Mechanical Strength and Water Absorption of Natural Fiber-Reinforced Cement Mortars: A Comparative Experimental Study

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Received: 19 January 2026 | Revised: 15 February 2026 | Accepted: 4 March 2026

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ABSTRACT

This study examined the use of five natural fibers (cotton, coconut coir, jute, sisal, and sheep wool) as reinforcements for cement mortars with a standard mix design. Sixteen fiber-reinforced mixtures were prepared with a constant fiber length of 10 mm. The mixtures were tested after 28 days for Water Absorption (WA) and mechanical performance. Fracture sections were visually assessed to evaluate dispersion quality, with some fiber additions improving flexural behavior. The highest flexural strength was obtained with sisal at 5% by volume (5.53 MPa versus 3.90 MPa for the control), and compressive strength was better at low dosages. Jute and coconut fibre of 1% reached 19.59 MPa and 19.50 MPa, respectively, while the initial mixture reached 14.62 MPa. WA generally increased with fiber content, reaching 30.44% for sheep wool at 4%, which led to severe strength reductions and visibly non-uniform fiber distribution. Overall, when the dosage remains within a dispersion-stable window, untreated natural fibers can improve mortar performance. Low contents of jute and coconut coir provided the most consistent compressive gains. However, excessive sheep wool led to connected porosity, high water uptake, and severe strength loss.

Keywords-natural fibers; fiber-reinforced mortar; water absorption; flexural strength; compressive strength; sustainable cementitious composites

I. INTRODUCTION

In cement mortars, the addition of natural fibers to the mix is primarily intended to enhance crack control and flexural toughness via crack bridging. The outcomes depend heavily on the type, dosage, geometry, and dispersion of the fibers. Increasing the dosage beyond the dispersion-stable range decreases workability, causes the fibers to agglomerate, and increases entrapped air, which can lead to higher porosity and water uptake, and ultimately reduce strength [1, 2]. Natural fibers are considered lower-impact reinforcements because they are renewable and can be sourced from agricultural or textile waste, which could reduce reliance on manufactured fibers and their associated environmental impacts [1, 3]. While many studies report improvements for individual fibers, direct comparisons across multiple natural fibers under an identical mortar platform are uncommon. Authors in [4, 5] revealed a narrow practical window: modest fiber additions may increase flexural response, whereas higher contents often increase voids, disturb compaction, and increase WA, resulting in a loss of compressive strength. Coir performance depends strongly on its hydrophilicity and interaction with mixing water, influencing both dispersion and pullout behavior. Authors in [6] reported similar sensitivities for jute, where factorial assessments indicate that fiber length and volume fraction govern hardened properties, but excessive contents degrade fresh behavior. Sisal Fiber (SF) mortars have shown benefits related to toughness; however, their compressive behavior is often inconsistent when porosity increases or distribution becomes nonuniform at higher dosages [4]. Fiber-specific responses that align with the above-highlighted dispersion-porosity sensitivity are also observed. The addition of waste cotton fibers to cement mortars can enhance flexural response at moderate levels, while higher concentrations tend to increase entrapped air and scatter due to orientation and loss of workability [7]. Direct comparisons of coir and jute at matched fiber lengths within a common mortar matrix show that flexural gains are achievable; however, performance depends significantly on dosage and maintaining uniform dispersion [2]. In rendering mortars, the durability-related performance of wool and coir has been examined, revealing that fiber morphology and moisture interaction can alter water transport and cracking susceptibility. This emphasizes the importance of interpreting strength alongside absorption-related indicators [8]. Sisal cementitious matrices used for strengthening applications demonstrate that dosage and fiber distribution control the balance between toughness gains and matrix continuity, explaining non-monotonic strength trends as content increases [9]. Fiber dosage plays an important role in mortar mix design. In many studies, the chosen fiber-specific dosage is limited to maintain workability and avoid severe balling, resulting in less robust cross-fiber interpretation unless common-level comparisons are included [2]. Another important factor that can directly affect the results is the WA characteristics of the fibers. Since most natural fibers are hydrophilic, they can alter pore connectivity, capillary uptake, and the fiber-matrix interfacial zone. Consequently, changes in WA can track, and sometimes dominate, changes in strength [2]. The issue is not only the mix design. Specimen conditioning prior to strength testing also matters, particularly when specimens undergo immersion-based absorption protocols before mechanical testing. For this reason, absorption-strength interpretations are stronger when the moisture conditions at the time of flexural and compressive testing are explicitly stated and when trends are discussed using direct, data-based comparisons rather than general narrative statements. This study examined five widely available natural fibers—cotton, coconut coir, jute, sisal, and sheep wool—as cement mortar reinforcements, emphasizing WA and mechanical performance. The selection covers distinct morphologies and expected dispersion behavior. Jute and sisal are bast/leaf fibers with relatively high tensile capacity and notable hydrophilicity; coir has a higher lignin content and characteristic pullout response; cotton is linked to waste textile streams; and wool is flexible and crimped. This can assist with bridging, but it can also promote entanglement and clumping if dispersion is not controlled [1, 7]. Surface treatments, such as alkalization or silane modification, are often used to improve bonding and reduce moisture sensitivity. However, they introduce an additional variable that complicates cross-fiber comparisons. Therefore, the present work adopts an untreated-fiber baseline so that differences in performance can be primarily attributed to fiber type and dosage under consistent mixing and curing regimes [6, 10]. Unlike many single-fiber studies, this experimental analysis compares five untreated fibers within one mortar mix design and evaluates absorption and strength after 28 days. Based on the results from [11, 12] on sustainable mortar reinforcement utilizing agricultural and recycled materials, this work extends the evaluation from single fibers to a comparative framework with explicit attention to dosage definition, specimen conditioning, and absorption-strength coupling. The objectives are to quantify the effects of fiber type and content on WA, flexural strength, and compressive strength; to relate absorption trends to mechanical response by making direct comparisons across mixes; and to interpret the results in relation to dispersion quality and observed fracture behavior. This approach provides a clearer basis for selecting natural fibers for mortar applications where mechanical performance and moisture absorption are both crucial.

II. MATERIALS AND METHODS

The mortar mixes were prepared using ordinary Portland cement (Type I, ASTM C150 [13]), sand (ASTM C33 [14]), water, and fibers. All fibers were cut to a nominal length of 10 mm prior to mixing. To minimize rapid water uptake during batching and improve dosing repeatability, the fibers were pre-soaked in water for 1 h and brought to a Saturated-Surface-Dry (SSD) state before being added to the mixer. SSD was achieved by draining the fibers and gently blotting them until no visible sheen remained, and they did not release free water when lightly pressed. Five fiber types were investigated: Cotton Fiber (CF), Coconut Coir Fiber (CCF), Jute Fiber (JF), SF, and Sheep Wool Fiber (SWF), with key properties used for mix design and interpretation shown in Table I. The mix design for all specimens is summarized in Table II. To ensure that differences in performance were primarily attributed to fiber type and dosage, the water-to-cement ratio (w/c = 0.50) was kept constant for all mixtures. Similarly, a cement-to-sand ratio of 1:3 by weight was maintained across all mixes. For each fiber type, three volume fractions were selected to quantify the effect of fiber content on mortar performance. To enable cross-fiber comparisons and interpretation of trends, a common dosage level of 1% by volume was adopted for all five fibers. Additional higher dosages were used to map each fiber's dosage-response while keeping the fiber length constant at 10 mm. Since dispersion stability and balling tendency varied among fibers, the upper dosage was chosen based on each fiber's characteristics (3.5% for CF, 4% for SW, and 5% for CCF, JF, and SF).

TABLE I. FIBER PROPERTIES

Fiber type	CF	CCF	JF	SF	SWF
Main feature	Soft, flexible cellulose fiber	Relatively high lignin; more resistant to microbial degradation	High cellulose content (~64%); rough, hydrophilic surface	Stiffer leaf fiber extracted from agave	Keratin-based; crimped, flexible
Tensile Strength (MPa)	287–597	up to 590	393–773	400–700	~137
Density (g/cm^3)	~1.54	1.10–1.50	1.30–1.50	~1.45	~1.32
Young's Modulus E (GPa)	~4.8	2–8	10–30	~9–22	2.3–3.4
Expected effect on cement mortars	Enhances crack resistance and ductility; increases energy absorption; may improve flexural performance	Improves impact resistance; reduces shrinkage; moderate gains in tensile/flexural behavior via crack bridging	Rough surface supports mechanical interlock; improved post-crack performance and energy absorption	Improves crack-bridging efficiency, flexural strength, and toughness, especially after first cracking	Improves crack resistance; reduces shrinkage cracking; increases post-peak deformability
Key limitations	High dosages may reduce compressive strength due to increased porosity and variable orientation	Excessive content may reduce workability and strength	Moisture sensitivity may increase WA and compromise durability unless addressed	Alkali-sensitive; degradation in cement matrix should be considered	Dispersion/ entanglement sensitivity can be critical
Ref.	[7]	[15]	[16]	[17]	[18]

TABLE II. MIX DESIGN SUMMARY

Specimen ID	Cement (g)	Water (g)	Sand (g)	Fiber (% by vol.)	Fiber mass (g)
Control	450	225	1350	0	0
MCCF1%	450	225	1350	1.0	3.21
MCCF3%	450	225	1350	3.0	9.61
MCCF5%	450	225	1350	5.0	16.01
MSWF1%	450	225	1350	1.0	3.40
MSWF2%	450	225	1350	2.0	6.81
MSWF4%	450	225	1350	4.0	13.60
MCF1%	450	225	1350	1.0	3.97
MCF2%	450	225	1350	2.0	7.94
MCF3.5%	450	225	1350	3.5	13.90
MJF1%	450	225	1350	1.0	3.74
MJF2.5%	450	225	1350	2.5	9.34
MJF5%	450	225	1350	5.0	18.68
MSF1%	450	225	1350	1.0	3.71
MSF2%	450	225	1350	2.0	7.42
MSF5%	450	225	1350	5.0	18.56

The experimental program involved casting 48 mortar prisms at the Construction Materials Laboratory of the American University of the Middle East, as depicted in Figure 1. The mortars were prepared using a planetary mixer according to an EN 196-1 [19] type mixing sequence. First, cement and sand were dry-mixed at low speed for 30 sec, and then, water was added over 10 sec while mixing continued. Finally, the mixture rested for 30 sec at low speed. Then, mixing was paused for 90 sec. During the first 15 sec, the bowl and paddle were scraped down, and the mixture rested for the remainder of the pause. Then, mixing resumed at high speed for 60 sec. Fibers preconditioned to the SSD condition were introduced gradually during mixing to limit agglomeration, maintaining the same total mixing time for all batches. Workability was monitored visually during mixing and casting. No water adjustments were permitted, and the water-to-cement ratio was kept constant for all mixtures. The fresh mortar was cast into 40 mm × 40 mm × 160 mm three-gang molds. The specimens were covered to prevent moisture loss, demolded after 24 h, and cured in water at 20 °C until the test age.

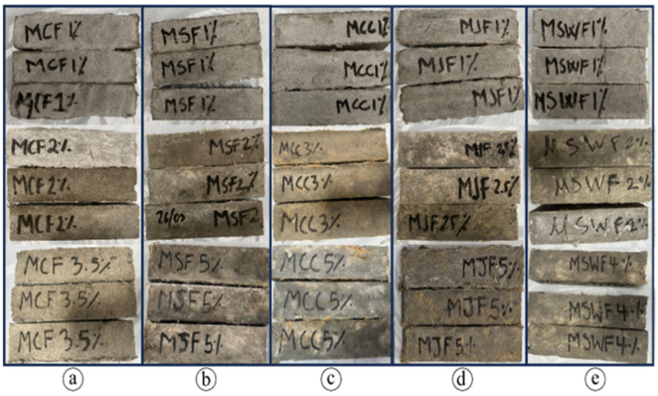

Fig. 1. Fiber-reinforced mortar prisms prepared for testing: (a) cotton, (b) sisal, (c) coconut, (d) jute, (e) sheep wool.

The specimens were labeled using the letter "M" for mortar, followed by the abbreviation for the type of fiber and the percentage of fiber volume. For instance, MCCF5% indicates a mortar reinforced with 5% coconut fibers. After 28 days of standard curing, WA was determined according to ASTM C642 [20] (oven-drying the specimens at 110 °C until a constant mass was reached, followed by immersion and SSD mass measurements). Then, the prisms were tested for flexural strength (three samples per mix). The resulting six halves were used to determine compressive strength in accordance with BS EN 1015-11 [21].

III. RESULTS AND DISCUSSION

The experimental results are presented for the following properties of fiber-reinforced mortars: (i) WA, (ii) flexural strength, (iii) compressive strength, and (iv) fiber distribution. The emphasis is on how fiber type and dosage affect moisture uptake and mechanical performance. At the common level of 1%, fibers are compared directly. Higher dosages are interpreted as sensitivity to dosage at a constant length of 10 mm.

A. Water Absorption

The WA capacity of the fibers was quantified to determine their moisture requirements and potential impact on mortar performance. The measured absorptions were 1,010%, 870%, 410%, 340%, and 220% for JF, SWF, CF, CCF, and SF, respectively. These values represent fiber mass gain relative to dry fiber mass. Figure 2 displays the WA of the hardened mortars. The control mortar recorded 12.21%. Generally, WA increases with fiber addition, especially at higher dosages, when dispersion becomes more difficult, and the likelihood of entrapped air and interconnected voids increases. The most significant case was MSWF4% (30.44%), which was more than double that of the control. This high uptake is consistent with the strong water affinity of wool fibers and their tendency to entangle and form clusters, creating local defects and connected transport pathways. Similarly, dosage-sensitive increases in absorption have been attributed to the loss of matrix continuity and increased void connectivity when fiber content exceeds the workable dispersion range [1].

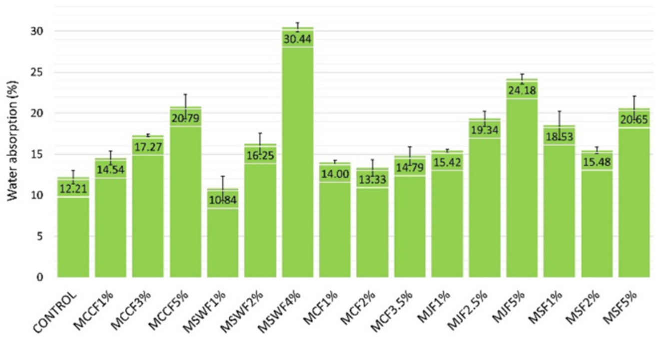

Fig. 2. WA of all mortar specimens.

Other higher-dosage mixtures also exhibited elevated WA, MJF5% (24.18%), MCCF5% (20.79%), and MSF5% (20.65%). While the magnitude varied by fiber type, these mixtures have high fiber volume fractions, which increase the internal surface area and disturb packing. When fibers are not uniformly dispersed, micro-voids and interfacial gaps form around clusters, which increases moisture uptake. In contrast, several low-to-moderate dosage mixes remained closer to the control. For instance, MSWF1% had the lowest WA (10.84%), and MCF2% was close to the control (13.33%). These results suggest that within a stable dispersion window, fibers can be incorporated without significantly impacting transport properties. From a performance standpoint, WA is not only a durability indicator, but also demonstrates mechanical behavior, particularly in compression. In this dataset, WA was negatively correlated with compressive strength (Pearson r = −0.626, p = 0.0095). This supports the idea that increased moisture uptake, which is consistent with higher connected porosity and dispersion-related voids, hinders compressive load transfer, as portrayed in Figure 3.

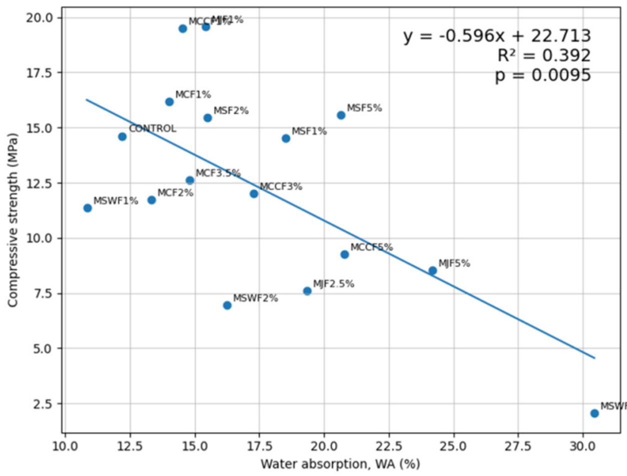

Fig. 3. Relationship between WA and compressive strength.

B. Flexural Strength

The flexural strength results are presented in Figure 4 and summarized in Table III. The control mix reached a strength of 3.90 MPa, and significant overall differences among the mixes (one-way ANOVA, $p < 0.001$) were found. However, Tukey HSD comparisons versus the control (α = 0.05) revealed significant changes only for certain mixtures. MSF5% achieved the highest flexural strength (5.53 MPa), which was 42% higher than the control. MCF3.5% (5.11 MPa) and MCCF5% (4.70 MPa) exhibited higher mean values (+31% and +21%, respectively); however, they did not differ significantly from the control due to variability. Conversely, MSWF4% (1.89 MPa) and MJF5% (2.15 MPa) were significantly lower than the control, which is consistent with clumping, poor dispersion, and void-related weakening at excessive fiber content levels [1, 3, 22]. Overall, flexural gains were obtained when fibers remained sufficiently dispersed to act as effective crack bridges, whereas dispersion loss at high dosages overrode the benefits of reinforcement.

C. Compressive Strength

The control mix reached 14.62 MPa, and there were significant differences among the mixes (one-way ANOVA, $p < 0.001$), as illustrated in Figure 4 and Table III. Tukey HSD comparisons versus the control (α = 0.05) revealed dosage-dependent increases and decreases. The highest compressive strengths were obtained at a low fiber content: 19.50 MPa for MCCF1% and 19.59 MPa for MJF1%, which were both significantly higher than the control, exceeding it by ~33–34%.

Several mixtures, however, were significantly lower than the control, including MCCF5% (9.27 MPa), MSWF2% (6.96 MPa), MSWF4% (2.06 MPa), MJF2.5% (7.61 MPa), and MJF5% (8.52 MPa). The most severe reduction occurred for MSWF4%, indicating that excessive content leads to dispersion loss and void-related discontinuities that dominate compressive load transfer. Compression results confirm a narrower optimal window than flexure. Low dosages can enhance compressive strength when matrix continuity is maintained. Nevertheless, higher dosages, particularly for fibers prone to entanglement or high moisture affinity, lead to significant strength deterioration.

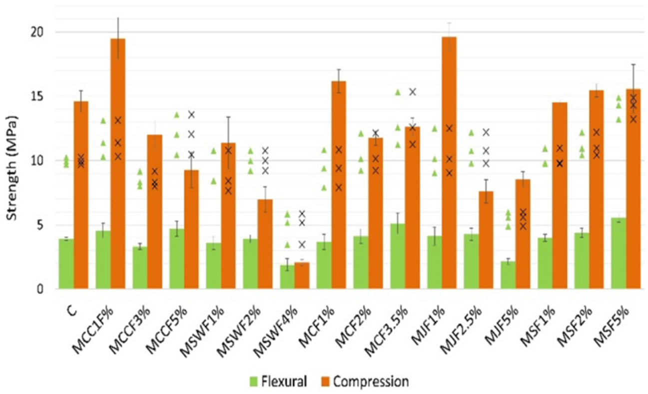

Fig. 4. Strength results for mortar mixes (mean ± SD; replicate points shown). Bars show mean values, error bars denote ±1 SD, and markers represent individual replicates. Horizontal jitter is applied only to avoid overlap and has no physical meaning.

TABLE III. SUMMARY STATISTICS AND SIGNIFICANCE VERSUS CONTROL (N = 3 PER MIX)

Mix	Flexural (MPa) mean ± SD	versus C	Compressive (MPa) mean ± SD	vs. C
C	3.90 ± 0.11	—	14.62 ± 0.82	—
MCCF1%	4.54 ± 0.56	ns	19.50 ± 1.61	↑
MCCF3%	3.32 ± 0.24	ns	12.63 ± 1.10	ns
MCCF5%	4.70 ± 0.61	ns	9.27 ± 1.38	↓
MSWF1%	3.60 ± 0.53	ns	14.01 ± 2.03	ns
MSWF2%	3.91 ± 0.31	ns	6.96 ± 0.99	↓
MSWF4%	1.89 ± 0.48	↓	2.06 ± 0.26	↓
MCF1%	3.67 ± 0.57	ns	16.18 ± 0.91	ns
MCF2%	4.11 ± 0.58	ns	11.74 ± 0.58	ns
MCF3.5%	5.11 ± 0.82	ns	12.60 ± 0.68	ns
MJF1%	4.13 ± 0.70	ns	19.59 ± 1.07	↑
MJF2.5%	4.27 ± 0.47	ns	7.61 ± 0.89	↓
MJF5%	2.15 ± 0.22	↓	8.52 ± 0.61	↓
MSF1%	3.98 ± 0.27	ns	14.52 ± 0.23	ns
MSF2%	4.38 ± 0.36	ns	15.44 ± 0.49	ns
MSF5%	5.53 ± 0.34	↑	15.58 ± 1.86	Ns

Values are mean ± SD (n = 3). Overall differences among mixes were significant for flexural and compressive strengths (one-way ANOVA, $p < 0.001$ for both). Significance versus control (C) is based on Tukey HSD ($\alpha = 0.05$): ↑ higher, ↓ lower, ns not significant

D. Failure Mode under Flexure

Figure 5 illustrates representative specimens after three-point bending. The control mortar exhibited a typical brittle response with a dominant mid-span crack and abrupt separation, as shown in Figure 5 (a). For the CF mortar, the crack remained mainly localized at the midpoint, and partial integrity across the fractured section indicates fiber bridging and delayed crack opening, as depicted in Figure 5 (b). A similar mid-span crack pattern with visible bridging and reduced crack opening was observed for the CCF specimen, as demonstrated in Figure 5 (c), which is consistent with fiber engagement across the crack plane. SWF specimens, on the other hand, exhibited more irregular cracking and reduced post-cracking integrity, as shown in Figure 5 (d), consistent with nonuniform reinforcement and localized weak zones. The JF specimen also exhibits a more localized fracture with limited bridging compared to the better-performing systems, as displayed in Figure 5 (e). The SF specimen retained clearer post-crack connectivity and bridging across the fracture plane, as presented in Figure 5 (f), which aligns with the superior flexural response obtained for SF at a higher dosage in this study. The failure mode results suggest that the quality of fiber dispersion governs whether the fibers act as effective crack bridges, as shown in Figures 5(b), 5(c), and 5(f) or whether localized defects dominate and reduce flexural capacity, as portrayed in Figures 5(d) and 5(e).

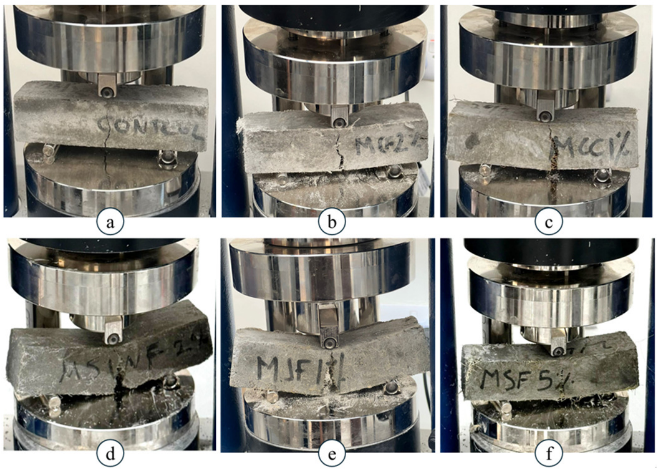

Fig. 5. Failure mode mortar specimens under flexure: a) control, b) cotton, c) coconut, d) sheep wool, e) jute, and f) sisal.

E. Fiber Distribution within the Mortar Matrix

Figure 6 shows representative cross-sectional views obtained after flexural testing. These views are used to qualitatively assess fiber dispersion and matrix continuity. The control specimen, depicted in Figure 6 (a), contains no fibers and has a relatively dense, continuous matrix. It serves as the baseline for comparison. The CF-mortar specimen, shown in Figure 6 (b), exhibits comparatively even fiber dispersion, suggesting acceptable workability and fiber-matrix compatibility at the selected dosage. CCF, illustrated in Figure 6 (c), exhibits a more irregular distribution with locally aligned fiber domains, which can promote local discontinuities and directional void pathways. SWF, demonstrated in Figure 6 (d), shows the poorest dispersion with clear entanglement and formation of bundles or mats, which are indicative of clumping and incomplete distribution. This clustering is consistent with void generation and weak zones, aligning with the significant strength deterioration observed for wool at higher dosages. JF, shown in Figure 6 (e), has coarse, overlapping fibers and localized accumulation, which can disrupt matrix continuity. This helps explain the significant reductions recorded at higher jute contents. In contrast, SF, displayed in Figure 6 (f), shows more stable dispersion with less pronounced bundling. This supports the reliable mechanical response observed for sisal mixes and the significant flexural gain achieved at the highest sisal dosage.

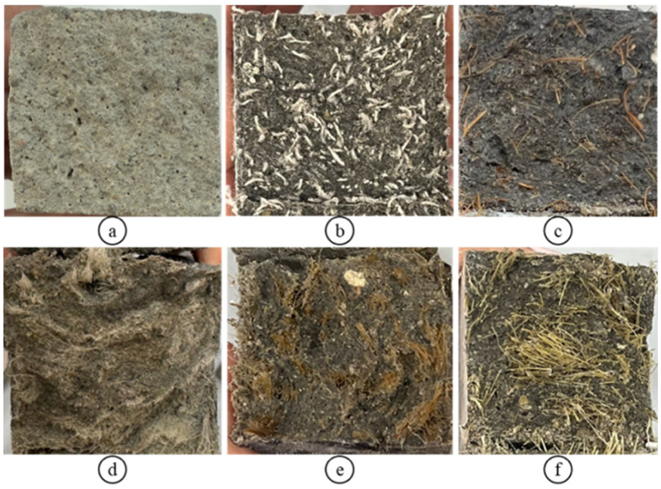

Fig. 6. Cross-sectional view of the fiber distribution within: a) control and the mid-dosage fiber reinforced specimen for b) cotton, c) coconut, d) sheep wool, e) jute, and f) sisal.

In summary, the cross-sectional observations confirm that dispersion stability is closely linked to fiber morphology. A more uniform distribution of fibers promotes effective stress transfer and crack bridging. In contrast, bundling and the presence of fiber-rich and fiber-poor zones increase heterogeneity and porosity, ultimately reducing mechanical strength.

IV. CONCLUSIONS

This study examined the performance of cement mortars reinforced with five natural fibers. The 28-day flexural and compressive strengths, as well as the Water Absorption (WA) of the mortars, were assessed. The results confirm that fiber type and dosage govern performance. There are improvements within a dispersion-stable range, but there are also disadvantages when higher fiber contents increase porosity, heterogeneity, and moisture uptake. Sisal at 5% by volume produced the greatest enhancement in flexural response, consistent with effective crack bridging. However, this gain was accompanied by increased WA, indicating a strength-absorption trade-off. Conversely, low dosages of jute and coconut coir provided the most favorable strength-absorption balance, delivering the strongest compressive gains with comparatively limited absorption penalties. Mixtures prone to fiber entanglement and non-uniform dispersion at high fiber contents showed reductions in both flexural and compressive strengths and increased absorption. This was most clearly observed in sheep wool at 4% by volume. These results highlight the importance of selecting the correct dosage and controlling dispersion to avoid matrix discontinuities. From an application perspective, the findings support using low-to-moderate fiber contents where crack control and strength improvement are required while maintaining acceptable moisture uptake. A limitation of this study is that dispersion quality was assessed visually. Future work should extend the evaluation to durability exposures, such as wet-dry cycling, sulfate attack, and freeze-thaw, where relevant, and couple macroscopic performance with microstructural assessment to quantify fiber clustering, fiber-matrix bonding, and pore connectivity.

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