fibers

MDPI

Article

Effects of Fiber Length, Content, and Surface Treatment on the Compressive and Flexural Response of Date Palm Fiber-Reinforced Concrete

Wafa Abdelmajeed Labib

Architecture Department, College of Architecture and Design, Prince Sultan University, Riyadh 11586, Saudi Arabia; wlabib@psu.edu.sa

Abstract

Date palm fiber provides a local approach to utilizing agricultural residues in cement-based materials, yet reported strength changes vary with fiber geometry, dosage, moisture condition, and treatment. Evidence remains limited for direct comparisons of untreated, alkali-treated, and hornified fibers across the same length–content matrix. This study examines one fiber-free C40 concrete and 27 fiber-reinforced conditions comprising three fiber volume fractions (1%, 2%, and 3%); three fiber lengths (10, 20, and 30 mm); and three fiber states (untreated, 1% NaOH-treated, and hornified through ten wet–dry cycles). Compressive strength is measured at 7, 14, and 28 days, while flexural strength is measured at 28 days. All conditions exhibit increased compressive strength with age. Concrete containing untreated 3%–30 mm fibers exhibits the highest 28-day compressive strength of 40.8 MPa, which is 8.5% above the reference value of 37.6 MPa. Concrete containing untreated 2%–20 mm fibers exhibits the highest flexural strength of 3.6 MPa, which is 12.5% above the reference value of 3.2 MPa. The untreated 2%–30 mm condition is the only condition that exceeds the reference in both tests, with gains of 4.0% and 3.1%, respectively. Alkali treatment and hornification reduce 28-day compressive strength relative to every corresponding untreated condition, with mean reductions of 17.9% and 18.0%, respectively. Their mean flexural strengths are also lower than those of the untreated group. The findings show that the measured mechanical response varies with the combination of fiber length, nominal content, and fiber state, and that neither treatment method provides an overall strength advantage over untreated fibers under the tested conditions. Untreated fibers produce the leading compression–flexure combinations, highlighting the importance of selecting fiber length and content based on the target mechanical response. All differences and rankings represent descriptive comparisons of the reported mean strengths.

Keywords: date palm fiber; natural fiber concrete; compressive strength; flexural strength; alkali treatment; hornification; fiber length; fiber content; agricultural residue

Check for updates

Academic Editor: Martin J. D. Clift

Received: 19 September 2026
Revised: 20 October 2026
Accepted: 26 October 2026
Published: 28 October 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Date palm cultivation generates large quantities of fibrous residues through pruning, trunk cleaning, frond removal, and fruit harvesting. Disposal practices vary among producing regions, yet open burning, landfilling, and low-grade reuse remain common routes for materials that have a fibrous structure and low direct market value. Saudi Arabia and neighboring countries therefore have a steady local supply of lignocellulosic residues that can be directed toward higher-value material applications [1–4]. Date palm fiber, abbreviated as DPF, is obtained from various parts of the tree, and its composition, diameter,

density, moisture uptake, and tensile response vary with cultivar, location, tree age, fiber source, extraction method, and storage conditions [5–7]. Such variability requires caution when results from one fiber source are applied to another concrete system.

Concrete carries compressive loads efficiently, whereas its low tensile strain capacity allows cracks to form under bending, restrained shrinkage, impact, and repeated loading. Discrete fibers can bridge developing cracks and can modify the post-cracking response, although the outcome depends on fiber modulus, strength, length, aspect ratio, orientation, dosage, dispersion, and bonding with the cement paste. Plant fibers introduce additional variables because their porous cell walls absorb water, swell during wetting, and can release absorbed water as the surrounding paste dries. Soluble sugars, waxes, lignin-rich surface layers, and weakly bonded constituents can affect cement hydration and the fiber–paste contact zone. Reviews of vegetable-fiber–cement composites therefore describe a balance between crack bridging and adverse changes in workability, void content, fiber durability, and matrix continuity [8–12]. Mechanical strength cannot be predicted from fiber tensile strength alone.

Date palm fibers have been investigated in mortar, conventional concrete, roller-compacted concrete, pervious concrete, and concrete containing mineral additions. Early studies in hot and dry climates reported that DPF can modify compressive, tensile, and flexural behavior, with outcomes governed by fiber content, geometry, and curing conditions [13,14]. Subsequent studies reported strength gains at selected dosages, strength losses at higher dosages, and mixed responses when silica fume, recycled aggregate, or alternative production methods were introduced [15–20]. The considerable variation in published results is consistent with differences in concrete grade, fiber source, dosage definition, fiber length, mixing sequence, treatment history, specimen geometry, and testing age. Recent studies on hybrid date palm and polypropylene fibers, date palm microfibers, and silica-fume-modified mixtures confirm that fiber addition can improve one measured property while reducing another [21–23]. A general statement that DPF either improves or reduces concrete strength is therefore overly broad.

Fiber length and fiber content are key design variables because they govern the number of fibers crossing a potential crack plane, the available bond length, and the difficulty of achieving uniform distribution. Short fibers are generally easier to disperse, yet their embedment length can be insufficient for effective stress transfer. Longer fibers can provide greater anchorage length, although balling, entanglement, poor compaction, and preferential orientation become more likely as fiber length and dosage increase. DPF studies have reported different optimal ranges, which is expected because percentages are expressed on different mass or volume bases and fiber geometry is rarely identical [15,24–26]. Related fiber–cement research also indicates that length and content can produce nonlinear responses rather than consistent gains with each increase [27–29]. An experimental matrix that varies both factors within a single concrete composition is therefore more informative than a single-factor comparison.

Comparisons across published DPF mixtures are further complicated by differences in how fiber content is reported. Some studies use fiber volume, whereas others use a percentage of cement mass, aggregate mass, sand volume, or total mixture mass. A numerical level such as 1% can therefore represent substantially different quantities of fiber. Reviews of DPF concrete have repeatedly emphasized the need for clearer reporting of fiber source, geometry, moisture, treatment, and dosage basis [30]. A similar need has been identified in recent natural-fiber reviews [31]. Clear factor definitions are particularly important when a study seeks to identify an optimal range, since an apparent disagreement can arise from different denominators rather than differences in material behavior. The

present study compares three fiber contents—1%, 2%, and 3%—by total concrete volume within a common concrete mixture.

Surface treatment is commonly proposed as a method for reducing fiber water uptake, removing weak surface materials, and modifying surface roughness. Alkali treatment with sodium hydroxide can remove portions of hemicellulose, lignin, waxes, and extractives, yet the outcome depends strongly on concentration, temperature, exposure time, rinsing, and drying. Mild treatment can clean the fiber surface, whereas excessive exposure can damage the cell wall, reduce fiber strength, or create defects that offset any improvement in bonding [32–38]. Studies on chemically treated date palm fibers have reported changes in rheology and mechanical strength, but the direction and magnitude of these changes have varied with the treatment procedure and composite type [39–41]. Treatment should therefore be evaluated as an experimental factor rather than assumed to be beneficial.

Hornification is a physical treatment involving repeated wetting and drying cycles. Irreversible rearrangement of cellulose microfibrils during drying can reduce subsequent dimensional changes and water uptake. Research on sisal, jute, curaua, and other vegetable fibers has linked hornification to changes in fiber stiffness, pull-out response, and long-term stability in cement matrices [42–45]. Recent research on hornified bamboo fibers also indicates that treatment conditions can modify interfacial behavior [46]. These findings provide a sound rationale for investigating hornification with DPF, yet they do not guarantee improvements in concrete strength. Fiber-scale changes must be considered alongside workability, fiber distribution, paste volume, aggregate packing, and the moisture condition of the fibers during mixing.

A closely related experimental matrix was reported by Awad et al. [40]. Their OPC-GGBS composite varied DPF loading from 1 to 3 wt.% of binder and fiber length from 10 to 40 mm, with alkali-treated 20 mm fibers at 1 wt.% producing the highest strength response under water curing. That study reported a beneficial treatment response in a fine cementitious composite containing a supplementary binder. The present experimental program examines C40 concrete containing coarse aggregate and a fixed admixture system. It includes hornification as a second treatment method and compares each treated condition with an untreated condition of the same nominal length and content. Differences from the OPC-GGBS study can therefore be examined in relation to matrix scale, curing, fiber moisture, and treatment procedures, each of which can influence the composite response.

Direct comparisons of different DPF treatment methods have recently emerged. Moawad and Moussa compared mechanical, chemical, and biological pretreatments at a single fiber length of 60 mm in M30 concrete with low fiber additions, whereas Ali-Boucetta et al. evaluated treated date palm mesh in fiber–cement composites [39,47]. Recent studies have also investigated untreated DPF length and content in mortars, chemically treated palm microfibers in concrete, and the flexural and fracture responses of DPF mortars [23,48]. These studies provide a basis for assessing treatment-dependent mechanical performance. Few studies, however, have compared untreated DPF, low-concentration NaOH treatment, and repeated hornification within the same concrete mixture while varying both fiber length and nominal content across a complete three-by-three matrix. Evidence remains particularly limited regarding whether a treatment intended to improve fiber condition produces a better combined compressive and flexural response than the corresponding untreated fiber.

The present study addresses this question using one reference concrete and 27 DPF-reinforced conditions. Three fiber states—untreated, 1% NaOH-treated, and hornified—were combined with nominal contents of 1%, 2%, and 3% and fiber lengths of 10, 20, and 30 mm. Compressive strength was measured at 7, 14, and 28 days, whereas flexural strength was measured at 28 days. The study aimed to determine how curing age, fiber length, nominal content, and treatment state influenced the measured strength. A secondary aim

was to identify the best-performing combinations among the tested levels for compression, flexure, and their combined response. The central premise was that surface treatment will not necessarily increase composite strength and that the response will depend on the length–content combination. Varying all three factors within the same base concrete composition allows matched treatment comparisons at each length and content, rather than confounding the comparisons with changes in binder, aggregate, or admixture systems. The advancement over the cited DPF studies is the inclusion of hornification alongside untreated and alkali-treated fibers across the complete length–content matrix in coarse-aggregate concrete, together with descriptive screening of compression–flexure trade-offs. This experimental design can reveal variations in the apparent treatment response with fiber geometry and content.

2. Materials and Methods

2.1. Concrete Materials and Mix Proportions

The concrete was designed as a Grade C40 ordinary Portland cement mixture. A single base composition was used for the reference concrete and all fiber-reinforced conditions so that changes in strength could be attributed to the fiber variables rather than changes in binder or aggregate proportions. The mixture consisted of ordinary Portland cement, two crushed coarse-aggregate fractions with nominal maximum sizes of 20 and 10 mm, coarse natural sand, dune sand, and two commercial admixtures, Arcrete D8 and Fluidum PC175.

Table 1 lists the batch quantities for 1 m^3 of concrete. The cement content was 440 kg/m^3, and the water content was 158 L/m^3, giving a nominal water–cement ratio of 0.359 when the water density is assumed to be 1 kg/L. The coarse aggregate content totaled 1000 kg/m^3, while the two fine-aggregate fractions totaled 841 kg/m^3. The respective admixture contents were 2.2 and 4.9 kg/m^3. Trial mixtures were prepared to produce C40 concrete with medium workability and a target slump of 70 to 120 mm. The total quantity reported in Table 1 is 2446.1 kg/m^3, including 7.1 kg/m^3 of admixtures but excluding fibers.

Table 1. Concrete mix proportions for 1 m^3.

Material	Unit	Quantity
Cement	kg/m^3	440
Water	L/m^3	158
Coarse aggregate, 20 mm	kg/m^3	550
Coarse aggregate, 10 mm	kg/m^3	450
Coarse sand	kg/m^3	210
Dune sand	kg/m^3	631
Arcrete D8	kg/m^3	2.2
Fluidum PC175	kg/m^3	4.9
Total (excluding fibers)	kg/m^3	2446.1

2.2. Date Palm Fiber Source and Geometry

Fibers were collected from the mesh surrounding the outer surfaces of date palm trunks. The mesh was separated into individual strands, cleaned, and cut to nominal lengths of 10, 20, and 30 mm. Fiber diameters ranged from 0.2 to 1.0 mm. Therefore, the resulting aspect ratios varied considerably, even within a single nominal length. Published characterization studies have shown that DPF properties vary across tree parts and sources [5,6,40]. Therefore, the dimensions used in this study characterize the geometry of the tested fibers. Dividing the nominal lengths by the reported diameter limits gives aspect-ratio ranges of 10–50, 20–100, and 30–150 for the 10, 20, and 30 mm fibers, respectively.

Three fiber volume fractions—1%, 2%, and 3%—of the total concrete volume were used, corresponding to fiber volumes of 0.01, 0.02, and 0.03 m^3 per cubic meter of concrete, respectively. Fiber volume was determined after the corresponding treatment procedure to account for potential treatment-induced changes in fiber volume. The specified volume fractions were maintained across the untreated, alkali-treated, and hornified conditions. Each volume fraction was combined with fiber lengths of 10, 20, and 30 mm to assess the combined influence of fiber content and geometry. The term nominal content, used elsewhere in the manuscript and figures, refers to these specified fiber volume fractions.

2.3. Fiber Treatment Procedures

The experimental program included untreated fibers, fibers exposed to a 1% aqueous sodium hydroxide solution, and fibers subjected to hornification. Untreated fibers were cut to the required lengths and incorporated into the concrete without alkali treatment or hornification. Fiber moisture can influence the effective water available to the cement paste and is therefore relevant to the interpretation of the mechanical response [49]. The alkali-treated and hornified fibers were air-dried at room temperature before mixing.

2.3.1. Alkali Treatment

Fibers assigned to the alkali series were immersed in a 1% aqueous NaOH solution before mixing. The treatment was intended to remove surface impurities and increase fiber roughness. Alkali-treatment response depends on solution concentration, exposure conditions, and subsequent fiber conditioning, which influence fiber mass loss and strength [33–35]. Following treatment, the fibers were air-dried at room temperature before mixing. The results characterize the 1% NaOH treatment applied in this study.

2.3.2. Hornification

Hornified fibers underwent ten successive wetting and oven-drying cycles. Hornification is commonly applied to reduce repeated swelling and shrinkage during subsequent moisture changes. Studies on other vegetable fibers have shown that treatment conditions influence fiber structure and bond response [42,44,45]. The hornification series was evaluated against untreated fibers at matching nominal contents and lengths. After completing the ten cycles, the fibers were air-dried at room temperature before mixing.

2.4. Experimental Matrix and Specimen Preparation

The experimental program comprised one fiber-free reference series and 27 DPF-reinforced series. The fiber-reinforced matrix consisted of three treatment states, three fiber volume fractions, and three fiber lengths. Figure 1 illustrates the experimental methodology. For each condition, compressive strength was measured at 7, 14, and 28 days, while flexural strength was measured at 28 days. The same base concrete composition was maintained throughout the experimental matrix.

The concrete was batched, mixed and used in accordance with the specifications of ASTM C192 [50]. For each of the DPF-treated conditions, a concrete mix was produced. Prior to mixing, all the constituent materials were weighed. The water plus admixtures were mixed in a single container. The fine aggregate and cement were first added to the concrete mixer and mixed thoroughly; then, the DPF was added gently into the mixer as mixing progressed to avoid any agglomeration. Next, half of the mixing water plus admixture was added, and the coarse aggregate was also added. As mixing was ongoing, the remaining part of the mixing water was added gently. The mixing continued until a homogeneous mix was obtained. After mixing, the fresh concrete was cast into the designated molds. The molds were cleaned, tightened and oiled before casting. The fresh concrete was cast

into cylindrical molds with dimensions of 150 mm in diameter and 300 mm in height and prisms with dimensions of 150 mm × 150 mm × 600 mm. The fresh concrete was placed into the molds in three layers, and each layer was compacted using a vibrating table to remove entrapped air. Excessive vibration was avoided to limit segregation, and the exposed surfaces were leveled after compaction. After casting, the specimens were covered with plastic sheets to minimize moisture loss and kept undisturbed in their molds at 23 ± 2 °C for 24 h. They were then demolded and fully immersed in a water-curing tank maintained at 23 ± 2 °C until their respective testing ages.

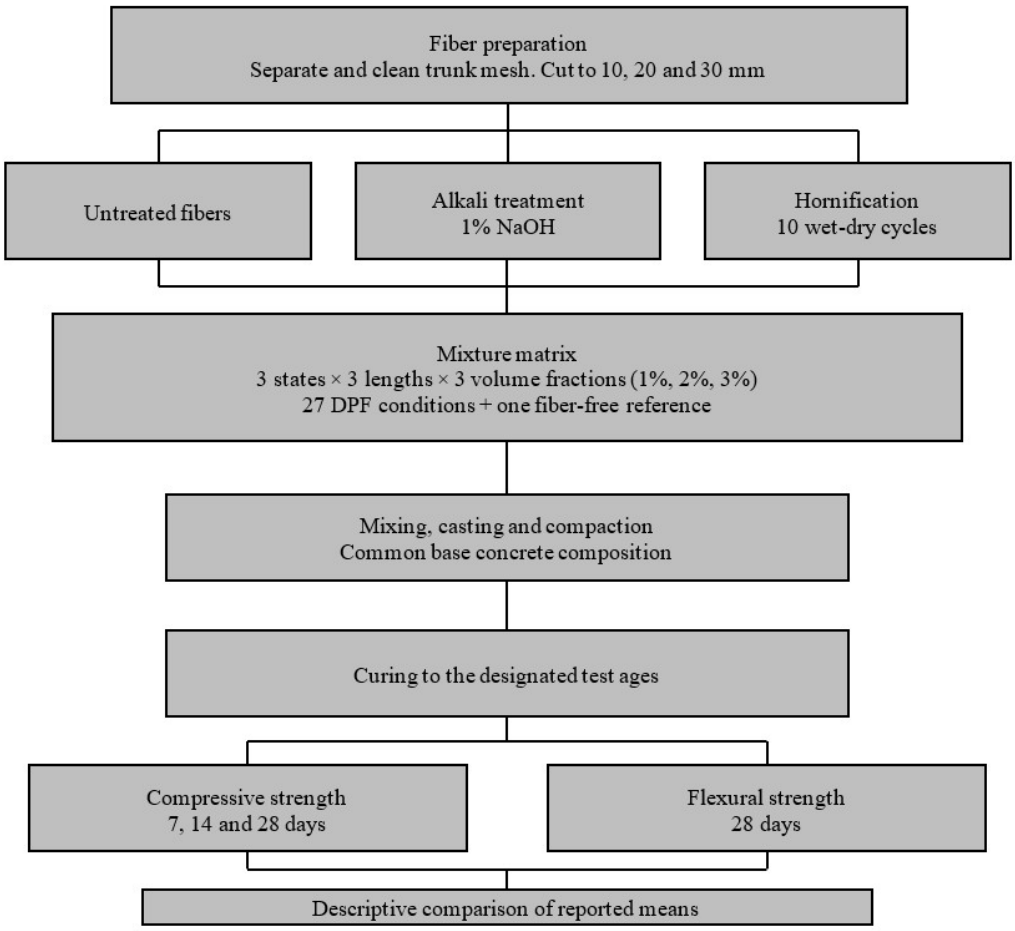

Figure 1. Experimental methodology.

Table 2 lists the experimental conditions and their codes. A code such as U2-30 denotes untreated DPF at 2% fiber volume fraction and 30 mm length. Codes A and H identify the alkali-treated and hornified groups. The reference is labeled REF. The condition code is used in the results table and selected figure annotations. Separate specimens were tested at each compressive-strength age, and separate beams were used for flexural testing.

Table 2. Experimental matrix and test ages.

Code Family	Fiber State	Fiber Volume Fraction (%)	Length (mm)	Compressive Age (Days)	Flexural Age (Days)
REF	Reference	0	0	7, 14, 28	28
U	Untreated	1, 2, 3	10, 20, 30	7, 14, 28	28
A	1% NaOH	1, 2, 3	10, 20, 30	7, 14, 28	28
H	Hornification, 10 cycles	1, 2, 3	10, 20, 30	7, 14, 28	28

All mixtures were prepared using the base composition. Fibers were added based on their treatment state, nominal content, and length, after which the concrete was cast into the required molds and compacted.

2.5. Mechanical Testing

2.5.1. Compressive Strength

Compressive strength tests were conducted at 7, 14, and 28 days in accordance with ASTM C39/C39M [51]. The results for each condition and test age are presented as arithmetic means.

2.5.2. Flexural Strength

Flexural strength was measured at 28 days using 150 × 150 × 600 mm concrete prisms under center-point loading, following ASTM C293/C293M [52]. The prisms were positioned on two supports spaced 450 mm apart, with a 75 mm overhang at each end. A single load was applied at midspan, 225 mm from either support, until failure, as shown in Figure 2. Results are expressed as the modulus of rupture for each condition.

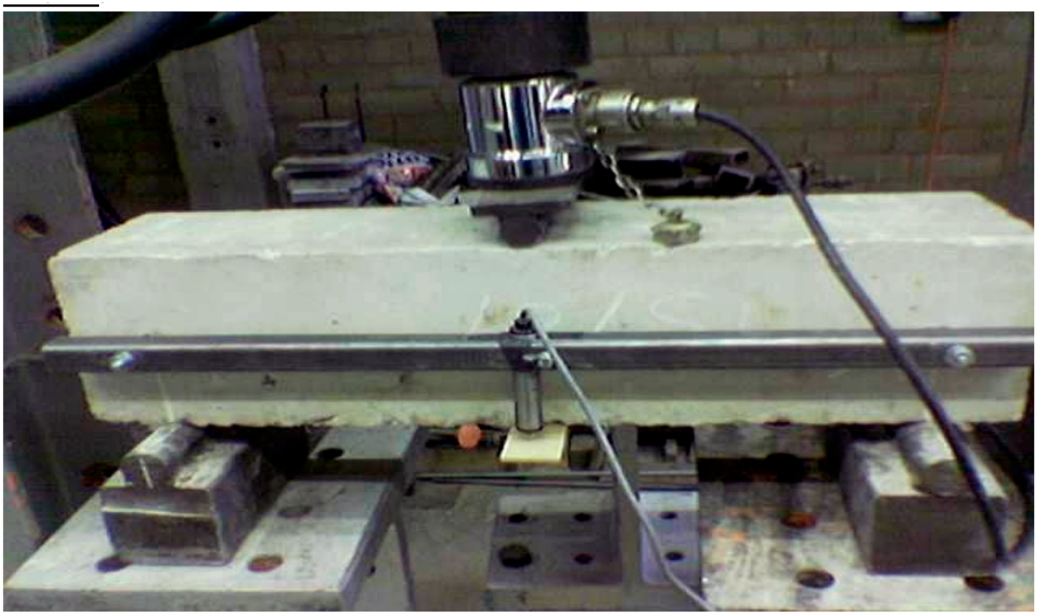

Figure 2. Flexural test arrangement.

2.6. Data Analysis

The experimental results were analyzed using condition means and descriptive comparisons. Compressive-strength development was examined at each test age; the 28-day compressive and flexural strengths were compared to those of the reference, and each treated condition was compared to the corresponding untreated condition having the same nominal content and length. The percentage difference from the reference was calculated as $100(x_i - x_{\text{ref}})/x_{\text{ref}}$, where x_i represents the measured mean for a fiber condition and x_{ref} represents the mean of the fiber-free concrete at the same test age. Positive values indicate results above the reference, while negative values indicate results below it. Calculations were based on condition means reported to 0.1 MPa.

Marginal means were calculated across the nine length–content combinations within each fiber treatment state. These averages summarize the strength response across the tested matrix. A two-response screening analysis was also conducted at 28 days. Descriptive Pareto screening was utilized to identify the non-dominated combinations of reported compressive

and flexural means within the tested matrix. This procedure identifies trade-offs without assigning arbitrary weights to compression or flexure. A condition was considered non-dominated when no other tested condition had equal or higher means for both responses and a higher mean for at least one response. Membership in this front is conditional on the rounded means and can change with unrounded values or sampling variation. The front describes performance within the tested matrix rather than a universal optimum.

All percentage differences and performance rankings are descriptive and refer to the measured mean strengths of the tested mixtures.

3. Results

3.1. Strength Data and Compressive Development with Age

Table 3 presents the mean compressive and flexural strengths for all experimental conditions. Every compressive-strength series showed an increase between 7 and 28 days. The compressive strength of the reference concrete increased from 27.8 MPa at 7 days to 33.3 MPa at 14 days and 37.6 MPa at 28 days. This corresponds to an increase of 9.8 MPa, or 35.3%, over the testing interval. The fiber-reinforced conditions followed the same general age-related trend, although their absolute values and rates of strength gain differed.

Table 3. Mean compressive and flexural strengths of the tested concrete mixtures.

Code	Fiber State	Fiber Volume (%)	Length (mm)	CS 7 d (MPa)	CS 14 d (MPa)	CS 28 d (MPa)	FS 28 d (MPa)
REF	Reference	0	0	27.8	33.3	37.6	3.2
U1-10	Untreated	1	10	28.3	31.7	37.3	3.3
U2-10	Untreated	2	10	24.3	30.7	34.3	3.3
U3-10	Untreated	3	10	27.0	31.1	35.4	3.5
U1-20	Untreated	1	20	28.3	29.2	36.8	3.5
U2-20	Untreated	2	20	26.0	33.3	35.2	3.6
U3-20	Untreated	3	20	26.2	31.2	36.3	3.4
U1-30	Untreated	1	30	27.1	29.5	34.4	3.1
U2-30	Untreated	2	30	28.3	32.9	39.1	3.3
U3-30	Untreated	3	30	29.4	34.7	40.8	3.1
A1-10	Alkali	1	10	22.5	23.3	26.2	2.5
A2-10	Alkali	2	10	22.1	24.3	29.0	2.8
A3-10	Alkali	3	10	22.1	22.8	27.8	2.8
A1-20	Alkali	1	20	24.9	27.5	29.7	3.2
A2-20	Alkali	2	20	23.0	26.9	31.8	3.3
A3-20	Alkali	3	20	26.7	29.2	32.8	3.1
A1-30	Alkali	1	30	24.3	27.9	31.2	3.3
A2-30	Alkali	2	30	25.4	28.5	34.9	2.8
A3-30	Alkali	3	30	22.5	23.3	26.2	3.1
H1-10	Hornification	1	10	23.6	27.8	31.0	2.5
H2-10	Hornification	2	10	24.6	27.4	29.0	2.8
H3-10	Hornification	3	10	22.9	24.5	27.9	2.8
H1-20	Hornification	1	20	23.9	27.4	33.0	3.2
H2-20	Hornification	2	20	22.0	25.3	29.1	3.3
H3-20	Hornification	3	20	22.5	23.8	32.5	3.1
H1-30	Hornification	1	30	26.7	28.4	31.1	3.3
H2-30	Hornification	2	30	22.8	26.2	27.9	2.8
H3-30	Hornification	3	30	20.9	23.5	27.7	3.1

Untreated DPF concrete exhibited the highest compressive-strength values at each age when the nine untreated conditions were considered as a group. The group means increased from 27.21 MPa at 7 days to 31.59 MPa at 14 days and 36.62 MPa at 28 days. The increase

from 7 to 28 days averaged 34.7% across the nine conditions. Individual 28-day values ranged from 34.3 to 40.8 MPa. Figure 3 shows that the ranking of the untreated conditions changed with age. For example, the 2%-20 mm condition was below the reference at 7 days, equaled the reference at 14 days, and reached 35.2 MPa at 28 days. The 3%-30 mm condition remained the strongest untreated mixture at all three ages, with compressive strengths of 29.4, 34.7, and 40.8 MPa, respectively.

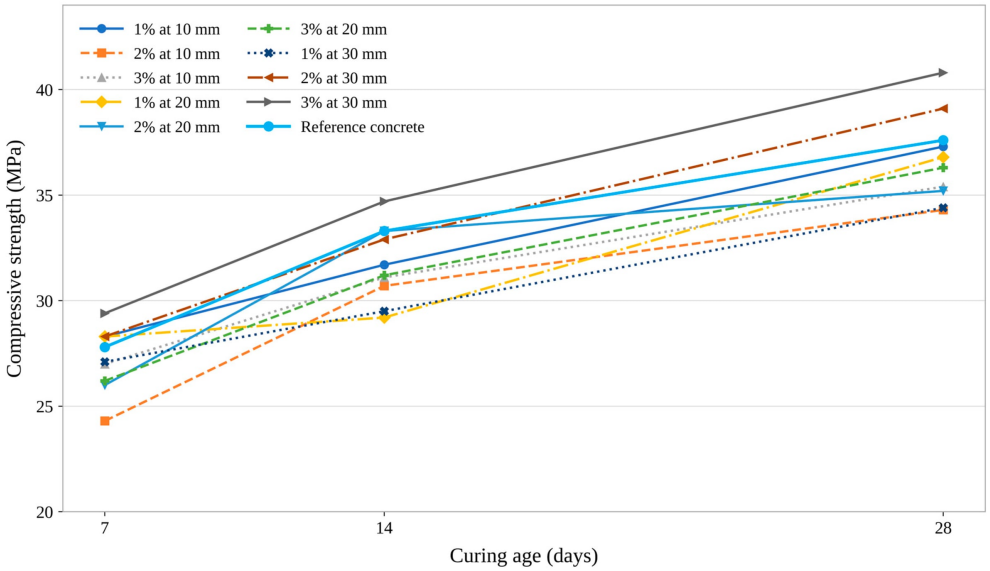

Figure 3. Compressive strength development for untreated DPF concrete. Values represent the mean strength for each condition and test age.

The alkali-treated group exhibited mean compressive strengths of 23.72 MPa at 7 days, 25.97 MPa at 14 days, and 29.96 MPa at 28 days. The corresponding mean increase from 7 to 28 days was 26.2%. Figure 4 shows a clear separation from the reference line throughout the testing period. The strongest alkali-treated condition at 28 days was A2-30, with a compressive strength of 34.9 MPa. The lowest 28-day value of 26.2 MPa was observed for both A1-10 and A3-30. Both conditions reached compressive strengths of 22.5, 23.3, and 26.2 MPa at 7, 14, and 28 days, respectively.

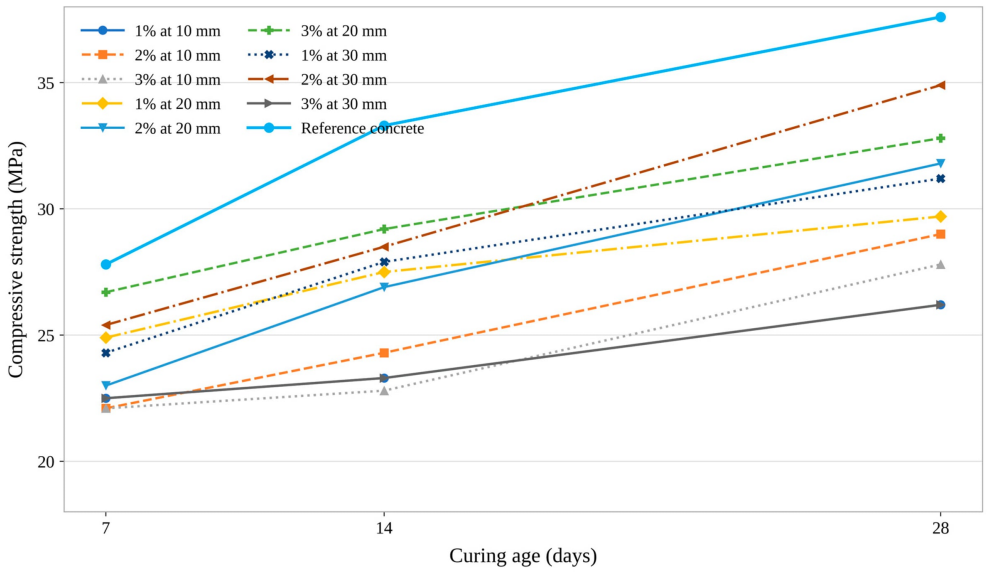

Figure 4. Compressive strength development for alkali-treated DPF concrete. Values represent the mean strength for each condition and test age.

Hornified concrete exhibited group means of 23.32, 26.03, and 29.91 MPa at 7, 14, and 28 days, respectively. The mean increase from 7 to 28 days was 28.6%. Figure 5 shows that H1-20 produced the highest 28-day compressive strength within the hornified group, reaching 33.0 MPa, followed by H3-20 at 32.5 MPa. H3-30 exhibited the lowest strength at all three ages within the hornified group, reaching 27.7 MPa at 28 days. The absolute strength gain of H3-20 from 7 to 28 days was 10.0 MPa, the largest within the hornified series, although its final strength remained 5.1 MPa below the reference.

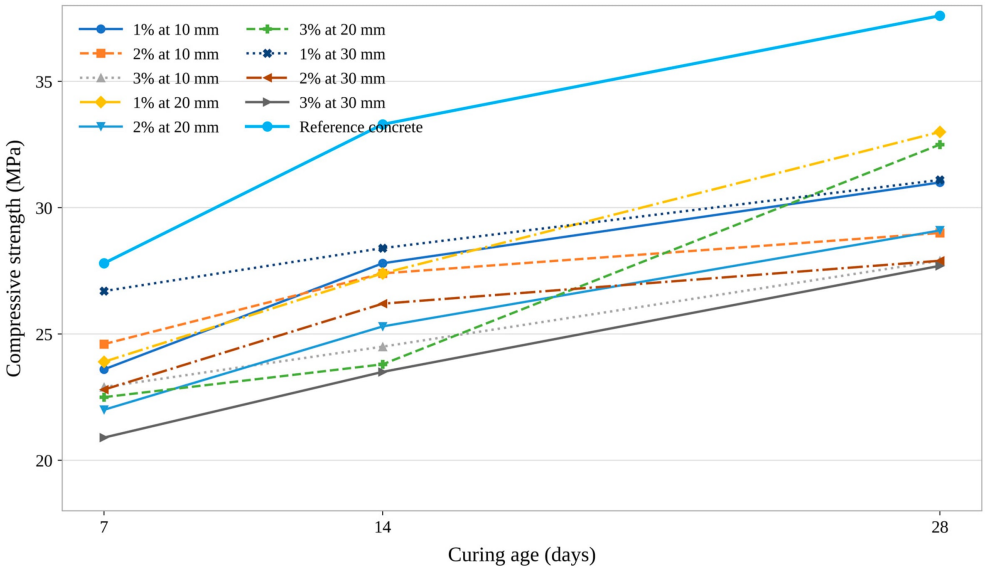

Figure 5. Compressive strength development for hornified DPF concrete. Values represent the mean strength for each condition and test age.

Table 4 details the treatment-state means and ranges. At 28 days, the untreated group mean was 6.67 MPa higher than the alkali-treated group mean and 6.71 MPa higher than the hornified group mean. The two treated group means were nearly identical, differing by only 0.04 MPa. These group means indicate that neither treatment method increased the average compressive strength relative to untreated fibers under the tested conditions.

Table 4. Treatment-state mean strengths and ranges across the tested matrix (MPa). Ranges describe different mixtures, not replicate variability.

Fiber State	Mean CS 7 d	Mean CS 14 d	Mean CS 28 d	CS 28 d Range	Mean FS 28 d	FS 28 d Range
Reference	27.80	33.30	37.60	37.6	3.20	3.2
Untreated	27.21	31.59	36.62	34.3–40.8	3.34	3.1–3.6
Alkali	23.72	25.97	29.96	26.2–34.9	2.99	2.5–3.3
Hornification	23.32	26.03	29.91	27.7–33.0	2.99	2.5–3.3

3.2. Effects of Fiber Length, Content, and Treatment on 28-Day Compressive Strength

Figure 6 compares the 28-day mean compressive strengths across the nine length–content combinations. Three untreated conditions approached or exceeded the reference strength of 37.6 MPa. U1-10 reached 37.3 MPa, representing a difference of −0.8%. U2-30 reached 39.1 MPa, representing an increase of 4.0%, while U3-30 reached 40.8 MPa, representing an increase of 8.5%. The remaining untreated conditions ranged from 34.3 to 36.8 MPa, corresponding to reductions of 2.1% to 8.8%.

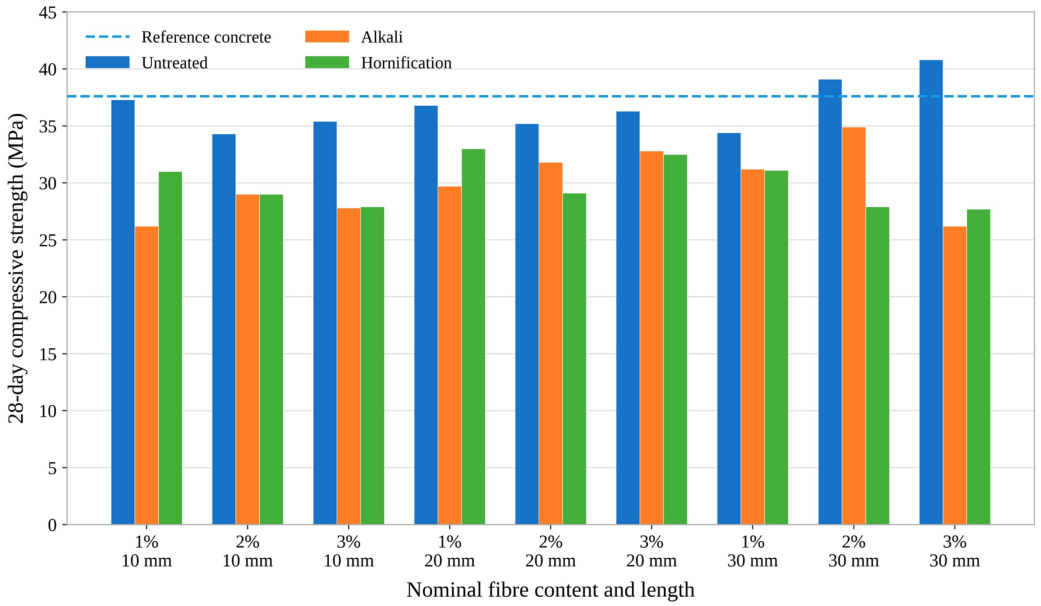

Figure 6. Comparison of 28-day compressive strength across the length–content matrix. The dashed line marks the reference mean.

Fiber length did not exhibit a uniform effect across the untreated series. At a nominal content of 1%, compressive strength was 37.3 MPa with 10 mm fibers, 36.8 MPa with 20 mm fibers, and 34.4 MPa with 30 mm fibers. Increasing fiber length therefore reduced strength at this content level. At 2%, the length-dependent trend was reversed, with strengths of 34.3 MPa at 10 mm, 35.2 MPa at 20 mm, and 39.1 MPa at 30 mm. At 3%, strength increased from 35.4 MPa at 10 mm to 36.3 MPa at 20 mm and 40.8 MPa at 30 mm. The benefit of a 30 mm fiber length was therefore dependent on fiber content. An interpretation based on fiber length alone will not fully capture this response.

Nominal fiber content exhibited a similar dependence on fiber length. At 10 mm, the 1% condition exhibited the highest strength, while the 2% condition exhibited the lowest. At 20 mm, the three results fell within a narrow range of 35.2 to 36.8 MPa, with the 1% condition producing the highest value. At 30 mm, strength increased substantially from 34.4 MPa at 1% to 39.1 MPa at 2% and 40.8 MPa at 3%. The highest fiber content was therefore favorable only at the longest tested fiber length. This descriptive pattern indicates the apparent combined influence of nominal fiber content and fiber length within the tested matrix.

Alkali treatment reduced the 28-day compressive strength relative to the corresponding untreated condition in all nine comparisons. The reductions ranged from 9.3% for the 1%-30 mm pair to 35.8% for the 3%-30 mm pair, with a mean matched reduction of 17.9%. The strongest alkali-treated condition, A2-30, reached 34.9 MPa, remaining 7.2% below the reference and 10.7% below U2-30. The 20 mm alkali-treated conditions exhibited the highest average strength among the length groups, at 31.43 MPa, compared to 27.67 MPa at 10 mm and 30.77 MPa at 30 mm. The response to alkali treatment was therefore non-monotonic with respect to both fiber length and content.

Hornification also reduced the 28-day compressive strength relative to each corresponding untreated condition. The strongest hornified condition, H1-20, reached 33.0 MPa, which was 12.2% below the reference and 10.3% below U1-20. The mean strengths for the hornified length groups were 29.30 MPa at 10 mm, 31.53 MPa at 20 mm, and 28.90 MPa at 30 mm. As observed with alkali treatment, the intermediate fiber length produced the highest group mean, while the longer fibers exhibited lower strengths at 2% and 3%.

The treated conditions therefore exhibited different responses from those of the untreated 30 mm fibers. Longer untreated fibers produced the two highest compressive

strengths at 2% and 3%, whereas longer treated fibers yielded mixed or lower results. The strengths of A3-30 and H3-30 were 14.6 and 13.1 MPa below that of U3-30, respectively. This treatment-by-geometry pattern represents one of the principal findings of the experiment. The observed results indicate that the relationship between fiber length and compressive strength depends on the fiber treatment state.

3.3. Flexural Strength at 28 Days

Figure 7 shows that thehe fiber-free reference exhibited a 28-day flexural strength of 3.2 MPa. Untreated DPF concrete exhibited flexural strengths ranging from 3.1 to 3.6 MPa, with a group mean of 3.34 MPa. Seven of the nine untreated conditions equaled or exceeded the reference strength. U2-20 produced the highest value of 3.6 MPa, representing an increase of 12.5% relative to the reference. U1-20 and U3-10 each reached 3.5 MPa, representing an increase of 9.4%, while U3-20 reached 3.4 MPa, representing an increase of 6.3%. U1-30 and U3-30 each exhibited a flexural strength of 3.1 MPa, which was 3.1% below the reference.

The untreated flexural-strength pattern differed from the corresponding compressive-strength pattern. The 30 mm fibers produced the highest compressive strengths at 2% and 3%, although their corresponding flexural strengths were 3.3 and 3.1 MPa, respectively. The 20 mm series exhibited the highest average flexural strength of 3.50 MPa, compared to 3.37 MPa for the 10 mm fibers and 3.17 MPa for the 30 mm fibers. At 20 mm, all three fiber contents produced flexural strengths equal to or greater than 3.4 MPa. This finding indicates that the highest flexural-strength range occurred at an intermediate fiber length rather than at the longest tested length.

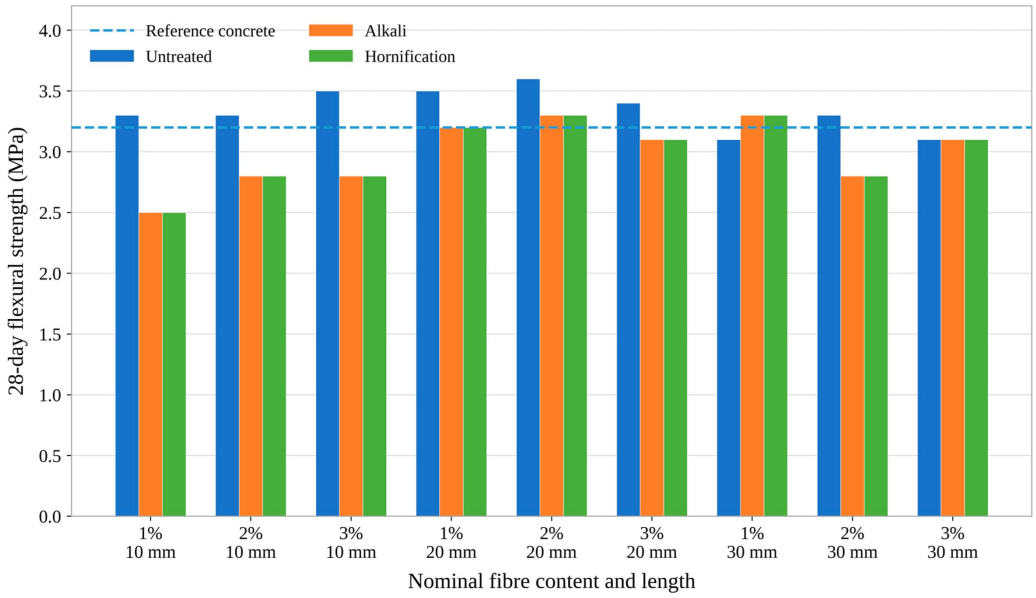

Figure 7. Comparison of 28-day flexural strength across the length–content matrix. The dashed line marks the reference mean.

The flexural means for the alkali-treated specimens ranged from 2.5 to 3.3 MPa, with a group mean of 2.99 MPa. The maximum value of 3.3 MPa was recorded for A2-20 and A1-30, which was 3.1% above the reference. A1-20 matched the reference at 3.2 MPa. The remaining six alkali-treated conditions were below the reference. Relative to the corresponding untreated condition, the change in flexural strength following alkali treatment ranged from a 24.2% reduction for the 1%-10 mm pair to a 6.5% increase for the 1%-30 mm pair. The mean matched difference was −10.4%.

The flexural means for the hornified and alkali-treated specimens were identical at the reported precision for every length–content combination. H2-20 and H1-30 reached 3.3 MPa, H1-20 reached 3.2 MPa, and the hornified group mean was 2.99 MPa. Both treatment groups therefore exhibited the same mean 28-day flexural strength, which was lower than the untreated group mean.

Fiber content alone did not provide a consistent flexural ranking. The untreated group means were 3.30 MPa at 1%, 3.40 MPa at 2%, and 3.33 MPa at 3%. The alkali-treated and hornified content means were 3.00, 2.97, and 3.00 MPa, respectively. The relatively narrow range of content-based means indicates that nominal fiber content alone did not determine flexural performance within each treatment state.

3.4. Combined Compressive and Flexural Response

Figure 8 presents the 28-day compressive and flexural means on the same axes. Four untreated conditions formed the descriptive Pareto front based on the rounded means. U3-30 exhibited the highest compressive strength of 40.8 MPa, with a flexural strength of 3.1 MPa. U2-30 exhibited 39.1 MPa in compression and 3.3 MPa in flexure. U1-20 exhibited 36.8 MPa in compression and 3.5 MPa in flexure, while U2-20 exhibited 35.2 MPa in compression and 3.6 MPa in flexure. Movement along this front represents a direct trade-off between higher compressive and flexural strengths.

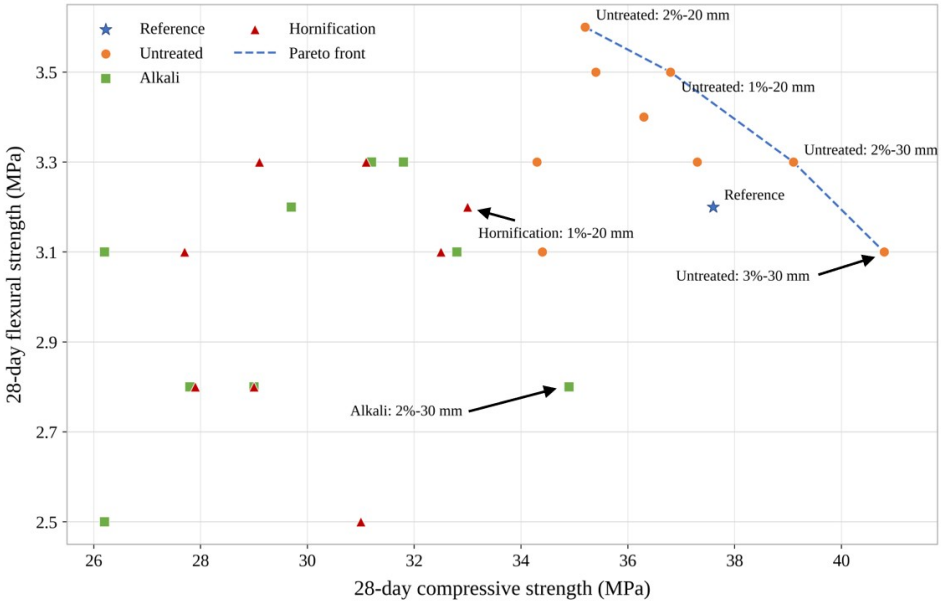

Figure 8. Combined 28-day compressive and flexural response. The dashed line joins the Pareto-efficient conditions. This is a descriptive front of rounded means.

U2-30 was the only tested condition that exceeded the reference in both measured properties, with increases of 4.0% in compression and 3.1% in flexure. U3-30 exhibited the largest compressive strength increase but a 3.1% reduction in flexural strength. U2-20 exhibited the largest flexural strength increase but a 6.4% reduction in compressive strength. U1-20 exhibited a smaller compressive strength reduction of 2.1%, accompanied by a 9.4% increase in flexural strength. These distinctions are more informative than identifying a single best mixture because the preferred condition depends on which mechanical response is given greater weight.

None of the alkali-treated or hornified conditions appeared on the Pareto front. Each treated condition was exceeded in both properties by at least one untreated condition. A2-30 exhibited the highest compressive strength among the treated conditions at 34.9 MPa

but reached only 2.8 MPa in flexure. A2-20 and H2-20 reached 3.3 MPa in flexure, with compressive strengths of 31.8 and 29.1 MPa, respectively. H1-20 exhibited the highest compressive strength among the hornified conditions at 33.0 MPa, with a flexural strength of 3.2 MPa. Table 5 presents the four non-dominated conditions and their percentage differences from the reference.

Table 5. Descriptively Pareto-efficient untreated conditions based on rounded 28-day means.

Code	Fiber Volume (%)	Length (mm)	CS (MPa)	CS Change (%)	FS (MPa)	FS Change (%)	Position on Trade-off
U3-30	3	30	40.8	+8.5	3.1	−3.1	Highest compression
U2-30	2	30	39.1	+4.0	3.3	+3.1	Both above references
U1-20	1	20	36.8	−2.1	3.5	+9.4	Small CS loss, high FS
U2-20	2	20	35.2	−6.4	3.6	+12.5	Highest flexure

4. Discussion

4.1. Untreated Fiber Response and the Joint Role of Length and Content

The untreated results indicate that the DPF response cannot be characterized by a simple increase or decrease with fiber dosage. The same 30 mm fiber length produced the lowest compressive strength within the 1% untreated series and the two highest compressive strengths at 2% and 3%. This reversal indicates an apparent length–content dependence but does not establish its underlying physical cause. One possible explanation is that the 1% content of 30 mm fibers provided too few appropriately positioned strands to offset voids or local disturbances during compaction, whereas the 2% and 3% contents provided a more extensive fiber network across potential cracks. Another possibility is that fiber distribution varied between batches. These explanations remain hypotheses regarding the observed strength pattern.

The higher compressive strength mean for U3-30 is consistent with earlier reports in which selected DPF dosages maintained or increased compressive strength [13,16,17]. However, this result does not indicate that 3% and 30 mm will necessarily be optimal in another matrix. Kriker et al. demonstrated that DPF behavior varies with hot–dry exposure and mixture conditions, while subsequent concrete studies reported strength reductions when fiber content increased or fiber geometry impaired compaction [14,15,23].

The flexural response indicated that the strongest untreated conditions occurred at a fiber length of 20 mm. Crack bridging depends on factors beyond embedment length. A long fiber strand can effectively bridge a crack, yet unfavorable orientation, local fiber clustering, inadequate paste coating, and fiber pull-out before complete stress transfer can reduce the measured modulus of rupture. Mortar studies have demonstrated that DPF length influences flexural and fracture responses through fiber engagement and pull-out behavior [24,25,48]. The reported means favor an intermediate fiber length in the investigated concrete.

Water retained within porous plant fibers could have contributed to age-related strength development if the fibers were incorporated into the mixture in a wet or partially saturated condition. Plant fibers can release water as hydration progresses, potentially improving local curing, whereas dry fibers can absorb water from the paste during mixing and reduce initial workability [49]. The consistent increase in strength across all conditions is primarily consistent with continued cement hydration. Differences among the untreated mixtures could have resulted from the combined effects of hydration, fiber moisture, compaction, and fiber–paste contact.

Earlier work by Labib proposed DPF as a feasible reinforcement for cement composites and established a broader framework for incorporating plant fibers into cement systems [53,54]. The present results indicate that the mechanical target and fiber geometry are central to this assessment. Different testing priorities can therefore lead to apparently conflicting conclusions.

4.2. Influence of Alkali Treatment and Hornification on Strength

Alkali treatment is frequently associated with surface cleaning and increased fiber surface roughness. These changes can increase friction and bond strength, but they can also remove cell-wall constituents, reduce fiber cross-sectional area, and decrease tensile capacity when the treatment concentration or exposure is excessive [32–35]. Although the NaOH concentration was 1%, treatment severity also depends on exposure temperature and duration. Treatment-induced changes in fiber composition, tensile capacity, and moisture state could have contributed to the lower strengths.

A second possible explanation relates to the properties of fresh concrete. If treatment increased surface roughness or water absorption, mixing resistance or entrapped air content could increase when the water and admixture dosages remain fixed. Longer fibers can further intensify this effect.

Studies on date palm fiber treatments have not reported a universal outcome. Ali-Boucetta et al. found that treatment altered the rheological and mechanical responses of date palm mesh cement composites, while Lahouioui et al. reported treatment-related changes in mechanical, thermal, and acoustic properties [39,41]. Moawad and Moussa compared mechanical, chemical, and biological treatment methods and identified a mechanically treated mixture with low fiber content as the strongest among their tested conditions [47]. Their fiber length, content range, treatment sequence, and concrete system differed from those of the present study. These differences highlight the dependence of treatment response on processing conditions and the concrete system.

Studies involving sisal and other natural fibers have reported reduced water absorption, improved dimensional stability, and changes in pull-out response following repeated wetting and drying cycles [42–45]. Improvements at the fiber scale can, however, coincide with reductions in strength at the composite scale. Changes in stiffness, brittleness, moisture absorption, fiber shape, or packing can explain the lower mean strengths observed for the hornified specimens.

4.3. Compression and Flexure as Separate Design Responses

Compressive and flexural strengths did not exhibit consistent trends across the experimental matrix. U3-30 exhibited the highest compressive strength but remained slightly below the reference in flexure. U2-20 exhibited the highest flexural strength but remained below the reference in compression. This distinction is expected because the two tests involve different failure mechanisms. Compressive strength is sensitive to matrix continuity, voids, aggregate packing, and lateral restraint around fibers. Flexural strength is more sensitive to tensile-zone behavior, crack initiation, fiber orientation across cracks, bond length, and pull-out resistance.

DPF can therefore improve flexural performance even when compressive strength decreases. Natural fibers can bridge small cracks and delay crack opening, while the same fibers can introduce voids or weak regions under compression. Research on fracture behavior and damage control in fiber–cement composites similarly distinguishes between first-crack strength, post-crack response, residual capacity, and compressive strength [25,48,55]. The present experiment evaluated peak flexural stress, expressed as the modulus of rupture.

Therefore, the 3.6 MPa value for U2-20 represents peak bending resistance rather than post-cracking ductility.

Recent work by Wei et al. [56] on steel-fiber-reinforced alkali-activated slag materials provides a related example of matrix-dependent flexural behavior. They associated retarder-modified rheology and flow-induced casting with fiber alignment and flexural strength. This finding supports the consideration of matrix flow and fiber orientation, in addition to matrix strength, when interpreting bending performance. However, their binder and reinforcement differed from those used in the present study, so their findings do not establish the mechanism underlying the observed DPF response.

Pareto screening provides a direct approach to distinguishing between compressive and flexural performance without imposing a weighted score. The Pareto front represents the trade-offs among the rounded means within the tested experimental matrix. U2-30 is therefore a candidate for further investigation rather than an established optimum.

Fiber distribution can contribute to variation among experimental conditions. Studies of reinforced composites indicate that perfectly uniform fiber distribution is not always achievable and that local fiber concentrations influence stress transfer [27,57]. Concrete also contains coarse aggregate, which can restrict fiber movement and influence the orientation of long strands during casting. Future investigations combining cross-sectional imaging, fresh-density measurements, and hardened-void characterization can further clarify these mechanisms.

Threshold concepts for minimum, effective, and excessive fiber contents can help explain nonlinear responses [29]. These concepts relate composite performance to fiber volume fraction, fiber tensile properties, bond strength, and orientation. In the present study, the nominal fiber contents of 1% to 3% represent the experimental levels utilized to compare the measured strength responses within the selected concrete system.

4.4. Relation to Other Plant-Fiber–Cement Systems

The mixed strength response observed in the present study is consistent with the broader literature on plant-fiber–cement composites. Bagasse fibers can interfere with cement setting when botanical constituents remain on the fiber surface [58]. Sisal and coconut fibers can lose strength in alkaline pore solutions over time, prompting early durability investigations into fiber mineralization and matrix modification [59]. Hemp, abaca, coir, bamboo, coconut, and rainforest fibers have each produced improvements in some mixtures and reductions in others [60–65]. These differences arise from variations in fiber chemistry, geometry, processing, dosage basis, matrix composition, and curing conditions.

Reviews published in the polymer and cement-composite fields have reached a common conclusion: natural fibers are heterogeneous materials whose treatment and final performance depend on their source and processing conditions [31,57,66]. This observation is directly relevant to DPF. A treatment developed for another fiber species cannot be transferred without experimental verification. Hornification that performs well for sisal can produce a different moisture state or stiffness change in date palm mesh. Similarly, alkali exposure suitable for a polymer composite can be excessively severe, insufficiently effective, or poorly suited to cement mixing.

Studies on the durability of natural-fiber-reinforced concrete also caution against evaluating mixtures solely on the basis of 28-day strength [55,67]. Wet–dry cycling, alkaline aging, chloride exposure, water absorption, shrinkage, and freeze–thaw exposure can alter fiber condition and the surrounding cement paste. DPF has been investigated under hot–dry and high-temperature conditions, with outcomes depending on matrix modification and fiber content [14,22,68]. Therefore, the 28-day ranking reflects short-term mechanical performance rather than long-term service-life performance.

Research on pyrolyzed natural waste fibers and plant-based cement paste also indicates that processing methods and matrix scale can alter the balance between strength and dimensional response [69,70]. The concrete investigated in the present study contains coarse aggregate and two admixtures, whereas many fiber treatment studies involve mortar or paste. Direct numerical comparisons should therefore be limited. Relative trends, such as treatment-related strength reductions or a flexural strength peak at an intermediate fiber length, are more defensible than direct comparisons of absolute MPa values across dissimilar systems.

A 2025 palm-microfiber study reported reductions in compressive and tensile strengths as treated frond microfiber content increased, accompanied by lower density and higher water absorption [23]. Its fibers partially replaced the sand volume and differed from the longer mesh fibers investigated in the present study. However, both studies demonstrate that fiber treatment does not eliminate the possibility of strength reduction. A 2026 mortar fracture study demonstrated that DPF can provide a favorable fracture response relative to polypropylene under its specific material and testing conditions [48]. This recent evidence supports property-specific evaluation. DPF can be beneficial for fracture control, thermal performance, or agricultural waste utilization even when compressive strength does not increase.

4.5. Study Contribution and Research Perspectives

The main contribution of the present study is the matched comparison of three fiber states across the same three lengths and three nominal fiber contents within a single base concrete composition. The reported means reveal an apparent treatment-by-geometry response that can remain undetected in studies examining only one fiber length or content. Surface modification did not result in higher average strength in the present dataset.

The findings characterize the combined effects of fiber state, length, and nominal content on compressive strength development and 28-day flexural strength in the selected concrete system. These comparisons identify promising combinations within the investigated factor ranges, while the proposed mechanisms remain interpretations of the measured mechanical responses.

Further research can investigate treatment concentration and exposure duration, hornification schedules, and fiber moisture condition as additional experimental factors. Extending the mechanical assessment to splitting tensile strength, flexural load-deflection response, water absorption, shrinkage, and aging will help clarify application-specific performance. Fiber characterization, microscopy, and failure-surface imaging can help distinguish among fiber rupture, pull-out, clustering, and void-related failure mechanisms. The peak modulus of rupture does not quantify residual load capacity or fracture energy.

The use of DPF provides an opportunity to valorize a locally available agricultural residue. Treatment water, NaOH consumption, oven energy requirements, transportation, and concrete service life influence the overall environmental balance. Life-cycle assessment and treatment-energy inventories provide a basis for evaluating these factors alongside mechanical performance.

5. Conclusions

This study examines one fiber-free C40 concrete mixture and 27 date palm fiber conditions comprising three fiber volume fractions, three lengths, and three fiber states. Compressive strength is measured at 7, 14, and 28 days, while flexural strength is measured at 28 days. The full matrix permits direct comparisons among untreated, 1% NaOH-treated, and hornified fibers at matching length–content combinations. The following conclusions are drawn based on these findings.

All conditions exhibit an increase in compressive strength with age. The reference reaches 37.6 MPa at 28 days. Untreated DPF exhibits the highest treatment-state mean at 28 days, reaching 36.62 MPa, compared to 29.96 MPa for alkali-treated fibers and 29.91 MPa for hornified fibers.

The response of untreated fibers depends on the combined length–content combination. U3-30 exhibits the highest 28-day compressive strength of 40.8 MPa, representing an 8.5% increase over the reference. U2-30 reaches 39.1 MPa, representing a 4.0% increase. The same 30 mm length reduces strength at 1% nominal content, indicating that length cannot be assessed independently of content.

U2-20 exhibits the highest 28-day flexural strength of 3.6 MPa, which is 12.5% higher than the reference value of 3.2 MPa. The 20 mm untreated group exhibits the highest average flexural strength, whereas the 30 mm untreated group achieves the highest average compressive strength. Therefore, the mixture selected for one response differs from that selected for the other.

U2-30 is the only tested condition that exceeds the reference in both compression and flexure. Four untreated conditions form the descriptive Pareto front based on the rounded means: U3-30, U2-30, U1-20, and U2-20. These conditions define the measured trade-off between compression-led and flexure-led performance.

Alkali treatment and hornification do not improve 28-day compressive strength relative to any matching untreated condition. Their mean matched compressive strength reductions are 17.9% and 18.0%, respectively. The treated flexural strength means are also lower than the untreated mean. No treated condition appears on the Pareto front.

The reported means indicate that DPF can enhance selected peak strengths, but surface treatment cannot be assumed to produce stronger concrete. Treatment severity, fiber moisture, length, content, dispersion, and workability can jointly influence the response. The untreated U2-30 condition represents a candidate for further testing of a balanced response within this test matrix, whereas U3-30 and U2-20 are the leading conditions for compression and flexure, respectively. These labels identify the best-performing tested levels but do not establish universal optima.

Further investigation of fiber–matrix interactions, post-cracking behavior, and long-term durability is necessary to extend the assessment of these mixtures for application-specific use.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to acknowledge the support of Prince Sultan University for paying the Article Processing Charges (APC) of this publication.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DPF	Date palm fiber
CS	Compressive strength
FS	Flexural strength
NaOH	Sodium hydroxide
REF	Reference concrete

References

1. Hanieh, A.A.; Hasan, A.; Assi, M. Date Palm Trees Supply Chain and Sustainable Model. *J. Clean. Prod.* **2020**, *258*, 120951. [CrossRef]
2. Khoshnodifar, Z.; Ataei, P.; Karimi, H. Recycling Date Palm Waste for Compost Production: A Study of Sustainability Behavior of Date Palm Growers. *Environ. Sustain. Indic.* **2023**, *20*, 100300. [CrossRef]
3. Almutawa, A.A. Date Production in the Al-Hassa Region, Saudi Arabia in the Face of Climate Change. *J. Water Clim. Change* **2022**, *13*, 2627–2647. [CrossRef]
4. Saifullah, A.; Chacko, N.G.; Dhakal, H.N.; Khan, S.H.; Sarker, F.; Zhang, Z. Valorisation of Agricultural Residue Bio-Mass Date Palm Fiber in Dry-Blended Polycaprolactone (PCL) Bio-Composites for Sustainable Packaging Applications. *Waste Biomass Valor.* **2024**, *15*, 5805–5817. [CrossRef]
5. Alotaibi, M.D.; Alshammari, B.A.; Saba, N.; Alothman, O.Y.; Sanjay, M.R.; Almutairi, Z.; Jawaid, M. Characterization of Natural Fiber Obtained from Different Parts of Date Palm Tree (*Phoenix dactylifera* L.). *Int. J. Biol. Macromol.* **2019**, *135*, 69–76. [CrossRef] [PubMed]
6. Awad, S.; Zhou, Y.; Katsou, E.; Li, Y.; Fan, M. A Critical Review on Date Palm Tree (*Phoenix dactylifera* L.) Fibers Their Uses Bio-Composites. *Waste Biomass Valor.* **2021**, *12*, 2853–2887. [CrossRef]
7. AL-Oqla, F.M.; Alothman, O.Y.; Jawaid, M.; Sapuan, S.M.; Es-Saheb, M.H. Processing and Properties of Date Palm Fibers and Its Composites. In *Biomass and Bioenergy*; Hakeem, K.R., Jawaid, M., Rashid, U., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 1–25, ISBN 978-3-319-07640-9.
8. Pacheco-Torgal, F.; Jalali, S. Cementitious Building Materials Reinforced with Vegetable Fibers: A Review. *Constr. Build. Mater.* **2011**, *25*, 575–581. [CrossRef]
9. Camargo, M.; Adefrs Taye, E.; Roether, J.; Tilahun Redda, D.; Boccaccini, A. A Review on Natural Fiber-Reinforced Geopolymer and Cement-Based Composites. *Materials* **2020**, *13*, 4603. [CrossRef] [PubMed]
10. Rocha, D.L.; Júnior, L.T.; Marvila, M.; Pereira, E.; Souza, D.; De Azevedo, A. A Review of the Use of Natural Fibers in Cement Composites: Concepts, Applications and Brazilian History. *Polymers* **2022**, *14*, 2043. [CrossRef] [PubMed]
11. Jamshaid, H.; Mishra, R.K.; Raza, A.; Hussain, U.; Rahman, M.L.; Nazari, S.; Chandan, V.; Muller, M.; Choteborsky, R. Natural Cellulosic Fiber Reinforced Concrete: Influence of Fiber Type and Loading Percentage on Mechanical and Water Absorption Performance. *Materials* **2022**, *15*, 874. [CrossRef] [PubMed]
12. Kurpińska, M.; Pawelska-Mazur, M.; Gu, Y.; Kurpiński, F. The Impact of Natural Fibers' Characteristics on Mechanical Properties of the Cement Composites. *Sci. Rep.* **2022**, *12*, 20565. [CrossRef] [PubMed]
13. Kriker, A.; Debicki, G.; Bali, A.; Khenfer, M.M.; Chabannet, M. Mechanical Properties of Date Palm Fibers and Concrete Reinforced with Date Palm Fibers in Hot-Dry Climate. *Cem. Concr. Compos.* **2005**, *27*, 554–564. [CrossRef]
14. Kriker, A.; Bali, A.; Debicki, G.; Bouziane, M.; Chabannet, M. Durability of Date Palm Fibers and Their Use as Reinforcement in Hot Dry Climates. *Cem. Concr. Compos.* **2008**, *30*, 639–648. [CrossRef]
15. Alatshan, F.; Altlomate, A.M.; Mashiri, F.; Alamin, W. Effect of Date Palm Fibers on the Mechanical Properties of Concrete. *Sustain. Build. Res. Cent.* **2017**, *8*, 68–80. [CrossRef]
16. Althoey, F.; Hakeem, I.Y.; Hosen, M.A.; Qaidi, S.; Isleem, H.F.; Hadidi, H.; Shahapurkar, K.; Ahmad, J.; Ali, E. Behavior of Concrete Reinforced with Date Palm Fibers. *Materials* **2022**, *15*, 7923. [CrossRef] [PubMed]
17. Ibrahim, Y.E.; Adamu, M.; Marouf, M.L.; Ahmed, O.S.; Drmosh, Q.A.; Malik, M.A. Mechanical Performance of Date-Palm-Fiber-Reinforced Concrete Containing Silica Fume. *Buildings* **2022**, *12*, 1642. [CrossRef]
18. Tamimi, A.; Tabsh, S.W.; El-Emam, M. Pervious Concrete Made with Recycled Coarse Aggregate and Reinforced with Date Palm Leaves Fibers. *Materials* **2023**, *16*, 7496. [CrossRef] [PubMed]
19. Dehghan, S.; Hassani, A. Experimental Investigation of Mechanical Properties of Roller Compacted Concrete Pavement (RCCP) Reinforced with Date Palm Fibers. *Road Mater. Pavement Des.* **2024**, *25*, 2549–2562. [CrossRef]
20. Bouzred, F.; Laouar, M.S.; Boursas, F.; Bouzenada, S.; Hamidane, H. Experimental Investigation on the Behavior of Recycled Concrete Incorporating Date Palm Fibers. *Eng. Technol. Appl. Sci. Res.* **2025**, *15*, 23088–23094. [CrossRef]
21. Adamu, M.; Labib, W.A.; Ibrahim, Y.E.; Alanazi, H. Mechanical Behavior and Durability Performance of Concrete Reinforced with Hybrid Date Palm and Polypropylene Polymer Fibers. *Polymers* **2025**, *17*, 1350. [CrossRef] [PubMed]
22. Adamu, M.; Raut, A.N.; Ibrahim, Y.E.; Alanazi, H.; Ahmed, O.S. Multi-Criteria Decision-Based Optimization and Multivariable Regression Analysis of Date Palm Fiber Reinforced Concrete Modified with Silica Fume under Normal and Elevated Temperatures. *Sci. Rep.* **2025**, *15*, 5902. [CrossRef] [PubMed]
23. Yassin, M.H.; Lakys, R.E.; Merouani, Z.-E.; Jumah, A.; Farhat, M.H. Performance Analysis of Palm Tree Microfibers in Concrete. *Sci. Rep.* **2025**, *15*, 5128. [CrossRef] [PubMed]
24. Benaniba, S.; Djendel, M.; Boubaaya, R.; Raouache, E.; Kessal, O.; Driss, Z. Experimental Investigation on Thermomechanical Properties of Bio-Composites Reinforced with Two Lengths of the Date Palm Fibers. *J. Nat. Fibers* **2022**, *19*, 10193–10209. [CrossRef]

25. Benaimeche, O.; Carpinteri, A.; Mellas, M.; Ronchei, C.; Scorza, D.; Vantadori, S. The Influence of Date Palm Mesh Fiber Reinforcement on Flexural and Fracture Behaviour of a Cement-Based Mortar. *Compos. Part B Eng.* **2018**, *152*, 292–299. [CrossRef]
26. Tioua, T.; Kriker, A.; Barluenga, G.; Palomar, I. Influence of Date Palm Fiber and Shrinkage Reducing Admixture on Self-Compacting Concrete Performance at Early Age in Hot-Dry Environment. *Constr. Build. Mater.* **2017**, *154*, 721–733. [CrossRef]
27. Huang, L.J.; Geng, L.; Peng, H.-X. Microstructurally Inhomogeneous Composites: Is a Homogeneous Reinforcement Distribution Optimal? *Prog. Mater. Sci.* **2015**, *71*, 93–168. [CrossRef]
28. Zhang, D.; Tu, H.; Li, Y.; Weng, Y. Effect of Fiber Content and Fiber Length on the Dynamic Compressive Properties of Strain-Hardening Ultra-High Performance Concrete. *Constr. Build. Mater.* **2022**, *328*, 127024. [CrossRef]
29. Shah, D.U.; Schubel, P.J.; Licence, P.; Clifford, M.J. Determining the Minimum, Critical and Maximum Fiber Content for Twisted Yarn Reinforced Plant Fiber Composites. *Compos. Sci. Technol.* **2012**, *72*, 1909–1917. [CrossRef]
30. Adamu, M.; Alanazi, F.; Ibrahim, Y.E.; Alanazi, H.; Khed, V.C. A Comprehensive Review on Sustainable Natural Fiber in Cementitious Composites: The Date Palm Fiber Case. *Sustainability* **2022**, *14*, 6691. [CrossRef]
31. Eleutério, T.; Trota, M.J.; Meirelles, M.G.; Vasconcelos, H.C. A Review of Natural Fibers: Classification, Composition, Extraction, Treatments, and Applications. *Fibers* **2025**, *13*, 119. [CrossRef]
32. Alawar, A.; Hamed, A.M.; Al-Kaabi, K. Characterization of Treated Date Palm Tree Fiber as Composite Reinforcement. *Compos. Part B Eng.* **2009**, *40*, 601–606. [CrossRef]
33. Li, Q.; Ibrahim, L.; Zhou, W.; Zhang, M.; Yuan, Z. Treatment Methods for Plant Fibers for Use as Reinforcement in Cement-Based Materials. *Cellulose* **2021**, *28*, 5257–5268. [CrossRef]
34. Verma, D.; Goh, K.L. Effect of Mercerization/Alkali Surface Treatment of Natural Fibers and Their Utilization in Polymer Composites: Mechanical and Morphological Studies. *J. Compos. Sci.* **2021**, *5*, 175. [CrossRef]
35. Luchese, C.L.; Engel, J.B.; Tessaro, I.C. A Review on the Mercerization of Natural Fibers: Parameters and Effects. *Korean J. Chem. Eng.* **2024**, *41*, 571–587. [CrossRef]
36. Budtova, T.; Navard, P. Cellulose in NaOH–Water Based Solvents: A Review. *Cellulose* **2016**, *23*, 5–55. [CrossRef]
37. Mouhoubi, S.; Bourahli, M.E.H.; Osmani, H.; Abdeslam, S. Effect of Alkali Treatment on Alfa Fibers Behavior. *J. Nat. Fibers* **2017**, *14*, 239–249. [CrossRef]
38. Hashim, M.Y.; Amin, A.M.; Marwah, O.M.F.; Othman, M.H.; Yunus, M.R.M.; Chuan Huat, N. The Effect of Alkali Treatment under Various Conditions on Physical Properties of Kenaf Fiber. *J. Phys. Conf. Ser.* **2017**, *914*, 012030. [CrossRef]
39. Ali-Boucetta, T.; Behim, M.; Cassagnabere, F.; Mouret, M.; Ayat, A.; Laifa, W. Treatment of Date Palm Fibers Mesh: Influence on the Rheological and Mechanical Properties of Fiber-Cement Composites. *Constr. Build. Mater.* **2021**, *273*, 121056. [CrossRef]
40. Awad, S.; Ghaffar, S.H.; Hamouda, T.; Midani, M.; Katsou, E.; Fan, M. Critical Evaluation of Date Palm Sheath Fiber Characteristics as a Reinforcement for Developing Sustainable Cementitious Composites from Waste Materials. *Biomass Conv. Bioref.* **2024**, *14*, 6887–6902. [CrossRef]
41. Lahouioui, M.; Ben Arfi, R.; Fois, M.; Ibos, L.; Ghorbal, A. Investigation of Fiber Surface Treatment Effect on Thermal, Mechanical and Acoustical Properties of Date Palm Fiber-Reinforced Cementitious Composites. *Waste Biomass Valorization* **2020**, *11*, 4441–4455. [CrossRef]
42. Claramunt, J.; Ardanuy, M.; García-Hortal, J.A.; Filho, R.D.T. The Hornification of Vegetable Fibers to Improve the Durability of Cement Mortar Composites. *Cem. Concr. Compos.* **2011**, *33*, 586–595. [CrossRef]
43. Ferreira, S.R.; Silva, F.A.; Lima, P.R.L.; Toledo Filho, R.D. Effect of Fiber Treatments on the Sisal Fiber Properties and Fiber-Matrix Bond in Cement Based Systems. *Constr. Build. Mater.* **2015**, *101*, 730–740. [CrossRef]
44. Ferreira, S.R.; Silva, F.D.A.; Lima, P.R.L.; Toledo Filho, R.D. Effect of Hornification on the Structure, Tensile Behavior and Fiber Matrix Bond of Sisal, Jute and Curauá Fiber Cement Based Composite Systems. *Constr. Build. Mater.* **2017**, *139*, 551–561. [CrossRef]
45. Do Amaral, L.M.; Rodrigues, C.D.S.; Poggiali, F.S.J. Hornification on Vegetable Fibers to Improve Fiber-Cement Composites: A Critical Review. *J. Build. Eng.* **2022**, *48*, 103947. [CrossRef]
46. Ge, L.; Li, H.; Feng, Z.; Hosseini, M. Study on the Interfacial Bonding Properties between Modified Bamboo Fibers and Sea Sand Reactive Powder Concrete by Hornification Method. *Ind. Crops Prod.* **2025**, *225*, 120539. [CrossRef]
47. Moawad, D.R.M.; Moussa, R.R. The Effect of Using Data Palm Waste Fibers in Plain Concrete Mixture by Comparing Three Pre-Treatment Techniques. *Sci. Rep.* **2023**, *13*, 12032. [CrossRef] [PubMed]
48. Benaimeche, O.; Natali, S.; Ronchei, C.; Scorza, D.; Zanichelli, A.; Fiorillo, R.; Vantadori, S. From Date Palm Waste to Fracture-Resistant Mortars: Natural Fibers as an Alternative to Polypropylene. *Constr. Build. Mater.* **2026**, *540*, 147650. [CrossRef]
49. Choi, Y.C. Hydration and Internal Curing Properties of Plant-Based Natural Fiber-Reinforced Cement Composites. *Case Stud. Constr. Mater.* **2022**, *17*, e01690. [CrossRef]
50. ASTM Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. Available online: https://store.astm.org/c0192_c0192m-19.html (accessed on 11 October 2026).
51. ASTM Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Available online: https://store.astm.org/c0039_c0039m-21.html (accessed on 13 September 2025).

52. ASTM Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading). Available online: https://store.astm.org/c0078_c0078m-16.html (accessed on 13 September 2025).
53. Labib, W.A. Utilisation of Date Palm Fibers in Cement-Based Composites: A Feasibility Study. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *596*, 012028. [CrossRef]
54. Labib, W.A. Plant-Based Fibers in Cement Composites: A Conceptual Framework. *J. Eng. Fibers Fabr.* **2022**, *17*, 15589250221078922. [CrossRef]
55. Dadkhah, M.; Tulliani, J.-M. Damage Management of Concrete Structures with Engineered Cementitious Materials and Natural Fibers: A Review of Potential Uses. *Sustainability* **2022**, *14*, 3917. [CrossRef]
56. Wei, J.; Gu, Y.; Zhou, B.; Han, S.; Teng, L.; Zang, J. Effect of Retarder on Flexural Properties of Fiber-Reinforced Alkali-Activated Slag Materials. *J. Build. Eng.* **2025**, *111*, 113283. [CrossRef]
57. Pickering, K.L.; Efendy, M.G.A.; Le, T.M. A Review of Recent Developments in Natural Fiber Composites and Their Mechanical Performance. *Compos. Part A Appl. Sci. Manuf.* **2016**, *83*, 98–112. [CrossRef]
58. Bilba, K.; Arsene, M.-A.; Ouensanga, A. Sugar Cane Bagasse Fiber Reinforced Cement Composites. Part I. Influence of the Botanical Components of Bagasse on the Setting of Bagasse/Cement Composite. *Cem. Concr. Compos.* **2003**, *25*, 91–96. [CrossRef]
59. Toledo Filho, R.D.; Scrivener, K.; England, G.L.; Ghavami, K. Durability of Alkali-Sensitive Sisal and Coconut Fibers in Cement Mortar Composites. *Cem. Concr. Compos.* **2000**, *22*, 127–143. [CrossRef]
60. Zhou, X.; Saini, H.; Kastiukas, G. Engineering Properties of Treated Natural Hemp Fiber-Reinforced Concrete. *Front. Built Environ.* **2017**, *3*, 33. [CrossRef]
61. Alcivar-Bastidas, S.; Petroche, D.M.; Martinez-Echevarria, M.J. The Effect of Different Treatments on Abaca Fibers Used in Cementitious Composites. *J. Nat. Fibers* **2023**, *20*, 2177235. [CrossRef]
62. Asasutjarit, C.; Charoenvai, S.; Hirunlabh, J.; Khedari, J. Materials and Mechanical Properties of Pretreated Coir-Based Green Composites. *Compos. Part B Eng.* **2009**, *40*, 633–637. [CrossRef]
63. Bittner, C.M.; Oettel, V. Fiber Reinforced Concrete with Natural Plant Fibers—Investigations on the Application of Bamboo Fibers in Ultra-High Performance Concrete. *Sustainability* **2022**, *14*, 12011. [CrossRef]
64. Shcherban', E.M.; Stel'makh, S.A.; Beskopylny, A.N.; Mailyan, L.R.; Meskhi, B.; Shilov, A.A.; Chernil'nik, A.; Özkılıç, Y.O.; Aksoylu, C. Normal-Weight Concrete with Improved Stress–Strain Characteristics Reinforced with Dispersed Coconut Fibers. *Appl. Sci.* **2022**, *12*, 11734. [CrossRef]
65. Da Fonseca, R.P.; Rocha, J.C.; Cheriaf, M. Mechanical Properties of Mortars Reinforced with Amazon Rainforest Natural Fibers. *Materials* **2020**, *14*, 155. [CrossRef] [PubMed]
66. Karthik, K.; Rajamanikkam, R.K.; Venkatesan, E.P.; Bishwakarma, S.; Krishnaiah, R.; Saleel, C.A.; Soudagar, M.E.M.; Kalam, M.A.; Ali, M.M.; Bashir, M.N. State of the Art: Natural Fiber-Reinforced Composites in Advanced Development and Their Physical/Chemical/Mechanical Properties. *Chin. J. Anal. Chem.* **2024**, *52*, 100415. [CrossRef]
67. Paul, S.; Van Zijl, G.; Šavija, B. Effect of Fibers on Durability of Concrete: A Practical Review. *Materials* **2020**, *13*, 4562. [CrossRef] [PubMed]
68. Mokaddem, A.; Alami, M.; Belkheir, M.; Rouissat, M.; Taouaf, L.; Doumi, B. Studying the Effect of Thermal Stress on Cement Composite Materials Reinforced with Date Palm Fibers. *Strength. Mater.* **2025**, *57*, 212–221. [CrossRef]
69. Smarzewski, P.; Palou, M.T.; Moustafa, M.; El-Yamany, M.; Faried, A.S.; Sofi, W.H.; Tawfik, T.A. Influence of Utilization of Natural Waste Fibers Pyrolysis on Mechanical Properties and Microstructure of Concrete. *J. Nat. Fibers* **2024**, *21*, 2418348. [CrossRef]
70. Ramadan, R.; Ghanem, H.; Khatib, J.M.; ElKordi, A.M. Effect of Plant-Based Natural Fibers on the Mechanical Properties and Volume Change of Cement Paste. *Int. J. Build. Pathol. Adapt.* **2025**, *43*, 693–711. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.