



Valorisation of Agricultural Waste: Date Palm Fibers as Green Reinforcement in Sand Concrete

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ABSTRACT

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To address environmental challenges, the construction sector is focusing on natural resources, particularly resources from agricultural waste. Among these, date palm fibers show great potential. Their incorporation may contribute to the development of concrete that is more durable, cost-effective, and environmentally sustainable. This study investigates the incorporation of date palm (DPL) fibers into sand concrete as reinforcement, with the goal of producing a low-cost and eco-friendly material. Two types of date palm fibers: leaflets (LFL) and fibrillium (FBL) are used in the concrete mix. The fibers were added at three percentages: 0.5%, 1%, and 1.5%. For each dosage, tests were carried out to assess workability, density, compressive and flexural strength, along with water absorption and shrinkage. The results demonstrate that sand concrete reinforced with 0.5% fibrillium (FBL) fibers provides satisfactory flexural performance for practical applications. While, leaflet fibers (LFL) at a 1.5% incorporation ratio, were highly effective in minimizing shrinkage, with the greatest reduction observed at this dosage level.

1. INTRODUCTION

In the building industry, there is a growing focus on increasing the use of eco-friendly materials by utilizing natural resources and recycled products from industrial and agricultural waste. This study specifically examines natural fibers, particularly plant-based ones like hemp, straw, sisal, and waste from date palm trees. Incorporating these fibers into concrete presents multiple benefits, including enhanced resistance to cracking and shrinkage, reduced brittleness in the composite material, and, in some cases, improved mechanical performance, especially in tensile strength, flexural strength, and impact resistance [1-3]. Additionally, they offer valuable thermal properties [3] and contribute to significantly lowering the production costs of cement-based composites.

Date palm (DPL) fibers are among the most abundant natural fibers in several countries, including Algeria. They are not only economical but also environmentally friendly. These fibers come from the large amounts of waste generated by date palm trees, which are often disposed of without being properly utilized. In 2022, date production in Algeria reached 1.24 million tons, according to the United Nations Food and Agriculture Organization (FAO). After the annual fruit harvest, pruners typically trim 10 to 15 branches from a date palm tree, resulting in around 35 kg of waste, which includes around 20 kg of dry fibers and leaflets per tree [2, 4, 5]. The use of date

palm fibers (PDL) in concrete offers notable environmental and economic advantages compared to other plant-based fibers such as sisal, coconut, or straw. Unlike these fibers, which often require specific cultivation, fertilization, and processing resulting in higher costs and environmental burden PDL fibers are residual agricultural waste (rachis, leaflets, spadices, dry fronds, date residues, and fibrilliums, etc.) generated in large quantities during palm maintenance. Their reuse in concrete helps manage this waste effectively, reducing the need for incineration or landfill disposal.

Economically, PDL fibers are locally available and generally free of charge, minimizing both raw material and transportation costs. In contrast, imported fibers like sisal or coconut are often expensive and involve more complex processing. Thus, incorporating untreated PDL fibers into concrete not only reduces the consumption of non-renewable resources and conventional raw materials but also supports regional sustainability through low-cost, eco-friendly construction solutions.

Therefore, research studies conducted in this context explore the use of date palm waste as aggregates in concrete [3, 6, 7] and as fibers, added to the composition of concrete or mortars. However, concrete presents several major drawbacks, including its brittle nature, low tensile and flexural strength, and low deformation capacity, making it prone to cracking under tensile stresses. Sand concrete, the subject of our study,

is not exempt from this problem.

Numerous studies on sand concrete have demonstrated its economic advantages and technological specificity [8-14]. Sand concrete is comparable to ordinary concrete in terms of cement dosage (250 to 400 kg/m³) and can even replace it in certain structures [9, 11, 12, 15]. Sand concrete has been the subject of extensive research [9-14] and is considered a special concrete, adaptable to various applications such as compacted sand concrete for pavements [16], self-compacting sand concrete [15, 17], sprayed sand concrete [18], lightweight sand concrete [10], as well as repair concrete [11, 12, 19].

The integration of date palm fibers into sand concrete is a promising solution for improving its mechanical and physical performance. It positively contributes to reducing cracking while utilizing these fibers in concrete production and enhancing the material's properties for various applications. DPL can not only reduce microcracks and shrinkage in concretes but also improve flexural and impact resistance. On the other hand, the work [20-22] shows that increasing the content of DPL fibers decreases the compressive and flexural strength of mortars and ordinary concrete. Moreover, several researchers [20, 22-25] have concluded that the content and size of DPL fibers play a crucial role in the performance of concrete and mortar. Kriker et al. [20] and Bamaga et al. [23] studied the effects of DPL fiber length on compressive strength and found that concrete and mortar reinforced with shorter DPL fibers exhibit higher compressive strength. Furthermore, Ali-Boucetta et al. [26] noted that static mechanical properties can increase or decrease depending on the length and content of coconut fibers. However, Ozerkan et al. [24] observed a marginal improvement in compressive and flexural strength by incorporating 0.5% treated DPL fibers into mortar.

The majority of researchers [2, 20, 24-26] prefer to treat plant fibers before incorporating them into the cement matrix. Kriker et al. [20] also recommend treating date palm fibers before introducing them into concrete to improve their often poor mechanical properties and optimize their adhesion at the paste-fiber-cement interface.

The aim of this study is to investigate the potential of date palm fibers, specifically leaflets (LFL) and fibrillium (FBL), as reinforcement in sand concrete. The goal is to develop a construction material that is both cost-effective and environmentally friendly. To this end, the fibers are incorporated at varying percentages (0.5%, 1%, and 1.5%) to assess their effect on several properties of sand concrete, including workability, density, mechanical strengths, water absorption, and shrinkage.

2. MATERIALS

2.1 Sand

The sand used is a crushed sand from the region of Biskra (Algeria), with a continuous particle size distribution of 0/4 mm, conforming to the recommended range for concrete sands according to the standard NF EN 12620+A1 [27]. The grading curve is illustrated in Figure 1, while the physical characteristics of the sand are presented in Table 1.

2.2 Filler

The used filler in this study is derived from crushed limestone: a material abundantly available in most Algerian

quarries. With an average particle size of 23 μ m, this filler complies with the compactness criteria defined by the NF EN 12620+A1 standard [27]. Its physical properties are detailed in Table 1.

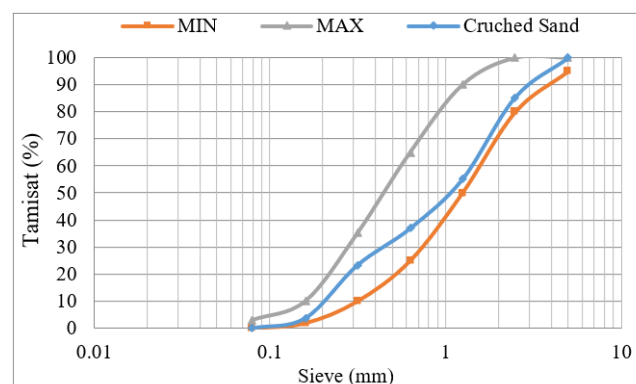


Figure 1. Particle size distribution of crushed sand

Table 1. Physical properties of used sand and filler

Properties	Sand	Filler
Apparent density (g/cm ³)	1.46	1.09
Specific density (g/cm ³)	2.51	2.7
Fineness modulus	3	-
Specific surface (cm ² /g)	-	5360

2.3 Cement

The binder used is an ordinary portland cement, classified as CEM II/A 42.5 N according to NF EN 197-1 standard [28]. This cement has an absolute density of 3.1 g/cm³ and a fineness of 3700 cm²/g.

2.4 Superplasticizer

The superplasticizer utilized is a high-range water reducer. It is a liquid admixture that is diluted with water in accordance with the NF EN 934-2 standard [29]. It has an absolute density of 1.065 $\pm$ 0.015 and is designed based on modified polycarboxylate ethers.

2.5 Water

Water temperature of 20 $\pm$ 1°C conforms to the requirements of NF EN 1008 standard [30].

2.6 Fibers

In this study, plant fibers derived from date palm trees were used. Two types of fibers were selected, each originating from different parts of the date palm tree. The first part consists of the fronds, which are composed of pinnate leaflets arranged regularly in an oblique position along the upper part of the rachis (Figure 2(a) and (b)). The leaflets (LFL) were used as fibers after being removed from the rachis and cut (Figure 2(c)). The second part is the fibrillium (FBL), a fibrous tissue surrounding the trunk of the date palm tree above the base of the fronds (Figure 2(d-f)). The fibrillium (FBL) was used as fiber after being extracted from the trunk, soaked in water to facilitate fiber separation, and then cut to obtain the fibers as shown in Figure 2(f). The physical and chemical characteristics of the fibers are presented in Table 2 and Table

3, respectively.



Figure 2. Date palm: (a) palm, (b) leaf regularly arranged on the rachis, (c) leaflets fibers, (d) trunk (stipe), (e) fibrillium tissue, (f) fibrillium fibers

Scanning Electron Microscopy (SEM) images of date palm fibers presented in Figure 3 reveals: (a) leaflet fiber, showing a compact lamellar structure with dense fibrillar bundles and occasional heterogeneous zones; (b) fibrillium fiber, exhibiting a highly porous and disordered texture with a spongy, alveolar-like morphology.

Table 2. Physical properties of DPL fibers (leaflets and fibrillium)

Fibers	LFL	FBL
Diameter (mm)	0.5-1.5	0.5-0.8
Average (mm)	70% (0.7-1.0)	80% (0.6- 0.7)
Length (mm)	20-25	20-25
Apparent density (g/cm ³)	0.7	0.5
Specific density (g/cm ³)	1.8	1.4
Absorption after 24h (%)	97	132

Table 3. Chemical properties of DPL fibers (leaflets and fibrillium) [31]

	Cellulose (%)	Hemicellulose (%)	Lignine (%)
(LFL) Fibers	33.5 -35	20.05	28.57
(FBL) Fibers	43-46	21.86	27.8

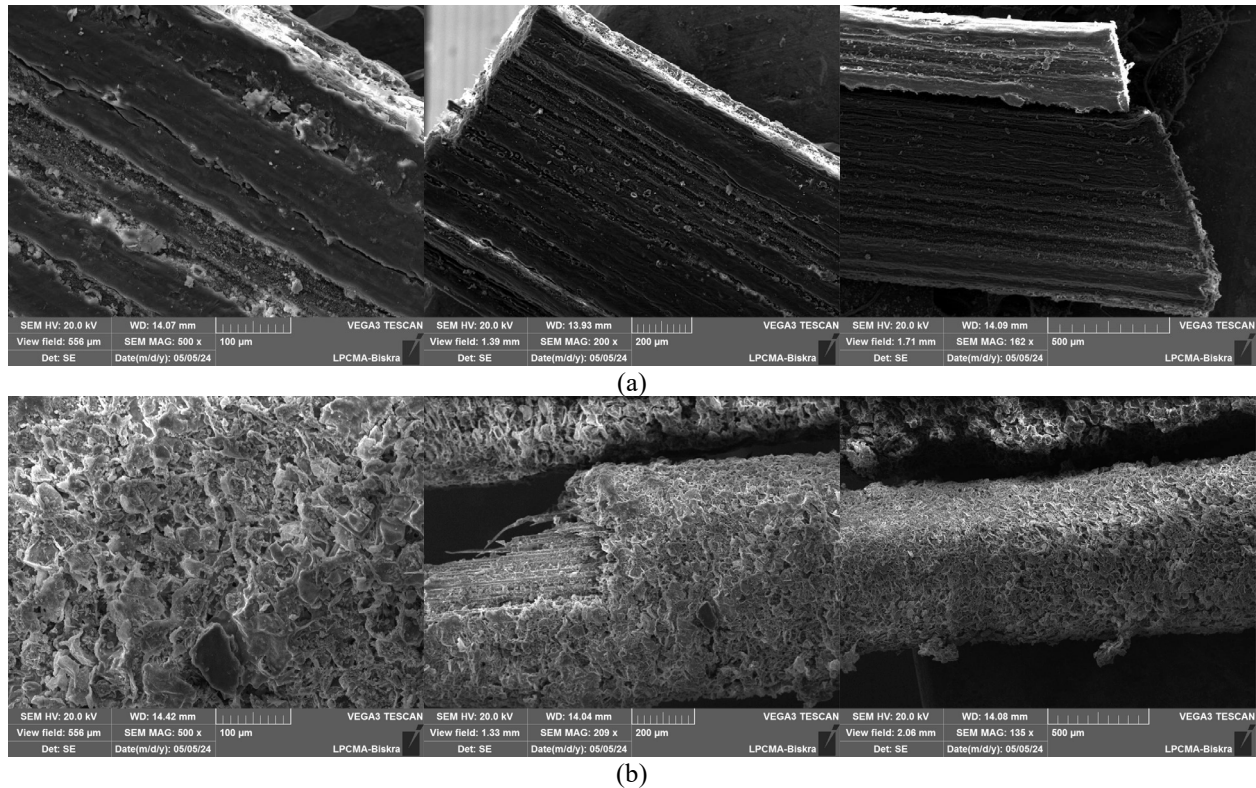


Figure 3. SEM image of date palm fibers: (a) Leaflets and (b) Fibrillium

3. EXPERIMENTAL TECHNIQUES

The preparation and curing of the sand concrete specimens follow the NF EN 196-1 [32] standard. All mechanical tests are conducted on prismatic specimens measuring $4 \times 4 \times 16$ cm³. Compressive and flexural strengths are evaluated in accordance with NF EN 196-1 [32]. The hardened density is measured following NF EN 18-459 [33], while water absorption by immersion is assessed according to ASTM C 642-21 [34]. Shrinkage is determined based on the NF EN

12390-16 [35] standard. Workability is evaluated using the flow table test, as specified in ASTM C 1437 [36].

4. FORMULATION OF SAND CONCRETE

The composition of the sand concrete is prepared according to a fundamental formulation based on an experimental approach [10-14, 18]. This method is based on the criterion of optimizing the compactness of the granular skeleton [11-14].

The cement dosage is set at 350 kg/m³, a common dosage adopted in most studies [10, 11, 14]. As for the volume of sand, it is determined by a compactness coefficient (γ) of the dry mix [37].

The compactness coefficient (γ) is the ratio of 1000 liters of the absolute volume of solids, relative to consistency criteria and the maximum diameter (D_{max}) of the aggregates. Given a mix with $D_{max} \leq 5$ mm and a plastic consistency by normal vibration, a compactness coefficient $\gamma = 0.770$ is obtained. Since the sand used is crushed sand, a correction is applied to the compactness coefficient (-0.33) [36]. Consequently, the volume of sand (V_s) is determined according to the following formula:

$$V_s = 1000\gamma - V_c, \text{ (} V_c: \text{ volume of cement) [8, 9, 14].}$$

After determining the basic composition of the sand concrete, the corresponding mechanical strengths at the age of 28 days were then determined, as shown in Table 4.

Table 4. Sand concrete composition and mechanical properties at the age of 28 days

Composition (Kg/m ³)		Mechanical Strength (MPa)	
Cement	350	Compressive	Flexural
Sand	1660		
W /C	0.75	21	3.9

Additionally, to improve the obtained mechanical properties, part of the sand was replaced with limestone filler to ensure proper aggregate distribution. The substitution rate 10.5% of the sand mass. Indeed, adding limestone filler to sand concrete is important for filling the voids between sand grains and achieving better compactness [9, 12, 14]. It has been established that limestone filler has a physicochemical activity that promotes the acceleration of cement clinker hydration [9]. Moreover, a superplasticizer (SP) was added to the base composition to improve the workability of the studied mixtures, and the mixing water (W) proportion was also reduced.

The above-described steps yielded an optimized sand concrete with specific mechanical characteristics, which became the reference concrete. This concrete has been investigated in other studies [10-12, 14, 15, 18, 19]. Table 5 presents the optimized composition and mechanical characteristics of the reference sand concrete (SC0).

Table 5. Optimized composition and mechanical properties of the reference sand concrete (SC0)

	Sand (Kg/m ³)	Cement (Kg/m ³)	Filler (Kg/m ³)	W/B	SP (%)	Strength (MPa)	
						Rc	Rf
SC0	1480	350	175	0.6	2	33.5	7.6

Table 6. Sand concrete composition with and without DPL fibers

	Fiber (%)	Sand (Kg/m ³)	Cement (Kg/m ³)	Filler (Kg/m ³)	W/C	SP (%)
SC0	0					
LFL05	0.5					
LFL10	1					
LFL15	1.5	1480	350	175	0.6	2
FBL05	0.5					
FBL10	1					
FBL15	1.5					

The mixtures were named as follows:

- SC0: Reference Sand Concrete
- LFL05: Sand Concrete contains 0.5% Leaflets Fibers
- LFL10: Sand Concrete contains 1% Leaflets Fibers
- LFL15: Sand Concrete contains 1.5% Leaflets Fibers
- FBL05: Sand Concrete contains 0.5% Fibrillium Fibers
- FBL10: Sand Concrete contains 1% Fibrillium Fibers
- FBL15: Sand Concrete contains 1.5% Fibrillium Fibers

In this study, we incorporated both types of date palm fibers, leaflets (LFL) and fibrillium (FBL), into the concrete at three different percentages of the total dry mix weight (0.5%, 1%, and 1.5%), without any chemical treatment.

The fibers were pre-soaked in water for at least 24 hours prior to use, in order to prevent them from absorbing the mixing water and to remove impurities, in accordance with the method adopted by Adamu et al. [4]. All of the sand concrete compositions studied are presented in Table 6.

5. RESULTS AND DISCUSSION

5.1 Workability

Figure 4 shows the slump variation based on the type and percentage of date palm fibers (DPL) incorporated into sand concrete, with slump being indicative of the fresh concrete's workability. A decrease in workability is observed as the percentage of DPL increases. Studies have shown that the addition of fibers to the cementitious matrix affects workability [20, 22]. In this study, the results show a decrease in workability compared to the reference concrete for both types of fibers (LFL and FBL). At 0.5% fibers ratio, a reduction reaches up to 41% for mixtures containing fibrillium fibers and 28.2% for those containing leaflet fibers.

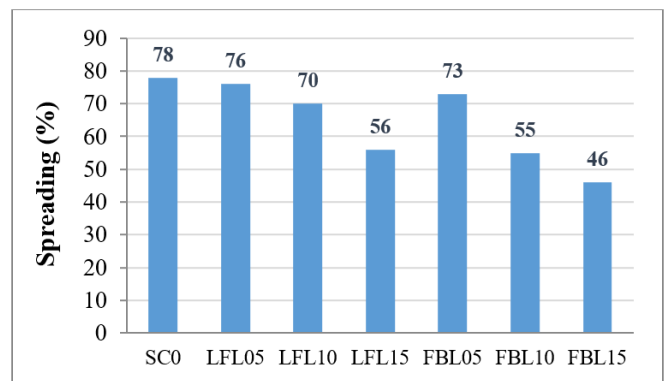


Figure 4. Spread variation of sand concrete mixtures

Therefore, as the DPL fibers content increases, the water demand also increases due to their high absorption capacity [20]. However, the leaflets had a lesser effect on workability due to their lower water absorption capacity, in contrast to the fibrillium fibers, whose high absorption is attributed to their highly porous, sponge-like network structure. As a result, DPL fibers must be saturated with water before being incorporated in a cementitious mix to minimize water absorption [4, 22]. The fibers were immersed in water for more than 24 hours until their mass stabilized. We then incorporated both types of fibers in a saturated surface-dry (SSD) state into the mix. Despite this, the immersion did not suffice to improve the slump compared to SC0. This prompts the consideration of

chemical treatment to reduce the fibers' water absorption capacity.

5.2 Dry density

According to the histogram presented in Figure 5, a slight decrease in density is observed as the fiber dosage increases. Specifically, for fiber percentages of 0.5%, 1%, and 1.5%, the reduction in density compared to the reference concrete is 0.82%, 1.94%, and 3.10% for (LFL) fibers, and 1.20%, 2.84%, and 3.62% for (FBL) fibers, respectively. Thus, incorporating FBL fibers in concrete contributes more to the reduction in density.

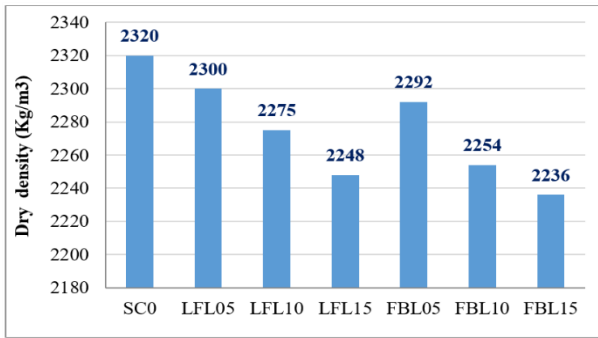


Figure 5. Dry density of sand concrete mixtures

The lower density of the fibers compared to sand and the increased void volume due to the porosity of the FBL fibers incorporated into the cementitious matrix led to a less dense sand concrete, as this observation reveals. Most studies agree that the introduction of plant fibers into concrete contributes to a reduction in density [38-40].

5.3 Compressive strength

Figure 6 shows the average compressive strength of each mixture, calculated from four (4) specimens, along with the corresponding standard error bars. The figure highlights the evolution of compressive strength in concrete mixes containing various proportions of date palm leaflet fibers (LFL) and fibrillium fibers (FBL). It can be noted that compressive strength consistently increases over time for all mixtures, from 7 to 28 and then 45 days. At a fiber content of 0.5%, both LFL05 and FBL05 exhibit compressive strength values that are relatively close to the reference concrete (SC0), with only minor reductions. At 28 days, LFL05 achieves 33 MPa, compared to 33.5 MPa for SC0, representing a slight decrease of 1.5%. In contrast, FBL05 reaches 32 MPa, indicating a more noticeable yet moderate reduction of 4.5%. At 45 days, the compressive strength continues to increase for all mixes.

LFL05 reaches 38 MPa, while FBL05 attains 37.5 MPa, compared to 39 MPa for the reference concrete. These values correspond to respective decreases of 2.5% and 3.8%. These findings suggest that incorporating 0.5% of date palm fibers, whether LFL or FBL, has a negligible impact on compressive strength, especially at later ages. The slight reduction observed remains within acceptable limits and confirms the viability of using a low fiber dosage without significantly compromising mechanical performance. Moreover, Fibrillium fibers (FBL) lead to a slightly greater reduction in compressive strength, estimated between 1% and 3%, compared to leaflet fibers (LFL) at the same dosage. This difference can be attributed to the porous and sponge like network morphology of FBL fibers, which weakens the fiber matrix interface and limits mechanical bonding. In contrast, leaflet fibers, with their denser and more layered structure, contribute to better mechanical interlocking and more efficient load transfer within the cementitious composite.

In fact, The ANOVA results (Table 7) indicated that the type of concrete significantly affects compressive strength overall ($p < 0.001$). However, Tukey's test (Table 8) showed that differences between FBL and LFL were mostly negligible at the same dosages ($p > 0.05$), becoming significant only at certain levels. This difference arises because ANOVA evaluates the global effect, while post hoc tests focus on pairwise comparisons. Consequently, the effect of fiber type is present but relatively weak and influenced mainly by dosage and curing age.

Furthermore, These results may be explained by the fact that, in some cases, date palm fibers absorb a portion of the mixing water despite being pre-soaked in water for 24 hours. This disrupts the effective water-to-binder ratio, hinders cement hydration, and reduces the density of the cement paste. Fiber shrinkage may further impair their bonding with the matrix, promoting the formation of micro-voids at the fiber paste interface, which weakens the overall concrete structure.

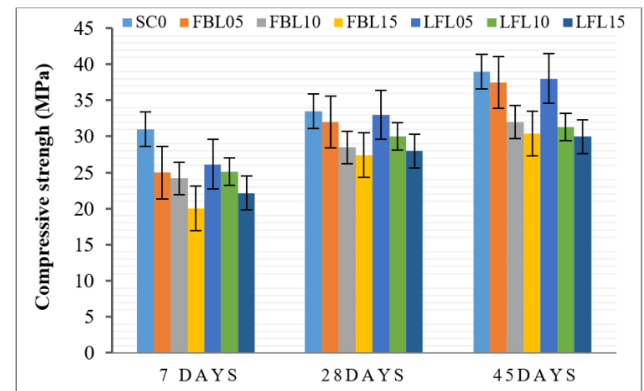


Figure 6. Compressive strength of sand concrete mixtures

Table 7. Analysis of variance (ANOVA) for compressive strength

Cases	Sum of Squares	df	Mean Square	F	p-Value
A: Concrete	8.147	1	8.147	12.852	< 0.001
B: Dosage	709.621	3	236.540	373.125	< 0.001
C: Age	996.232	2	498.116	785.741	< 0.001
AB: Interaction	3.123	3	1.041	1.642	0.192
AC: Interaction	5.729	2	2.865	4.519	0.016
BC: Interaction	72.869	6	12.145	19.158	< 0.001
ABC: Interaction	5.766	6	0.961	1.516	0.193
Residuals	30.429	48	0.634		

df: degrees of freedom

Table 8. Post hoc Tukey test: Comparisons concrete-dosage case of compressive strength

Concrete	Fiber Dosage	Mean Difference	SE	df	t	P _{Tukey}
SC0	LFL 0%	-8.438×10^{-15}	0.375	48	-2.248×10^{-14}	1.000
	FBL 0.5%	3.278	0.375	48	8.733	< 0.001
	LFL 0.5%	2.136	0.375	48	5.690	< 0.001
	FBL 1%	6.456	0.375	48	17.199	< 0.001
	LFL 1%	5.696	0.375	48	15.175	< 0.001
	FBL 1.5%	8.600	0.375	48	22.913	< 0.001
	LFL 1.5%	7.811	0.375	48	20.811	< 0.001
	FBL 0.5%	3.278	0.375	48	8.733	< 0.001
	LFL 0.5%	2.136	0.375	48	5.690	< 0.001
	FBL 1%	6.456	0.375	48	17.199	< 0.001
SC0	FBL 1%	5.696	0.375	48	15.175	< 0.001
	FBL 1.5%	8.600	0.375	48	22.913	< 0.001
	LFL 1.5%	7.811	0.375	48	20.811	< 0.001
	FBL 0.5%	-1.142	0.375	48	-3.043	0.068
	FBL 1%	3.178	0.375	48	8.467	< 0.001
FBL05	LFL 1%	2.418	0.375	48	6.442	< 0.001
	FBL 1.5%	5.322	0.375	48	14.180	< 0.001
	LFL 1.5%	4.533	0.375	48	12.078	< 0.001
	FBL 1%	4.320	0.375	48	11.510	< 0.001
	LFL 1%	3.560	0.375	48	9.485	< 0.001
LFL05	FBL 1.5%	6.464	0.375	48	17.223	< 0.001
	LFL 1.5%	5.676	0.375	48	15.121	< 0.001
	FBL 1%	-0.760	0.375	48	-2.025	0.477
	FBL 1.5%	2.144	0.375	48	5.713	< 0.001
	LFL 1.5%	1.356	0.375	48	3.612	0.015
LFL10	FBL 1.5%	2.904	0.375	48	7.738	< 0.001
	LFL 1.5%	2.116	0.375	48	5.636	< 0.001
FBL15	LFL 1.5%	-0.789	0.375	48	-2.102	0.428

Several previous studies have reported a decrease in compressive strength in fiber reinforced concrete with DPL fibers [2, 13, 24] a trend also attributed to air entrapment during mixing and casting [22, 23]. The increased porosity caused by fibers rising with fiber content results in lower matrix density, thereby leading to a gradual decline in mechanical performance, which is consistent with other experimental findings [23, 40, 41].

5.4 Flexural strength

According to the results presented in Figure 7, the average flexural strength values were obtained from three (3) specimens per mixture and are shown with the corresponding standard error bars. It is observed that, for all mixtures, the flexural strength increases consistently over time, from 7 to 28 days, and then to 45 days. Also, at 28 days, the mixes containing 0.5% fibers show flexural strengths of 8.0 MPa for FBL05 and 7.7 MPa for LFL05, reflecting slight increases of 5.2% and 1.3%, respectively, compared to the reference concrete (SC0) which achieved 7.6 MPa. This indicates a modest improvement in flexural strength at low fiber content, with fibrillium fibers (FBL) showing a more pronounced effect than leaflet fibers (LFL). At 45 days, this trend becomes more evident. The FBL05 mix records a flexural strength of 9.2 MPa, representing an increase of 9.5% over SC0 (8.4 MPa), while LFL05 reaches 8.6 MPa, indicating a smaller gain of 2.3%. As the fiber content increases, a general decline in flexural strength is observed, regardless of fiber type. These findings confirm that low fiber dosage (0.5%) is optimal for enhancing flexural performance, and that fibrillium fibers contribute more effectively to flexural strength than leaflet

fibers at equivalent dosages.

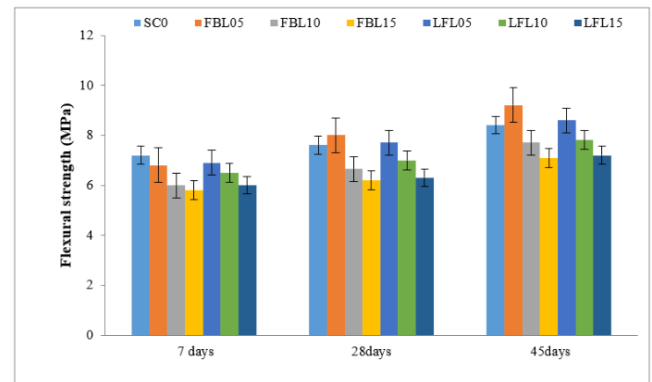


Figure 7. Flexural strength of sand concrete mixtures

Table 9. Analysis of variance (ANOVA) for flexural strength

Cases	Sum of Squares	df	Mean Square	F	p-Value
A: Concrete	0.040	1	0.040	0.382	0.540
B: Dosage	25.819	3	8.606	81.858	< 0.001
C: Age	28.614	2	14.307	136.079	< 0.001
AB: Interaction	0.769	3	0.256	2.439	0.076
AC: Interaction	0.368	2	0.184	1.749	0.185
BC: Interaction	1.324	6	0.221	2.100	0.071
ABC: Interaction	0.238	6	0.040	0.377	0.890
Residuals	5.047	48	0.105		

Table 10. Post hoc Tukey test: Comparisons concrete-dosage case of flexural strength

Concrete	Fiber Dosage	Mean Difference	SE	df	t	P _{Tukey}
SC0	LFL 0%	-3.726×10^{-15}	0.153	48	-2.438×10^{-14}	1.000
	FBL 0.5%	-0.233	0.153	48	-1.527	0.789
	LFL 0.5%	0.033	0.153	48	0.218	0.000
	FBL 1%	0.944	0.153	48	6.179	< 0.001
	LFL 1%	0.667	0.153	48	4.361	0.002
	FBL 1.5%	1.444	0.153	48	9.450	< 0.001
	LFL 1.5%	1.267	0.153	48	8.287	< 0.001
	FBL 0.5%	-0.233	0.153	48	-1.527	0.789
	LFL 0.5%	0.033	0.153	48	0.218	0.000
	FBL 1%	0.944	0.153	48	6.179	< 0.001
SC0	LFL 1%	0.667	0.153	48	4.361	0.002
	FBL 1.5%	1.444	0.153	48	9.450	< 0.001
	LFL 1.5%	1.267	0.153	48	8.287	< 0.001
	FBL05	0.267	0.153	48	1.745	0.659
	FBL 1%	1.178	0.153	48	7.705	< 0.001
FBL05	LFL 1%	0.900	0.153	48	5.888	< 0.001
	FBL 1.5%	1.678	0.153	48	10.976	< 0.001
	LFL 1.5%	1.500	0.153	48	9.813	< 0.001
	FBL05	0.911	0.153	48	5.961	< 0.001
	LFL 1%	0.633	0.153	48	4.143	0.003
LFL05	FBL 1.5%	1.411	0.153	48	9.232	< 0.001
	LFL 1.5%	1.233	0.153	48	8.069	< 0.001
	FBL10	-0.278	0.153	48	-1.817	0.612
	FBL 1.5%	0.500	0.153	48	3.271	0.038
	LFL 1.5%	0.322	0.153	48	2.108	0.425
LFL10	FBL 1.5%	0.778	0.153	48	5.088	< 0.001
	LFL 1.5%	0.600	0.153	48	3.925	0.006
FBL15	LFL 1.5%	-0.178	0.153	48	-1.163	0.938

The ANOVA results (Table 9) confirmed that the 'Concrete' factor was not statistically significant ($p = 0.540$), while the post-hoc Tukey test (Table 10) demonstrated that flexural strength was predominantly affected by fiber dosage and

curing age ($p < 0.001$). The effect of fiber type (FBL vs. LFL) appeared only marginal, which is consistent with the experimental observation that FBL fibers provide a slight improvement in flexural strength compared to LFL.

This limited contribution can be attributed to their slightly rough surface, which enhances interfacial bonding with the cementitious matrix, although not sufficiently to produce a strong statistical effect.

Indeed, the incorporation of untreated fibers does not have a significant effect on the flexural strength of sand concrete.

This is due to insufficient adhesion between the natural fiber and the cementitious matrix [20, 41]. The addition of fibers also encourages the formation of pores in the mix, thereby significantly reducing the composite material's cohesion. This conclusion aligns with the results obtained by Mouhous [41]. Some researchers advocate for pre-treating natural fibers before incorporating them into concrete. This treatment aims to make their surface rougher, thereby improving the adhesion between the fiber and the cement paste [4, 20, 41].

5.5 Water absorption

The results of the water absorption test by total immersion after 28 days, presented in Figure 8, indicate the absorption rates for each mixture. It was found that incorporating DPL fibers at percentages of 0.5%, 1%, and 1.5% for both types (FBL and LFL) leads to an increase in water absorption, which becomes more significant as the fiber percentage increases. Additionally, sand concrete compositions with FBL fibers exhibit a higher water absorption rate than those with LFL fibers. The composition with a 0.5% LFL fiber content achieved the lowest water absorption value, 6.9%, demonstrating a 32.7% increase over the reference concrete. Notably, 0.5% FBL fiber content results in a 22.5% increase in water absorption compared to LFL fibers.

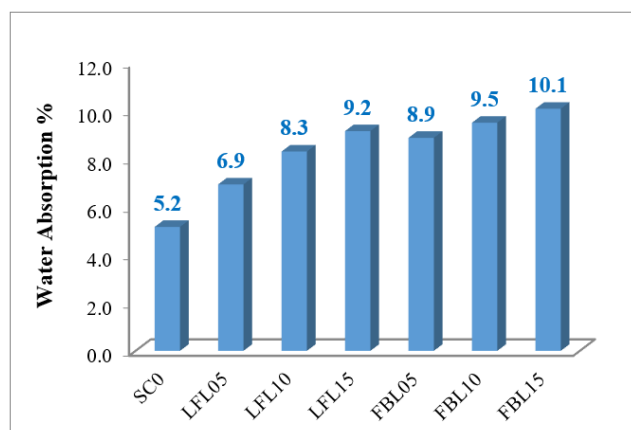


Figure 8. Water absorption of sand concrete mixtures

This difference is primarily attributed to the spongy morphology of FBL fibers, which exhibit a highly porous texture and, consequently, a greater water absorption capacity compared to LFL fibers. The increase in water absorption observed in sand concrete mixes incorporating date palm fibers (FBL and LFL), relative to the reference mix, can be explained by the intrinsic porosity of the fibers as well as the interstitial voids formed between fibers within the matrix. This porosity leads to insufficient adhesion at the fiber–matrix interface, particularly due to the lack of surface treatment applied to the fibers in all three dosages studied. These

observations are consistent with the findings reported by several researchers [13, 21–24, 40].

5.6 Time-dependent total shrinkage behavior of sand concrete mixtures

Figure 9 presents the development of total shrinkage over time for different sand concrete mixtures, with and without the incorporation of date palm fibers: fibrillium (FBL) and leaflets (LFL) at dosages of 0.5%, 1%, and 1.5%. Shrinkage measurements were taken daily over a 42-day period.

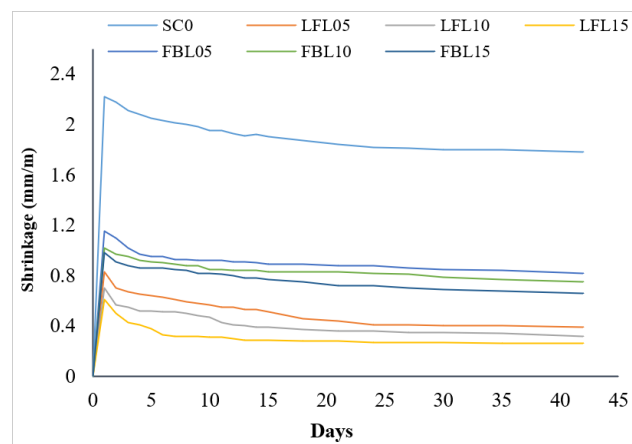


Figure 9. Evolution of shrinkage according to time

The results clearly demonstrate the significant effectiveness of natural fibers in reducing total shrinkage. The reference concrete (SC0) exhibited the highest shrinkage throughout the test, reaching approximately 1.78 mm/m at 42 days. In contrast, all DPL fiber reinforced sand concretes showed a progressive reduction in shrinkage as the fiber content increased. The most pronounced reduction was observed for the concrete containing 1.5% leaflet fibers (LFL15), with shrinkage stabilized around 0.26 mm/m, representing an 85.4% decrease compared to the control. Similarly, LFL10 and LFL05 showed significant reductions of 82% and 87%, respectively, indicating the high efficiency of leaflets even at low dosages. In comparison, the concretes incorporating fibrillium fibers also exhibited shrinkage reduction, but to a lesser extent. The FBL15 mixture showed shrinkage of 0.66 mm/m, a 63% reduction relative to SC0, while FBL10 and FBL05 recorded reductions of 57.8% and 54%, respectively.

The reduction in shrinkage observed with the incorporation of date palm fibers can be attributed to their physical action within the cementitious matrix. First, the fibers act as micro-bridges that limit the development of shrinkage cracks. In addition, their water absorption capacity plays a key role: even after 24 h of pre-soaking, the fibers retain a portion of the mixing water, which is then gradually released, providing internal curing that mitigates rapid water loss during early hardening.

In this study, shrinkage reduction improved with increasing fiber dosage in agreement with earlier findings[42–44]. This enhancement can be attributed to the higher number of fibers acting as micro-bridges that restrict crack propagation, while their water retention capacity promotes internal curing. Consequently, the incorporation of fibers alters the internal water flow within the concrete, as also reported by previous studies [43, 44]. Both fiber types (LFL and FBL) contributed to this effect; however, LFL were more effective due to their

dense lamellar structure, which retains water more efficiently and releases it gradually, providing superior internal curing. In contrast, the porous and spongy morphology of FBL leads to faster water release, favoring micro-void formation and diminishing their efficiency in controlling shrinkage. This may explain the more pronounced shrinkage reduction obtained with LFL fibers, which is consistent with the findings reported in earlier research [42].

These findings are consistent with recent studies on plant fiber-reinforced concretes [20, 25, 39, 42-45], which highlight the role of natural fibers as physical barriers that prevent microcrack development, limit early age water loss and they significantly reduce shrinkage [1], especially when properly dispersed and compatible with the cement matrix.

5.7 Statistical correlations

5.7.1 Compressive strength and density correlation

Figure 10 illustrates the linear relationship between dry density and compressive strength for sand concrete reinforced with date palm fibers (DPL), including both fibrillium (FBL) and leaflet fibers (LFL).

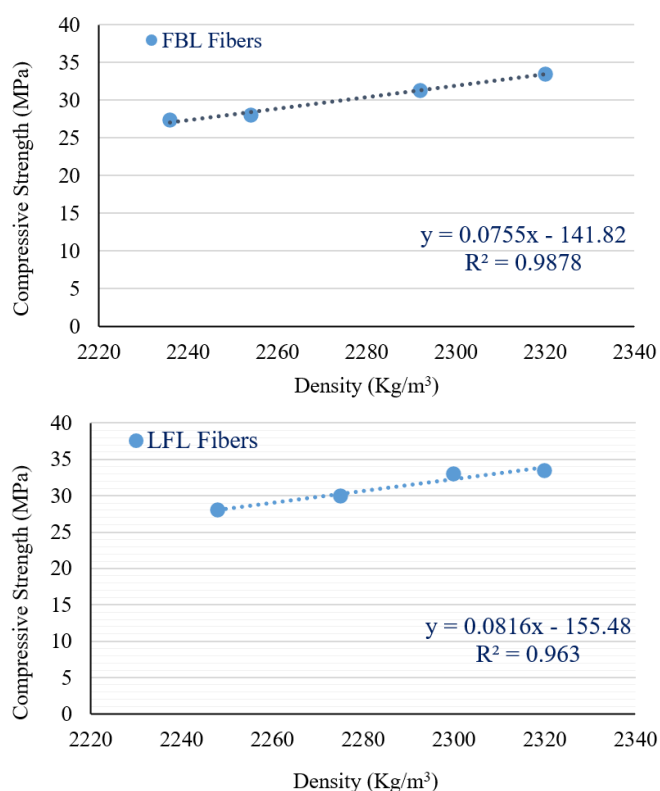


Figure 10. Relationship between compressive strength and density of mixtures with (FBL and LFL) fibers

A clear increasing trend is observed in both cases: as the concrete's density increases, its compressive strength also improves. For FBL fibers, the regression line is defined by the equation: $y = 0.0755x - 141.82$, with a coefficient of determination $R^2 = 0.9878$, indicating an extremely strong correlation and an excellent fit to the experimental data. Similarly, for LFL fibers, the relationship is described by the equation: $y = 0.0816x - 155.48$, with $R^2 = 0.963$, confirming a very strong positive correlation between density and compressive strength.

These results highlight that dry density is a key indicator for

predicting the mechanical performance of DPL fiber reinforced sand concrete. Higher density generally reflects better matrix compactness, reduced porosity, and enhanced strength. Therefore, proper fiber dispersion and optimized dosage contribute to achieving a balance between lightness, compactness, and mechanical performance of the material

5.7.2 Compressive strength and water absorption correlation

Figure 11 illustrates the linear relationship between compressive strength and water absorption rate for sand concretes reinforced with date palm fibers (DPL), whether in the form of leaflet fibers (LFL) or fibrillium fibers (FBL). A clear decreasing trend is observed, indicating that higher water absorption is associated with a reduction in compressive strength.

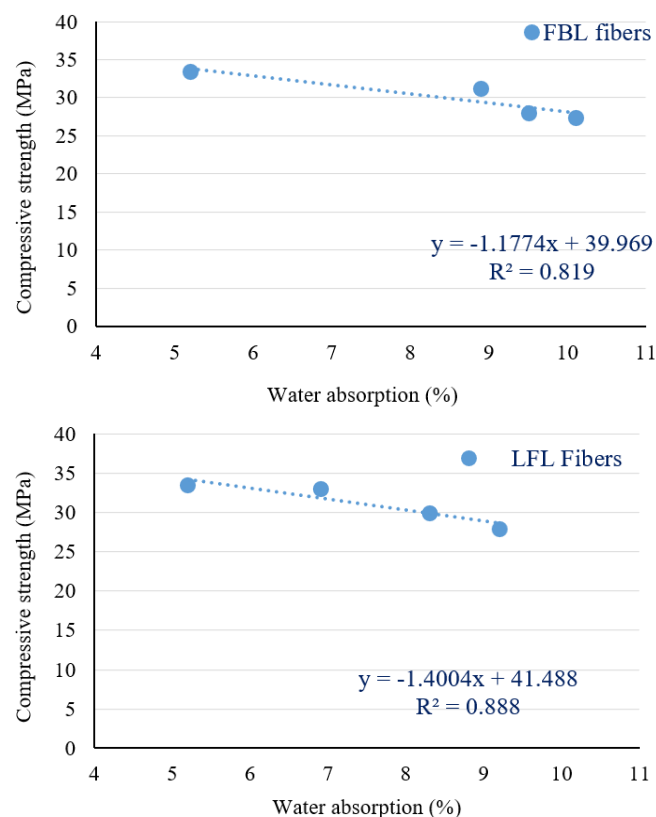


Figure 11. Relationship between compressive strength and water absorption of mixtures with (FBL and LFL) fibers

For the LFL fibers, the linear regression line is defined by the equation: $y = -1.4004x + 41.488$, the coefficient of determination $R^2 = 0.888$ indicates a strong and reliable correlation, showing that nearly 89% of the variability in strength can be explained by the water absorption rate. This relationship aligns with the fact that higher water absorption typically reflects increased capillary porosity, which weakens the compactness of the cement matrix. In the case of FBL fibers, the regression line follows the equation: $y = -1.1774x + 39.969$, with a coefficient of determination $R^2 = 0.819$, also indicating a strong, but slightly less robust, correlation compared to LFL. This difference can be attributed to the porous and spongy nature of FBL fibers, which tend to retain more water within the mix.

As a result, LFL fibers prove to be more effective in limiting water absorption due to their denser structure, which helps reduce capillary porosity and maintain higher mechanical

strength. In contrast, FBL fibers lead to a more adverse impact, mainly due to their higher water retention, which compromises the cementitious matrix.

5.7.3 Compressive strength and flexural strength correlation

Figure 12 illustrates the relationship between flexural strength and compressive strength for sand concrete reinforced with FBL and LFL fibers, highlighting the difference between the two reinforcement types. A positive correlation is observed between flexural and compressive strength in the case of sand concretes reinforced with fibrillium fibers (FBL).

A linear increasing trend is highlighted by the regression equation: $y = 3.1602x + 7.8732$, with a coefficient of determination $R^2 = 0.8353$, indicating a strong correlation. This implies that an increase in flexural strength is generally associated with an increase in compressive strength. This relationship suggests that the reinforcement mechanisms provided by FBL fibers; particularly crack bridging and load transfer have a simultaneous effect on both mechanical properties. Similarly, for mixes reinforced with leaflet fibers (LFL), a linear increasing trend is also observed, with a regression equation: $y = 3.94x + 2.954$ and a coefficient $R^2 = 0.9612$, indicating a very strong correlation between compressive and flexural strengths. This strong synergy reflects the high effectiveness of LFL fibers in enhancing both properties.

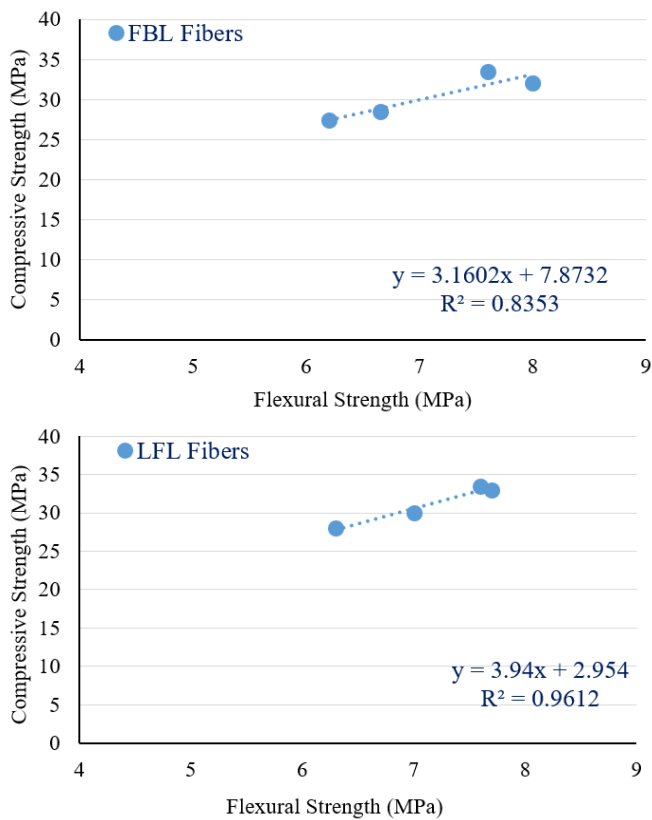


Figure 12. Relationship between compressive and flexural strengths of mixtures with (FBL and LFL) fibers

Moreover, the higher slope observed in the case of LFL fibers suggests that variations in flexural strength have a more significant impact on compressive strength compared to FBL fibers. This can be attributed to the more compact and lamellar structure of LFL fibers, which promotes better bonding with the cement matrix and a more uniform mechanical load transfer. In contrast, the higher porosity of FBL fibers may

result in a less uniform stress distribution within the matrix, which could explain the slightly lower correlation coefficient ($R^2 = 0.8353$).

6. CONCLUSIONS

This study examined the effects of incorporating agricultural waste-derived date palm fibers (DPL), specifically leaflets (LFL) and fibrillium (FBL), into sand concrete, with the goal of improving its mechanical and physical properties while promoting the development of eco-friendly sand concrete.

The use of locally available date palm fibers in sand concrete offers an affordable, eco-friendly solution for housing in arid regions such as Algeria, directly supporting SDG 11 on sustainable and resilient cities. This approach reduces dependence on imported materials while promoting circular economy practices.

The findings of this research highlighted the following key points:

- The sand concrete reinforced with date palm fibers (DPL), both leaflets (LFL) and fibrillium (FBL) has provided valuable insights into the impact of these natural fibers on the physical and mechanical properties of the material.
- The incorporation of DPL fibers led to a decrease in workability, density, and compressive strength, primarily due to their porous structure, high water absorption capacity, and influence on the compactness of the cementitious matrix.
- As fiber content increases, a general decrease in compressive strength is observed, regardless of the fiber type. However, a low fiber content (0.5%) proved optimal for improving flexural strength, with FBL fibers performing better than LFL at equivalent dosages.
- Despite the observed decreases, the performance remains within acceptable limits, confirming the feasibility of using low fiber dosages (0.5%) without significantly impairing mechanical properties.
- The inclusion of DPL fibers significantly reduced the total shrinkage of sand concrete, with leaflet fibers (LFL) proving more effective in this regard. Their more compact morphology and stronger interaction with the cementitious matrix helped limit shrinkage-related cracking. In comparison, FBL fibers were less efficient in controlling shrinkage.
- Toward sustainable concrete: Date palm fibers offer a promising, eco-friendly alternative for enhancing sand concrete. Achieving a balance between lightweight properties, mechanical performance, durability, and shrinkage control is possible through careful fiber type selection, optimized dosage, and proper treatment to reduce their absorbent nature.
- Need for pre-treatment of both fiber types (LFL and FBL) is essential to reduce water absorption and improve fiber matrix adhesion, ultimately enhancing the overall performance of the composite material.
- The environmental benefits of using locally available date palm fibers are qualitatively discussed in this study, we acknowledge that a full claim of “eco-friendliness” requires detailed lifecycle assessment (LCA) data. Our results therefore reflect laboratory-scale feasibility, and future work will address LCA to validate these findings at an industrial scale.

- Although this study demonstrates the promising mechanical and physical performance of date palm fibers in sand concrete, it does not address certain aspects of durability, such as resistance to sulfate and acid attack or carbonation, which are particularly relevant in the aggressive environments of some regions in Algeria. Future research should therefore investigate these durability parameters. Furthermore, strategies such as fiber hybridization (LFL + FBL) or nano-silica-based surface treatments could be explored to enhance long-term performance. In particular, combining LFL and FBL fibers may offer a synergistic benefit, simultaneously improving shrinkage control and flexural strength.

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