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Impact of Water-Cement Ratio and Desert Sand Powder on the Mechanical Properties of Eco-Self-Compacting Concrete

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Said Zaouai
ORCID: https://orcid.org/0009-0009-5936-1074
Laboratory of Eco-materials: Innovations & Applications (EMIA), Civil Engineering Department, University of Djelfa, 17000 Djelfa, Algeria
E-mail: said.zaouai@univ-djelfa.dz
Farid Benmerioul
ORCID: https://orcid.org/0009-0009-5936-1074
Laboratory of Eco-materials: Innovations & Applications (EMIA), Civil Engineering Department, Mohamed El Bachir El Ibrahimi University Elbourdj B, Algeria
E-mail: benmerioul.farid@univ-UBB.dz
Abdelkadir Makkani
ORCID: http://orcid.org/0000-0002-4027-9929
Laboratory of Eco-materials: Innovations & Applications (EMIA), Civil Engineering Department, TAHRI Mohamed University, Bechar, Algeria
E-mail: makkani.abdelkadir@univ-bechar.dz
Ahmed Tafraoui
ORCID: https://orcid.org/0000-0002-0278-935X
Laboratory of Eco-materials: Innovations & Applications (EMIA), Civil Engineering Department, TAHRI Mohamed University, Bechar, Algeria
E-mail: tafraoui.ahmed@univ-bechar.dz
Rachid Rabehi
ORCID: https://orcid.org/0000-0002-9398-7291
Faculty of Civil Engineering, University of Science and Technology Houari Boumediene (USTHB), BP 32 El Alia, Bab Ezzouar, 16111 Algiers, Algeria & Civil Engineering and Sustainable Development Laboratory, University of Djelfa, Algeria
E-mail: rachid.rabehi@usthb.edu.dz

Abstract
This study investigates the effects of varying water-cement (w/c) ratios (0.40-0.55) and the incorporation of 10% powdered dune sand from Taghit, Algeria, on eco-self-compacting concrete (E-SCC) properties. The research explores the potential of utilizing abundant desert sand resources as a partial cement replacement while maintaining concrete performance. Through experimental analysis and response surface methodology (RSM), the study demonstrates that lower w/c ratios significantly enhance compressive strength, with optimal performance achieved at a 0.40 w/c ratio reaching 55 MPa. The findings reveal that decreasing the w/c ratio reduces porosity and improves the concrete's overall structural integrity. Capillary absorption tests indicate that while E-SCC with a 0.40 w/c ratio shows slightly higher initial absorption rates over the first two hours, it demonstrates better long-term performance over 24 hours compared to higher w/c ratios. The results confirm that incorporating 10% powdered dune sand while maintaining a low w/c ratio can produce high-performance eco-self-compacting concrete that meets industry standards for workability and strength, offering a sustainable alternative for construction applications.
Keywords: Eco-self-compacting concrete, Water-cement ratio, Dune sand powder, Compressive strength, Sustainable construction materials.

1. Introduction

The Algerian desert is rich in vast quantities of dune sand, an abundant natural resource that has not been extensively utilized in construction. This sand is known for its high quartz silica content, making it clean and fine, with minimal extraction costs, aside from transportation expenses. Numerous studies have explored the potential applications of this sand in various construction sectors, driven by its high silica content and the increasing demand for construction sand in Algeria (Agha *et al*., 2023; Benmerioul *et al*., 2017; Rennani *et al*., 2020; Zaouai *et al*., 2020; Allout *et al*., 2023; Zaouai *et al*., 2016; Rabehi *et al*., 2023a). Additionally, the limited supply of fine sand from local quarries and the planned cessation of beach sand extraction, which poses significant ecological and industrial challenges for Algeria, further highlight the need to explore dune sand as an alternative. The use of this abundant resource in concrete formulation could offer substantial economic and environmental benefit.

Many researchers have explored the use of powder dune sand in concrete mixtures (Tafraoui *et al*, 2009; Guettala, *et al*, 2011) highlighted that the substitution of desert sand powder to Portland cement can help reduce CO_2 emissions while also improving both the compressive strength and the fresh mixture.

Arroudj, K *et al*., (2017) prepared mortars modified with 20% crushed desert sand, finding them to be both cost-effective and environmentally sustainable. This substitution reduces the reliance on traditional materials, lowering costs, while also promoting the use of locally available and often underutilized desert sand.

Dahmani, *et al*. (2016) reported that a cement substitution ratio of 0% - 20%, with about 10% dune sand crushed and 10% pozzolan, results in optimal resistance in concrete. However, exceeding this substitution level leads to a decrease in strength, suggesting that higher proportions of these materials can negatively impact the concrete's performance.

Liu *et al*. (2023) showed that a cement substitution ratio ranging from 0% to 60% demonstrated a positive influence of desert sand powder on the compressive strength of concrete during the hydration process, particularly between the 28th and 112th days. This indicates that while the initial strength may be impacted, the long-term strength development benefits from the inclusion of desert sand powder, especially after the first month.

The report by Alhozaimy *et al*. (2020) indicates that as the cement substitution ratio with ground desert sand increases (ranging from 0% to 40%), the compressive strength of the concrete decreases under standard curing conditions. However, despite this reduction in strength, ground desert sand can still be used as a partial substitute for cement, particularly in the production of precast concrete.

In concrete manufacturing, the precise balance between water and cement content emerges as a critical factor, with its variation substantially impacting the material's strength characteristics through its effect on internal pore structure (Wang *et al*., 2020; Liu & Sui, 2020; Briki *et al*., 2024; Mursaleen *et al* 2024). However, current studies often overlook the influence of the water-cement ratio on the size pore compaction stage. Waziri *et al*. (2011) achieved a maximum compressive strength of 23.71 N/mm² with a mix ratio and a water-cement ratio of 0.5 after 28 days of hydration. Shamsai *et al*. (2012) demonstrated that a reduction in the water/cement ratio from 0.50 - 0.33 resulted in an increase in compressive strength by 33.40% and 35.20%, respectively. This study aims to evaluate the compressive strength, water-accessible porosity, and capillary absorption of eco-self-compacting concrete modified with cement pastes containing dune sand powder under various water/binder ratios (0.4, 0.475 and 0.55).

2. Characterizations of materials and experimental study

2.1 Temperature evolution

For experimental purposes, Portland cement CEM II/B 42.5 was selected, adhering to NA 442 Algerian standards. The cement possessed a Blaine fineness of 3610 cm^2/g. The comprehensive physical properties, chemical makeup, and mineralogical profile of the cement are documented in Tables 1, 2, and 3 respectively. The powder sand dune (PSD) of Taghit, wilaya of Bechar (Algeria), the maximum coarse aggregate of powdre dune sand does not exceed 90µm.

Natural sand of 4 mm maximum size was used as fine natural granults and two size natural gravel aggregate ranges (3 /8 mm) and (8 /15mm) of Career Zekkar of Djelfa.

Table 1 – Physical propreties of cement and Powdre sand dune Taghit.

	A density	S density	Fineness
CEM II/B 42. 5	1030	3600	3242
PSD Taghit	1150	2650	3000

Table 2 – Mineralogical composition of cement (%).

Cement type	C3S	C2S	C3A	C4AF
Cement	61.54	14.83	7.04	11.05

Table 3 – Chemical analysis of the poudre sand Dune of zaafran and cement used.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	TiO_2	others	Loss of ignition (%)
P S D	97.15	0.79	0.21	0.11	0.05	0.14	0.18	0.05	<0.02	0.58
Cement	17.49	4.51	3.02	62.78	2.5	2.3	0.05	-	0.64	8.10

Figure 1 – Powder sand dune of Taghit.

Table 4 – Components of eco-selfcompacting concrete mixes.

MIXES	Components								Autoplacibility tests		
	W/C	**C**	**PSD**	**Sand 0/3**	**W**	**N A 3/8**	**N A 8/15**	**SP**	**Slump flow**	**Stability in sieve (p)**	**L – box (h2 / h1)**
ESCC1	0.4	378	42	870	168	150	720	8.1	63	7	0.8
ESCC2	0.475	378	42	870	199.5	150	720	8.1	67	9	0.85
ESCC3	0.55	378	42	870	231	150	720	8.1	75	13	0.9

2.2 Temperature evolution

Slump Flow: The slump flow test is performed using the Abrams cone, where the diameter of the concrete spread is measured along two perpendicular lines, and the average value is taken.

L-box: The L-box test is used to assess the mobility of confined concrete and to ensure that the concrete will not be obstructed by blocking phenomena during placement.

Stability by Sieve: The stability test by sieve evaluates the resistance of self-compacting concrete (SCC) to segregation and indicates the degree of segregation that may occur in the mix.

A-SLUMP FLOW B- STABILITY BY SIEVE C- L-BOX

Figure 2 – Autoplacibility tests of E-SCC.

3. Results and discussion

3.1 Compressive strength

The objective was to predict the compressive strength based on different parameters using the response surface methodology (RSM). Statistical analysis through Central Composite Design (CCD) modeling yielded a quadratic equation to predict 28-day compressive strength values (Aidjouli *et al*., 2023; Meymouna *et al*., 2023). The mathematical relationship, expressed using coded variables, is represented by:

Ycompressive strength at 28 days= 53.7857142857143 + -5.83333333333333 * ((X1 - 0.475) / 0.075) + -4.5 * ((X2 - 10) / 10) + (X1 - 0.475) / 0.075 * (X2 - 10) / 10 * 3 + (X1 - 0.475) / 0.075 * (X1 - 0.475) / 0.075 * -7.57142857142857 + (X2 - 10) / 10 * (X2 - 10) / 10 * -7.57142857142857.

Figure 3 displays the correlations between the predicted and experimental values. It is important to note that for the compressive strength at 28 days, all the linear parameters demonstrated statistical significance, with a high level of significance (R = 0.94). The histogram in Figure 4 shows the compressive strength results as a function of the water-cement ratio (W/C) for self-compacting concrete made with ground dune sand. It is evident that the compressive strength of the concrete generally increases as the W/C ratio decreases. An increase in the water content results in a decrease in strength, with the mix at (W/C = 0.4) exhibiting higher strength than the mix at (W/C = 0.55), showing a difference of 20 MPa between the two mixes.

During this process (Figure 5), the W/C ratio varied between 0.4 and 0.55, while the powder sand dune proportion ranged from 0 to 20%. The predicted strength values were 52.38 MPa, 53.78 MPa, and 40 MPa, respectively.

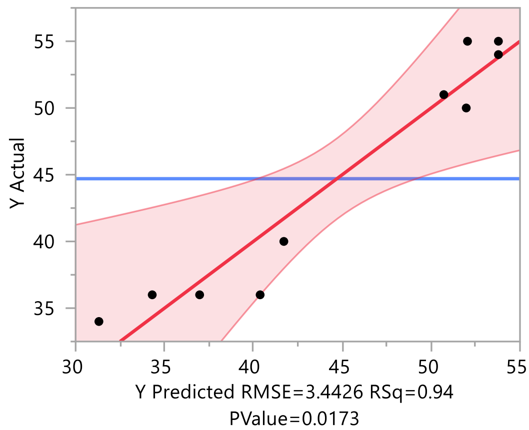

Figure 3 – The correlations between the predicted and experimental values.

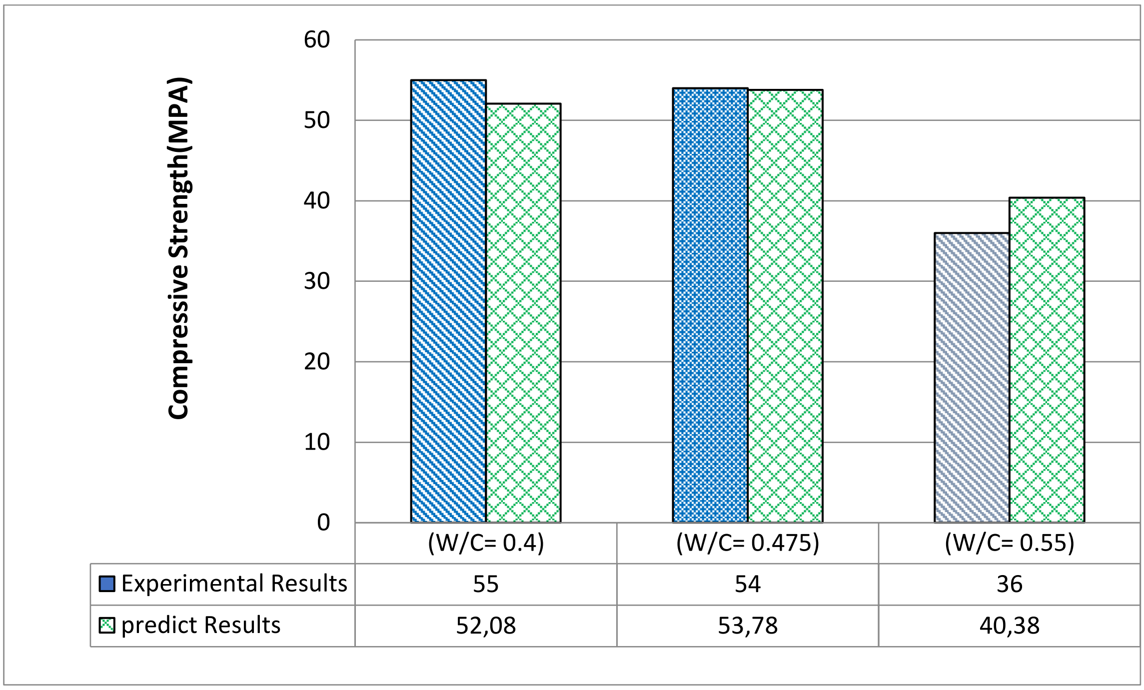

Figure 4 – Results of compressive strength at 28 days tests exprimental and predict of E-SCC.

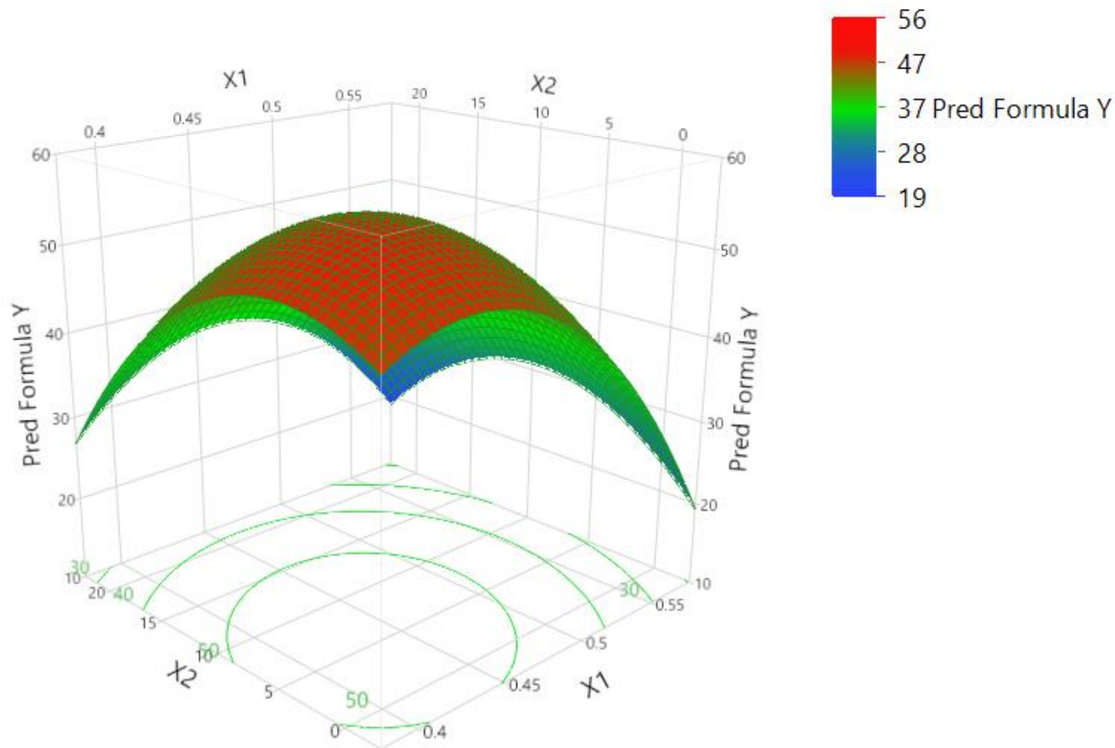

Figure 5 – Three-dimensional visualization of 28-day compressive strength variations based on water-cement ratio and powdered sand dose interactions using response surface analysis

3.2 Porosity accessible to water

Figure 6 demonstrates how the water-cement proportion fundamentally shapes paste porosity by determining the initial distribution of cement particles in the mixture. When less water is used relative to cement content, the particles naturally position themselves in closer proximity. This tighter particle arrangement creates smaller interstitial spaces, minimizing the formation of large unfilled cavities during the hydration process.

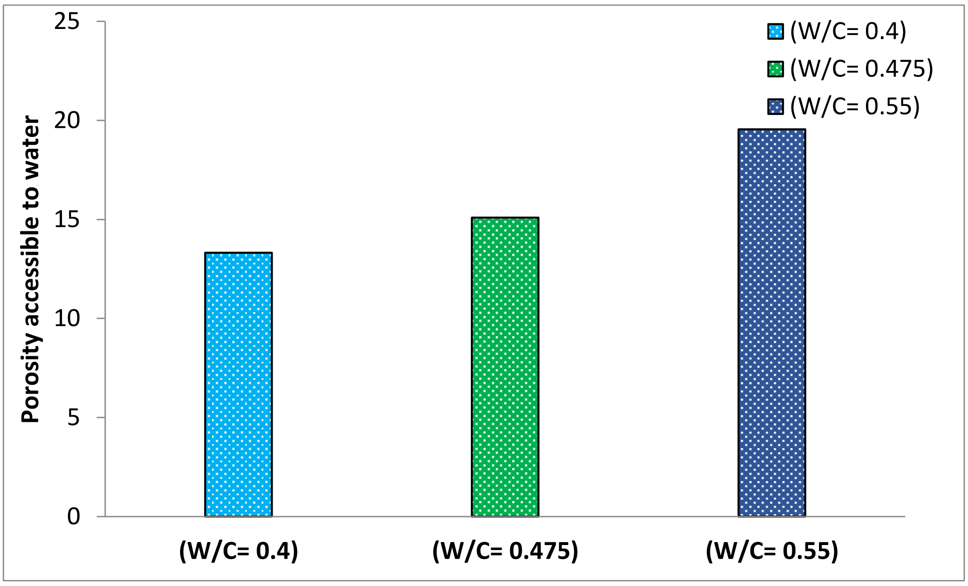

Figure 6: Porosity Measurements of Self-Compacting Concrete at Various Water-to-Cement Ratios.

3.3 Capillary absorption

The Capillary absorption is a physical phenomenon that allows aggressive substances from the outside to penetrate and pass through the pores into the interior of the concrete. It is first observed that water absorption changes significantly with the evolution of the water-cement ratio (W/C). The W/C ratio of 0.4 also exhibits the highest capillary absorption. This can be attributed, on one hand, to the competition between accessible porosity and capillary size, and on the other hand, to the different developments in the microstructures of the mixes.

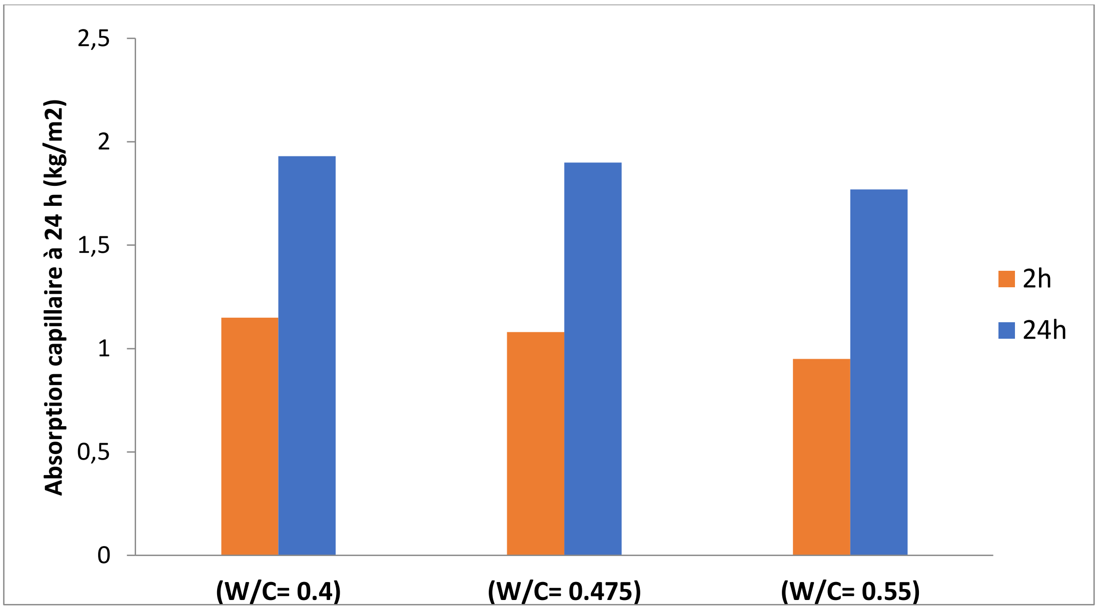

Figure 7 – Effect of Water-Cement Ratio on Capillary absorption of E-SCC.

It can be noted that at an early age, over a 2-hour period, the mix with a W/C ratio of 0.4 shows a slightly higher capillary absorption and absorption kinetics compared to the others. In the period from 0 to 2 hours, all mixes show higher absorption kinetics than in the 2 to 24-hour period.

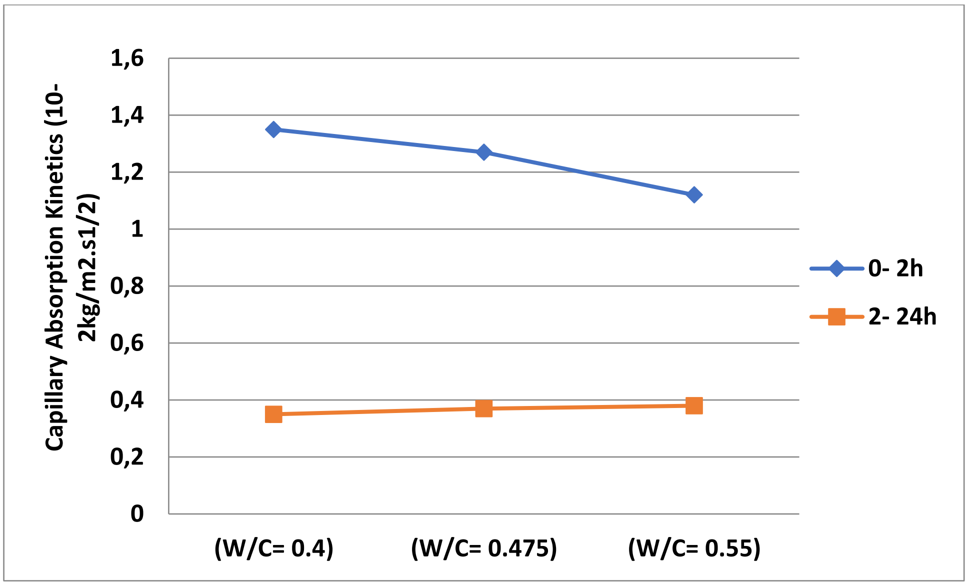

Figure 8 – Effect of Water-Cement Ratio on Capillary absorption kinetics of E-SCC.

This figure (see Figure 8), shows a very low absorption coefficient, below 2.5 kg/m³ for all the formulations studied. However, the samples absorb more water, especially those with dune sand. Figure 7 presents the results of capillary absorption kinetics per unit area as a function of the water-cement ratio (W/C). These results highlight that the capillary absorption kinetics is a decreasing function of the W/C ratio over the first 2 hours, and an increasing function over 24 hours. Specifically, during the first 2 hours, as the W/C ratio increases, the absorption kinetics decreases. For instance, the change in the W/C ratio from 0.4 to 0.55 results in a decrease in absorption kinetics by about 17%. Over 24 hours, however, as the W/C ratio increases, the absorption kinetics increases. The change in the W/C ratio from 0.4 to 0.55 results in an increase in absorption kinetics by approximately 8%.

4. Conclusions

The analysis of the experimental results allowed drawing the following conclusions:

- The variation in the W/C ratio in the formulation of E-SCC made with Powdre dune sand leads to a slight variation in the workability parameters in the fresh state, while remaining within the range of SCC requirements as outlined in the recommendations [AFGC, 2008].
- The mechanical strengths of the E-SCC increased with the decrease in the W/C ratio, with the compressive strength reaching significant values, such as 55 MPa for a W/C ratio of 0.4.
- The compressive strength results of the E-SCC, obtained using the surface response method, also show a similar trend and evolution when compared to the experimental results.
- The variation in the W/C ratio leads to concretes with different porosities. The E-SCC with a W/C ratio of 0.4 exhibits the least porous concrete compared to the other mixtures.
- The E-SCC with a W/C ratio of 0.4 exhibits high compressive strength, a less porous structure, and a low capillary absorption value.
- Capillary absorption changes with the variation in the W/C ratio. The E-SCC with W/C ratio of 0.55 also shows higher values compared to the other concretes.

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