa and 8.8 MPa, respectively, with a 20% DSP replacement. The findings demonstrate that up to 20% dune sand powder can be used as a Portland cement replacement, with a fineness of 5000 cm²/g, without adversely affecting mechanical performance. Despite its crystalline nature, dune sand powder exhibits partial pozzolanic reactivity.

Keywords: self-compacting mortars; dune sand; cementitious materials; mechanical properties; environmental impacts

1. Introduction

Concrete production is constantly increasing to meet the demands of the construction market. In addition, population growth necessitates the development of new infrastructure projects using large quantities of concrete [1]. The extensive use of construction materials has a significant negative impact on the environment, contributing to increasing pollution of the soil, water, and air [2]. The production of concrete consumes large amounts of cement and aggregates, which are essential for construction [3]. Concrete is the most widely used material in the construction sector and primarily comprises cement, aggregates, water, and admixtures [4]. Self-compacting mortar (SCM) represents a significant advancement in construction materials, offering a unique combination of functionality and efficiency [5,6]. Unlike traditional mortars, SCM is designed to be poured into moulds and compacted entirely under its own weight, eliminating the need for additional compaction. What sets SCM apart is its exceptional durability, enhanced viscosity, and remarkable cohesion, all achieved with a low water-to-powder ratio [2]. This innovative mortar ensures a smooth and even surface application, thanks to its controlled viscosity, which allows it to spread effortlessly without manual intervention [7]. As a result, SCM not only streamlines the construction process but also delivers a superior finish, making it a preferred choice in modern construction practices [8].

In recent decades, the use of SCM has increased in the construction industry due to its fluidity and resistance to segregation, without requiring vibration [9]. These properties contribute to the construction of strong and durable structures [10]. Cement is generally produced by grinding and calcining natural resources such as limestone and clay [11]. This process accounts for approximately 7% of total global CO_2 emissions [12]. Cement manufacturing is also highly energy-intensive due to the high temperatures required (1450 °C), which increases the final production cost [13]. The production of 1000 kg of cement generates approximately 900 kg of CO_2 [14]; such emissions have a harmful effect on ozone depletion and the global environment [15].

The use of mineral additives in the cement industry is an effective means of improving environmental protection and promoting sustainable development, as it helps reduce cement consumption. Additives are increasingly valued for their quantity, fineness, mineralogical composition, and the type of cement used, which can lead to improved strength [16]. The formation of calcium silicate hydrates increases the density of the cement paste. These hydrates are produced by introducing fine silica particles, which exhibit pozzolanic activity and contribute to enhancing the strength and durability of concrete to which they are added [17,18].

The search for new sources of renewable construction materials to address the shortage of sustainable development solutions remains a challenge for academics across all sectors. One of the most promising solutions to these challenges is the use of dune sand (DS) as a cementitious material in the production of concrete and mortar [19]. Dune sand is a material abundantly available in Algeria. Despite its potential characteristics, it is largely underutilised. The contribution of dune sand powder to cementitious activity results primarily from two effects: a physicochemical effect and a chemical effect. On the one hand, it alters the hydration process of cement and the structure of the hydration products; on the other hand, it reacts within the cementitious matrix to develop new hydration products. These effects act simultaneously and complementarily on the final properties of cement pastes [17].

Various studies have examined the use of dune sand in construction materials. According to [20], adding 20% dune sand to compressed earth concrete significantly improves its compressive strength and longevity. Similarly, [21] demonstrated the effectiveness of dune sand in producing Ultra High Performance Concrete (UHPC), which achieves high mechanical performance and durability. According to [22], it is important to highlight the influence of dune sand properties – such as water content, clay content, and grain size – on the mechanical characteristics and strength of concrete [23].

Several researchers have investigated the potential of using dune sand as a cementitious material in the production of concrete and mortar. Lawrence et al. [24] showed that the hydration rate of mortars containing dune sand powder was higher than that of mortars without such additions. Wang et al. [25] used local desert sand as a sustainable and renewable material to produce three-dimensional (3D) printed ecological concrete. The study found that a concrete mix with a desert sand/cement ratio of 1.7 yielded optimal mechanical performance and better resistance to freezing and thawing. In another study, Chuah et al. [26] investigated the production of geopolymer mortars using a combination of fly ash and desert sand. They observed that the mixture significantly influenced the physical and mechanical properties of the mortars. Additionally, Xue et al. [27] reported that desert sand can improve chlorine resistance, enhancing its suitability as a building material in chloride-exposed environments. Liu et al. [28] specifically studied the influence of desert sand on the freeze-thaw durability of concrete. Their findings revealed that the incorporation of an appropriate amount of desert sand improved the durability of concrete compared to the control sample.

In light of the above, the objective of this study is to experimentally evaluate the combined contribution of the rheological and mechanical characteristics, as well as the environmental impacts, of adding dune sand powder to cement on the workability, compressive strength, and flexural strength of self-compacting mortars (SCM).

2. Materials and methods

2.1. Materials

The cement used in this study is CPA-CEM I/B 42.5N, which conforms to the standard (NFP 15-301/9). It is a type of ordinary Portland cement (OPC) produced by GICA. The chemical composition and physical properties of the OPC used in this study are summarised in Table 1. The particle size distribution of the cement is illustrated in Fig. 1.

For this study, the sand used is dune sand sourced from the Oued-Souf region, located approximately 500 km south of Algeria. The physical properties and particle size distribution of the dune sand are summarised in Table 2 and Fig. 2, respectively.

Table 1. Chemical composition and physical properties of cement and DSP. *Source*: own study

Chemical composition (%)	Cement	DSP
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	-

Chemical composition (%)	Cement	DSP
SO_3	2.37	0.06
L.I	2.23	-
Cl	-	0.1
Physical properties		
Specific density (kg/m^3)	3110	2890
Blaine fineness (m^2/kg)	3420	5000

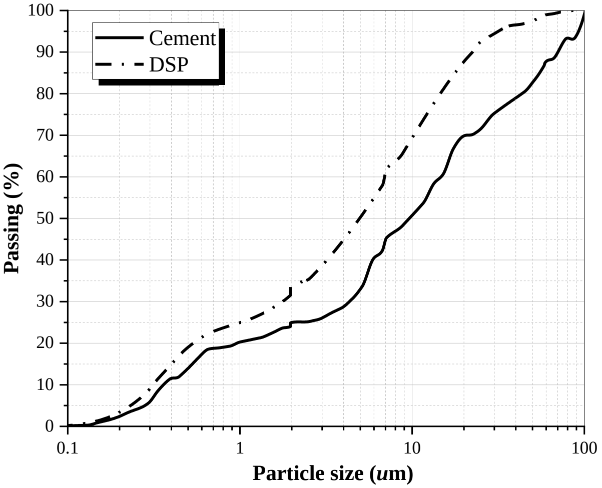

Fig. 1. Particle size distribution of cement and DSP. *Source*: own study

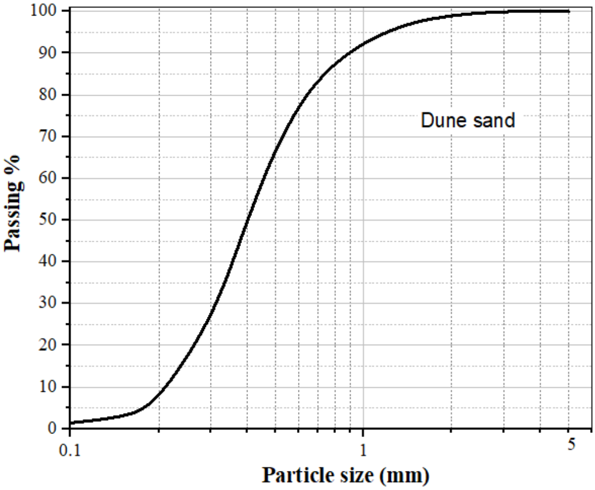

Fig. 2. Particle size distribution of dune sand. *Source*: own study

A single admixture was used as a high-range water-reducing superplasticiser (SP). This superplasticiser, supplied by Granitex and marketed under the name MEDAFLOW 30, is a yellowish liquid with a pH of 6 and a density of 1.07.

Table 2. Physical properties of dune sand. *Source*: own study

Properties	Dune sand	Standard
Specific density (kg/m^3)	2630	ASTM C 127
Fineness modulus	2.33	ASTM C 136
Maximum size (mm)	4.75	ASTM C 33
Water absorption (%)	0.96	ASTM C 127
Shape	Rounded	ASTM C-33

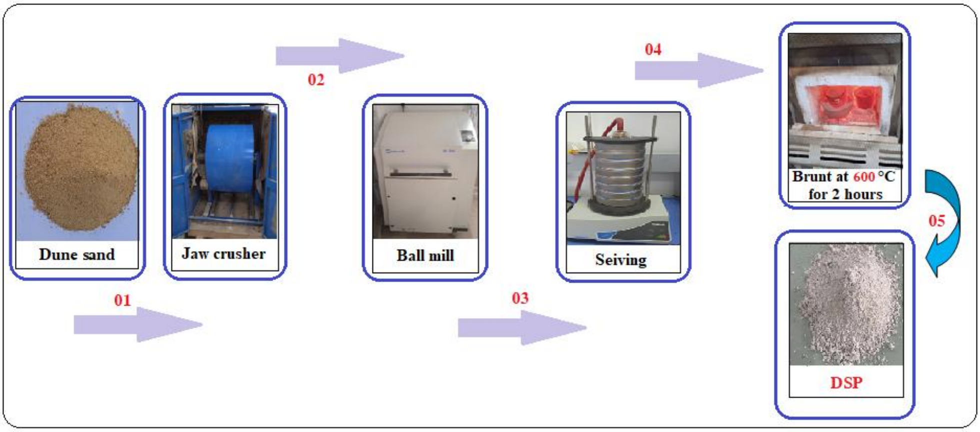

Fig. 3. Transformation process of dune sand into DSP. *Source*: own study

2.2. Formulation

In our study, we examined various optimisations related to the water/binder (W/B) ratio and adjusted additional factors, including the amount of sand in the mortar, defined as the sand/mortar (S/M) ratio, as well as the dosage of superplasticiser relative to the binder. Our formulation was based on the general method proposed by the Japanese company OKAMURA [29]. However, we introduced modifications concerning the sand content in the mortar, the W/B ratio, and the S/M ratio. These adjustments were experimentally evaluated to ensure that the resulting values for the Abrams cone spread and the V-funnel flow time met acceptable standards. The different components of the SCM mixes studied are presented in Table 3.

Table 3. Different components of SCM mixes. *Source*: own study

Mixtures	Cement (kg/m^3)	DSP (kg/m^3)	Dune sand (kg/m^3)	SP (%)
Control	690	0	1300	0.9
SCM+DSP5	655.5	34.5	1300	0.9
SCM+DSP10	621.0	69.0	1300	0.9
SCM+DSP15	586.5	103.5	1300	0.9
SCM+DSP20	552.0	138.0	1300	0.9

2.3. Testing

2.3.1. Fresh properties

To examine and characterise the fresh properties of self-compacting mortars (SCM), the following tests were conducted: slump flow diameter test and V-funnel flow time test, in accordance with the EFNARC standard [30].

2.3.2. Hardened properties

The compressive and flexural strengths of all SCM mixes were measured at 7 and 28 days, in accordance with ASTM C348 and ASTM C349, respectively (see Fig. 4). Flexural strength was tested on three prismatic specimens (4 × 4 × 16 cm), followed by compressive strength testing on three additional prismatic pieces (4 × 4 × 4 cm) obtained from the flexural rupture of the original specimens.

Scanning electron microscopy (SEM) analysis was conducted using a VEGA3-TESCAN SEM with a 25 kV accelerating voltage to examine the morphology and microstructure of selected SCM samples.

Fig. 4. Compressive and flexural strength tests of SCM. *Source*: own study

2.3.3. Environmental impacts assessment

As is well known, the manufacturing of cement and the conventional extraction of aggregates result in substantial CO_2 emissions compared to other components of concrete, thereby significantly contributing to global emissions from energy and industrial activities. Throughout its life cycle, concrete production passes through three main phases, as illustrated in Fig. 5. The CO_2 footprint assessment in this study is limited to cement production (specifically clinker production), conventional aggregate extraction, and material transport phases. The main objective of the environmental life cycle assessment was to evaluate the environmental impact of various compositions of self-compacting mortar made with the proposed blended cements (also referred to as alternatives). The system boundary for the life cycle assessment was defined to encompass mortar production, including all phases such as the extraction of raw materials (e.g., natural dune sand), processing (cement and DSP), and transportation of materials, as shown in Fig. 6.

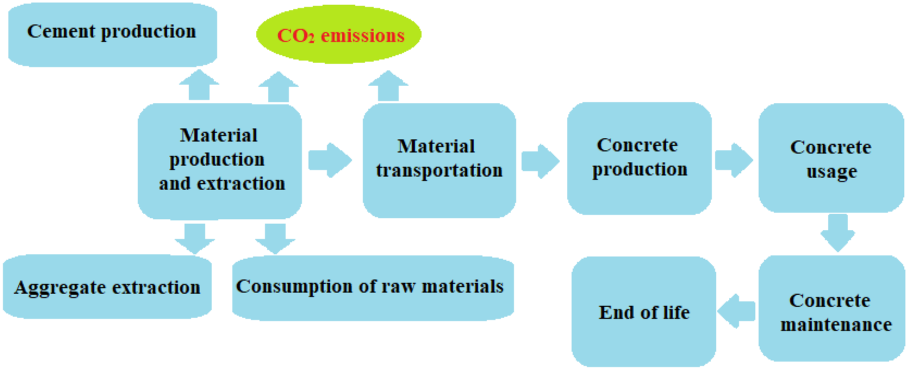

Fig. 5. Schematic of concrete production cycle including environmental impact assessment *Source*: own study

CO_2 emissions during the mortar usage phase, maintenance phase, and end-of-life phase were not analysed. This decision was made because conventional self-compacting mortar (Control) and the other self-compacting mortar mixtures (SCM-5, SCM-10, SCM-15, and SCM-20) are assumed to undergo similar processes during these phases, resulting in equivalent CO_2 emissions. The amount of CO_2 produced was calculated based on the production of one cubic metre of mortar (see Table 3). The production of Ordinary Portland Cement (OPC) also requires the consumption of natural resources such as limestone, iron ore, and gypsum, thereby increasing the volume of raw material use. This, combined with the CO_2 emission factor, is used to evaluate the environmental impact. In this study, the CO_2 emission factor for ordinary Portland cement, as reported by Sudjono and Yudhi [31], is 1.77 kg CO_2/kg. All values reflect the CO_2 emitted for each material [32,33].

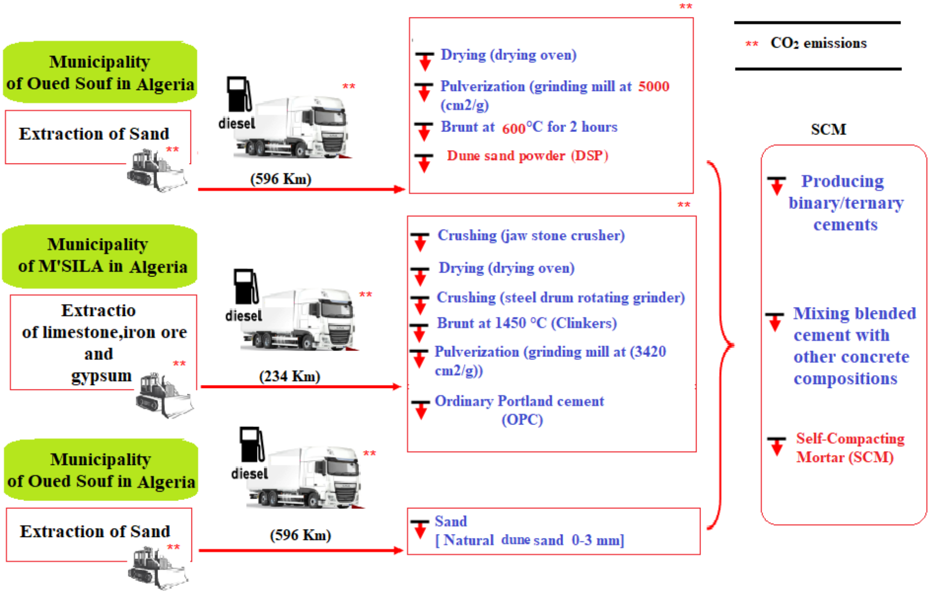

Fig. 6. Processes considered in the environmental impact analysis of the different SCM developed in this study. *Source*: own study

3. Results and discussion

3.1. Fresh properties of SCM mixtures

3.1.1. Optimization of S/M and SP/L ratios

In a recent study, a systematic approach was employed to develop a reference self-compacting mortar (SCM). The primary focus was on adjusting the superplasticiser/binder (SP/B) and sand/mortar (S/M) ratios to achieve a mortar with specific characteristics. The objective was to produce a mixture with a slump flow ranging from 270 to 330 mm, a flow time between 2 and 10 seconds, and strong resistance to segregation while avoiding bleeding. To optimise the SP dosage, three different mortar compositions (SCM1, SCM2, and SCM3) were tested, each with three SP percentages ranging from 0.8% to 0.9%, while maintaining a water-to-binder (W/B) ratio of 0.4. Key performance indicators, such as mini-cone slump and flow time from the mini V-funnel tests, were assessed to identify the most effective SP dosage and S/M ratio.

The results, illustrated in Table 4, indicate a clear correlation between SP dosage and mortar fluidity. Notably, an increase in SP dosage led to improved fluidity. For example, a 0.5% increase in SP dosage was associated with a 20 mm increase in slump diameter. At an SP dosage of 0.9% with an S/M ratio of 0.5, the mortar achieved a satisfactory slump flow of 30 mm, demonstrating desirable fluidity.

Table 4. Different components of SCM mixtures studied. *Source*: own study

Control SCM				
Mixtures		SCM1	SCM2	SCM3
SP %		0.80	0.85	0.90
S/M		0.40	0.40	0.40
		0.45	0.45	0.45
		0.50	0.50	0.50
Slump flow (mm)	S/M=0.4	313.0	337.0	342.0
	S/M=0.45	281.0	298.0	339.0
	S/M=0.5	280.0	292.0	304.0
V-funnel flow (Sec)	S/M=0.4	6.30	5.30	5.71
	S/M=0.45	7.80	5.92	6.35
	S/M=0.5	7.40	6.23	4.60
Visual Observation	S/M=0.5	Slightly firm mix	Fluid mix with signs of bleeding	Fluid mix with no signs of bleeding and segregation
				

According to the results obtained and illustrated in Table 4, formulations with lower S/M ratios of 0.4 and 0.45 failed to meet the SCM formulation requirements. Consequently, for advancing to the SCM formulation phase, formulation SCM3, which combines an S/M ratio of 0.5 with an SP dosage of 0.9%, was selected due to its superior performance in achieving the desired fluidity and slump characteristics.

3.1.2. Slump flow of SCM

The influence of DSP on the slump flow diameter of self-compacting mortar (SCM) is illustrated in Fig. 7. These figures show that, for all tested SCM mixtures, the slump flow as a function of DSP consistently falls within the 270 to 330 mm range. This range indicates acceptable fluidity according to EFNARC recommendations [30], suggesting that the SCM mixtures examined have good flow characteristics. The addition of DSP increases the slump flow diameter of SCM mixes. The slump flow values for mixtures containing 5%, 10%, 15%, and 20% DSP improved by 1.5%, 3.09%, 6.12%, and 7.56%, respectively, compared to the reference SCM. This improvement in the slump flow of DSP-based mixtures may be attributed to the slower hydration rate of DSP compared to cement; the SCM mixtures required only low dosages of water and superplasticisers to achieve the desired fluidity [21]. Allout et al. [34] reported that when the DSP content in the mix remains low (≤15%), workability improves and the concrete becomes more fluid, due to the enhanced compactness of the mix. This result is also supported by findings from other studies [17].

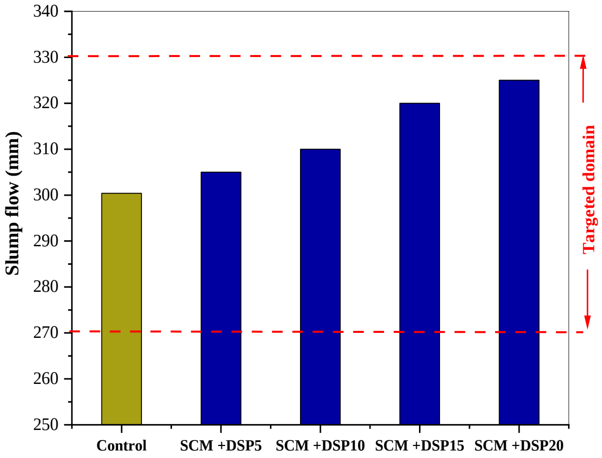

Fig. 7. Slump flow of SCM mixtures. *Source*: own study

3.1.3. V-funnel flow of SCM

The results presented in Fig. 8 demonstrate that the V-funnel flow time values for all SCM mixes, as a function of DSP content, consistently fall within the 2 to 10 second range. This range indicates acceptable flow times according to EFNARC recommendations [35], suggesting that the SCM mixtures exhibit good fluidity. The addition of DSP particles plays a key role in reducing the V-funnel flow time of the SCM mixtures. Notably, shorter flow times were observed with the addition of 20% DSP. For example, the flow time for the control SCM was 4.6 seconds, while it improved to 4.2, 3.20, 3.5, and 2.95 seconds with the addition of 5%, 10%, 15%, and 20% DSP, respectively, as a cement additive.

This improvement in flow time can be attributed to the slower hydration rate of DSP compared to cement, which contributes to enhanced fluidity in the fresh state.

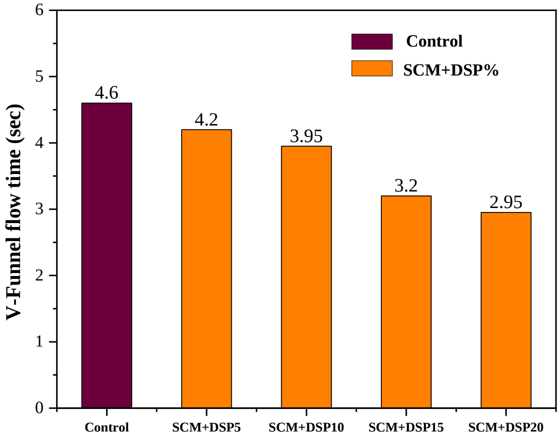

Fig. 8. V-funnel flow of SCM mixtures. *Source*: own study

3.2. Hardened properties of SCM mixtures

3.2.1. Compressive strength of SCM

Figure 9 illustrates the variation in compressive strength for various self-compacting mortar (SCM) mixtures at 7 and 28 days. It presents the compressive strength results for SCM mixtures incorporating DSP, with cement replaced by 5%, 10%, 15%, and 20%. The initial results highlight the significant benefit of DSP, with the strength of the SCM at 28 days being 1.08 times higher than that of the control SCM. The data indicate a notable increase in compressive strength with the incorporation of DSP into the mortar. Specifically, the 28-day compressive strength of the control SCM is 56.21 MPa, while the strength improves to 63.03 MPa with the addition of 20% DSP as a cement additive. This enhancement in long-term strength, particularly at 28 days, can be attributed to the pozzolanic reaction between DSP and calcium hydroxide ($Ca(OH)_2$) in the cement matrix [36,37]. Substituting 20% of Portland cement with DSP of 5000 cm^2/g fineness results in a new type of blended cement with compressive strength comparable to that of ordinary Portland cement.

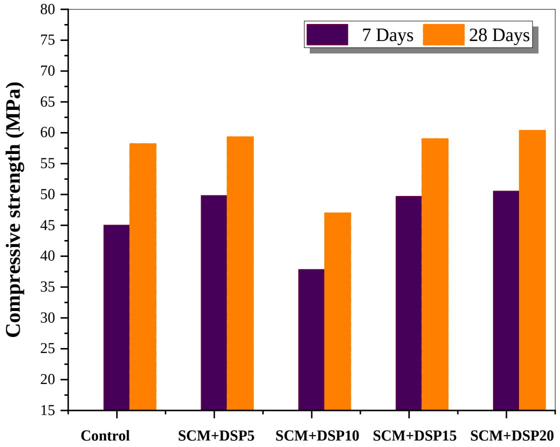

Fig. 9. Compressive strength of SCM mixtures. *Source*: own study

The pozzolanic reaction contributes to the development of compressive strength by forming additional calcium silicate hydrate (C-S-H) gel, which improves the internal bonding within the cement matrix and enhances overall strength. Furthermore, DSP exhibits pore-filling effects due to its high fineness (5000 cm²/g), which helps refine the mortar's microstructure and further contributes to strength improvement. Guettala and Mezghiche [38] confirmed that increasing the fineness of DSP from 3000 to 4000 cm²/g improved the compressive strength of cement pastes at all ages by approximately 12%.

3.2.2. Flexural strength of SCM

The evolution of flexural strength for various self-compacting mortars (SCMs) at 7 and 28 days is depicted in Fig. 10. The results shown in this figure are similar to those of the compressive strength. The data reveal a notable trend: mortars without DSP (control SCM) demonstrate lower flexural strength compared to those with DSP incorporated as a cement additive, particularly at replacement levels of 5% to 20%. Improvements in flexural strength values of 10.25%, 4.09%, 14.06%, and 19.43% were recorded for the SCM+DSP5, SCM+DSP10, SCM+DSP15, and SCM+DSP20 mixtures, respectively, compared to mixtures without DSP.

The incorporation of 20% DSP with a fineness of 5000 cm²/g provides a new type of compound cement with a compressive strength comparable to that of ordinary Portland cement. Moreover, mortars with higher quantities of DSP show an increase in flexural strength, suggesting that DSP enhances the bonding within the cement matrix, thereby improving the overall strength of the mortar. In summary, the use of DSP as a cementitious material in SCM can improve the flexural strength of SCMs and offers a beneficial alternative due to its contribution to flexural performance.

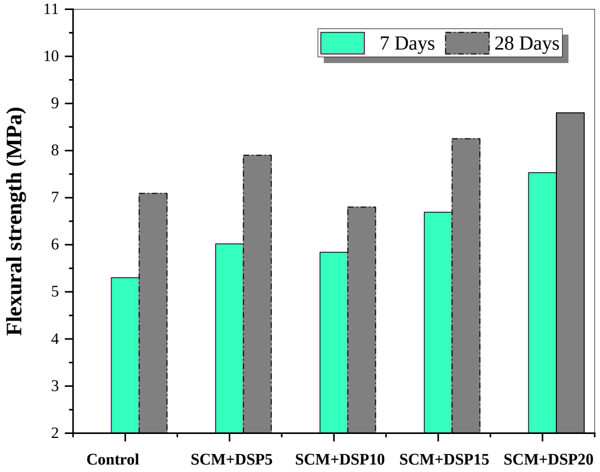

Fig. 10. Flexural strength of SCM mixtures. *Source*: own study

3.2.3. Microstructure of SCM

Figure 11 shows the SEM analysis of the SCM mixtures. From this figure, it can be observed that mixtures with SCM+DSP20 have a denser microstructure and a stronger interfacial transition zone (ITZ) between the cement paste and aggregates compared to mixtures with conventional SCM (SCM+DSP0), which exhibit more pores and a weaker ITZ.

This denser microstructure and stronger ITZ may be explained by the pore-filling effects attributed to the high fineness of DSP (5000 cm²/g), which help refine the microstructure of the SCM and further contribute to the improvement of its mechanical properties.

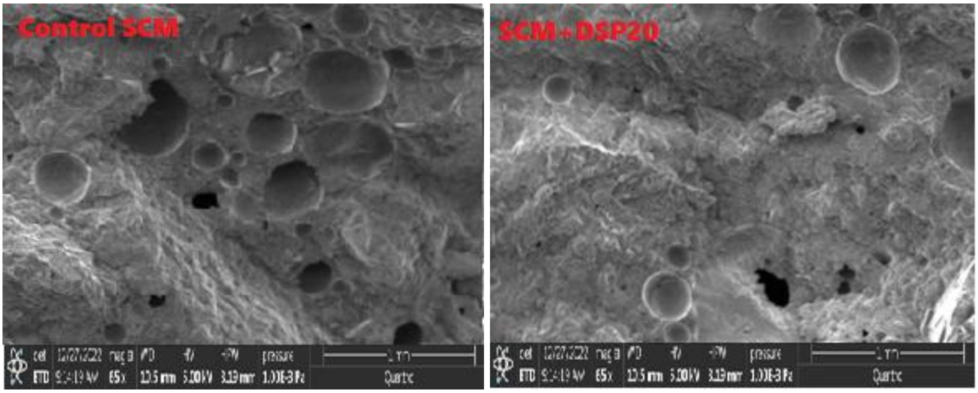

Fig. 11. EM images of SCM. *Source*: own study

3.3. Environmental impact of SCM mixtures

Figure 12 illustrates the variation in CO_2 emissions based on the DSP content used in SCM mixtures. The data presented in this figure indicate a clear proportional relationship between CO_2 emissions and the percentage of DSP incorporated into the mixtures. It can be observed that CO_2 emissions decrease linearly with an increase in DSP as a partial replacement for cement. Specifically, the CO_2 emissions for the control SCM are 1221.30 kg, while they are reduced to 1160.23 kg, 1099.17 kg, 1038.10 kg, and 977.04 kg with the addition of 5%, 10%, 15%, and 20% DSP as a cement additive, respectively. This result suggests that the use of DSP as a cement additive in SCM production leads to lower CO_2 emissions, thereby reducing the environmental impact.

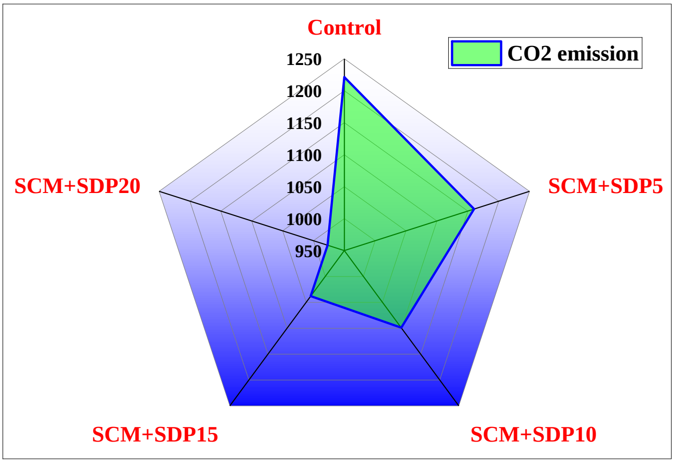

Fig. 12. SEM images of SCM. *Source*: own study

4. Conclusions

This study discusses the influence of DSP as a supplementary cementitious material on the behaviour of self-compacting mortar. Based on the results obtained, the following conclusions can be drawn:

- This experimental study is significant from both environmental and economic perspectives, given the vast availability of dune sand, particularly in Algeria and other countries..
- The workability of SCM is positively influenced by the presence of DSP. Incorporating 20% DSP as a supplementary cementitious material into the SCM mix led to a 7.56% increase in the wet slump flow diameter compared to the reference SCM.
- Adding 20% DSP to SCM mixtures increases compressive and flexural strengths by approximately 10.82% and 19.43%, respectively, compared to SCM mixes without DSP.
- SEM analysis showed that using DSP in SCM mixtures, at replacement levels up to 20%, resulted in a developed interfacial transition zone (ITZ) between the cement paste and aggregates due to the pozzolanic effect of DSP. Consequently, a denser microstructure was achieved, enhancing the mechanical performance of SCM.
- The use of DSP as a supplementary cementitious material in SCM production contributes to the development of eco-friendly SCM, improving both environmental and economic outcomes.
- Replacing 20% of cement with DSP in SCM production reduces CO_2 emissions by 19.97%.

It is recommended to explore other DSP replacement ratios and investigate additional SCM properties, particularly durability-related aspects such as chloride ion penetration, resistance to acid and sulphate attack, and permeability. Assessing the performance of SCM over extended curing periods is another important area for future research, to better understand the long-term effects of alternative materials on concrete performance.

Nomenclature

SCM	Self-Compacting Mortar
DS	Dune Sand
DSP	Dune Sand Powder
OPC	Ordinary Portland Cement
SP	Superplasticizer

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