



Opuntia Ficus-Indica Fibers: Innovative Solution for Crack Mitigation and Optimization of Concrete Mechanical Properties

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Abstract: Plastic shrinkage cracking significantly compromises concrete durability. *Opuntia ficus-indica* fibers were evaluated as a sustainable reinforcement to mitigate early cracking and enhance mechanical performance. Concrete mixtures ($w/c = 0.50$) incorporated fiber dosages of 0.50, 0.75, and 1.0 kg/m³. Cracking evolution was monitored via a repeated-measures design at 1, 7, 14, and 28 days; compressive and flexural strengths were assessed at 7, 14, and 28 days. Findings identify 0.75 kg/m³ (EG₂) as the optimum dosage, completely suppressing new cracks after 14 days and reducing cumulative width (1.53 to 0.21 mm) and length (909 to 72 mm). At 28 days, this dosage achieved increments of 27.12% in compressive strength and 22.64% in flexural strength relative to the control. Dosages exceeding 0.75 kg/m³ exhibited attenuated gains. *Opuntia* fibers effectively control early cracking and optimize mechanical capacity, providing a renewable alternative for resilient infrastructure.

Keywords: Materials construction, mechanical properties, strength of materials, natural fibers, sustainability.

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1. Introduction

Concrete is the most widely used construction material globally due to its versatility, durability, and cost-effectiveness. While its extensive use in urban infrastructure underscores its adaptability, it also presents significant environmental challenges, such as high carbon emissions during production (Nilimaa, 2023). A primary mechanism of early deterioration in this material is plastic shrinkage cracking, which severely compromises structural durability (Zhan & He, 2019). This phenomenon stems from accelerated surface water loss, facilitating the penetration of aggressive agents and accelerating degradation (Branston et al., 2016).

The brittle behavior of concrete, characterized by high compressive strength but limited tensile strength, increases its susceptibility to dynamic loads (Bertelsen et al., 2020). Plastic shrinkage is further influenced by construction conditions, environmental factors, and material properties—particularly autogenous shrinkage during cement hydration (Song et al., 2024). To address these limitations, the incorporation of natural fibers into cementitious matrices has advanced due to their technical and economic advantages over synthetic alternatives (Achour et al., 2017; Vafaei et al., 2022).

Recent studies demonstrate that natural fibers enhance shrinkage resistance and optimize mechanical properties. For instance, an established correlation between polypropylene fiber dosage (0.1–0.5%) and shrinkage mitigation (Lilargem et al., 2022), provides a foundation for optimized mix design. Improvements in impact resistance have also been observed with basalt fibers (0.5–1%) and polypropylene macrofibers (Zhang et al., 2019).

Furthermore, research has integrated experimental and analytical methods to characterize hybrid basalt-polypropylene fiber-reinforced concrete (Fu et al., 2021). Parallel studies on bamboo fibers have shown 10–15% improvements in flexural strength alongside reduced cracking (Ahmad et al., 2023), while synergistic interactions between natural fibers and chemical activators have increased flexural strength by 46% in fly ash cement mortars (Jin & Han, 2024).

Natural fibers not only enhance mechanical performance but also contribute to sustainability, provided that proper treatment and dosing are implemented (Abdalla et al., 2023). Specifically, *Opuntia ficus-indica* fibers act as shrinkage reducers by inducing compressive pre-stresses in the matrix (Aghaee & Khayat, 2021; León-Martínez & Cano-Barrita, 2024). Although these fibers require pre-treatment to ensure durability in aggressive

environments (García et al., 2024), they have demonstrated significant potential to improve both mechanical and thermal resistance (Rajkohila & Chandar, 2024; Ren et al., 2021).

In Peru, plastic shrinkage poses critical technological challenges, particularly in regions with extreme freeze-thaw conditions. These environments cause surface cracking and reduce mechanical properties during curing, thereby increasing maintenance and rehabilitation costs. Consequently, this study evaluates the effectiveness of *Opuntia ficus-indica* fibers in mitigating plastic shrinkage cracking and enhancing mechanical properties. The experimental phase follows ASTM (2006c) for crack evaluation, ASTM C39 (2024) for compressive strength, and ASTM C78 (2022) for flexural strength. The hypothesis posits that these fibers reduce crack formation and propagation while improving toughness and energy absorption due to their high tensile strength.

This research aligns with the United Nations' Sustainable Development Goals 9 and 12 by promoting resilient infrastructure and sustainable production models. Unlike prior studies focusing on individual properties, this work provides a joint evaluation of plastic-shrinkage metrics (count, cumulative width, and length) under a repeated-measures design. The identification of an effective dosage (0.75 kg/m³) that suppresses new cracking after 14 days provides a new dose–response benchmark for *Opuntia ficus-indica* in cementitious matrices, clarifying its positioning among natural-fiber alternatives.

2. Materials and Methods

2.1 Materials

2.1.1 Cement, Water, and Natural Aggregates

Portland cement type IP was selected due to its workability and compatibility with the construction components. This hydraulic cement, composed of Portland clinker and pozzolana, possesses a specific gravity of 2.85 g/cm³, which was utilized for the precise proportioning of the cementitious matrix.

The water utilized in concrete and mortar production complied with the physicochemical parameters established by the Peruvian Technical Standard NTP 399.088 and ASTM (2022). These standards ensure the absence of contaminants—such as oils, acids, alkalis, salts, and organic matter—that could adversely affect mechanical performance or long-term durability.

Aggregates were sourced from the Vicho quarry (Cusco, Peru), located at an elevation of 3,400 ± 50 meters

above sea level. The natural fine aggregate (NFA) and natural coarse aggregate (NCA) met regulatory requirements regarding deleterious materials, soluble salts, and organic matter content. Furthermore, both aggregates satisfied technical specifications for gradation, density, absorption, sulfate resistance, and abrasion resistance, in accordance with ASTM (2023); ASTM (2003b); ASTM (2015a); ASTM (2025b); ASTM (2006a); ASTM (2006c).

2.1.2 *Opuntia Ficus-Indica* Fibers

Fibers were extracted from mature *Opuntia ficus-indica* cladodes using a mechanical-thermal process designed to preserve mechanical integrity and minimize impurities. As illustrated in Figure 1, wild cladodes were collected in the Sacred Valley of the Incas (Cusco, Peru). The extraction procedure involved removing the thorny pericarp through longitudinal cuts, followed by heat treatment in water at 90 °C for 20 min. Subsequently, a two-week maceration process was implemented to facilitate mucilage separation. The fibers were then isolated via mechanical crushing, washed with distilled water, and air-dried at room temperature for 10 h.

Mechanical characterization of the extracted fibers was conducted through standardized laboratory testing. Tensile strength and elongation properties were evaluated using 12 plant fiber samples, each weighing 2.14 g. Additionally, physical properties—including absorption, bulk density, and specific gravity—were determined using 15 representative specimens (2.35 g each) following standardized procedures.

2.2 Methods

The research architecture employs an experimental design to evaluate the influence of *Opuntia ficus-indica* fibers on plastic shrinkage cracking and the mechanical properties of concrete. Four experimental configurations

were established based on fiber volume fractions: a control group (EG₀) and three reinforced dosages: EG₁ (0.5 kg/m³), EG₂ (0.75 kg/m³), and EG₃ (1.0 kg/m³).

2.2.1 Properties of *Opuntia Ficus-Indica*

Opuntia ficus-indica fibers were obtained through a multi-stage process involving cladode harvesting, removal of the thorny pericarp, heat treatment, mechanical extraction, and final purification of residual impurities. These fibers exhibit an average tensile strength of 5.34 kgf and an elongation at break of 4.72%, indicating adequate ductility for cementitious integration. Water absorption averaged 35.59%, a characteristic that promotes internal curing by facilitating uniform water release during cement hydration (Sanjeevi et al., 2021). With a bulk density of 0.73 g/cm³ and a specific gravity of 1.18, these fibers allow for efficient integration without compromising structural performance or significantly increasing dead weight (Elfaleh et al., 2023; Kesikidou & Stefanidou, 2019).

2.2.2 Gradation of Aggregates

Gradation analysis of the aggregates, illustrated in Figure 2, reveals consistent particle size distributions. The NFA exhibits a grading curve ranging from 0.075 mm to 4.76 mm, strictly adhering to the upper and lower limits specified by ASTM (2003b). This compliance ensures optimal gradation, which enhances workability and cohesion within the concrete mixtures.

The NCA displays a particle size distribution between 4.76 mm and 50.8 mm, with a curve that aligns with the normative parameters for controlled gradation. The complementary nature of the NFA and NCA distributions ensures an effective combination for concrete production, where continuous particle size gradation improves packing efficiency and density within the cementitious matrix.

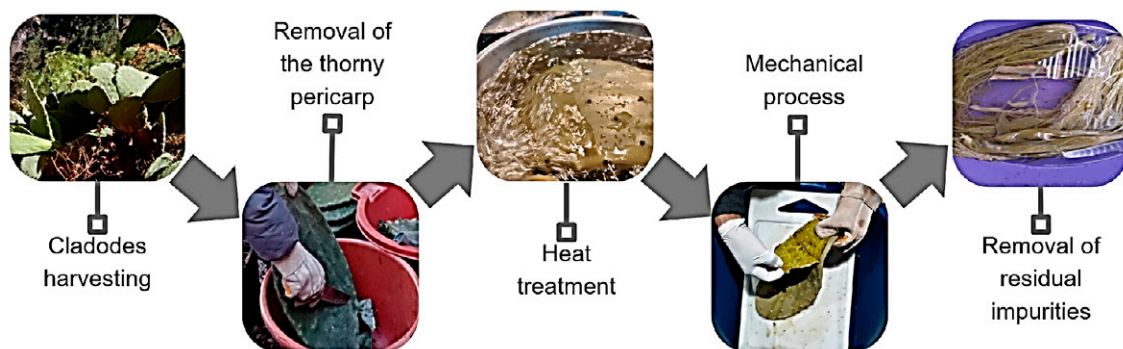


Figure 1. Extraction of *Opuntia ficus-indica* fibers.

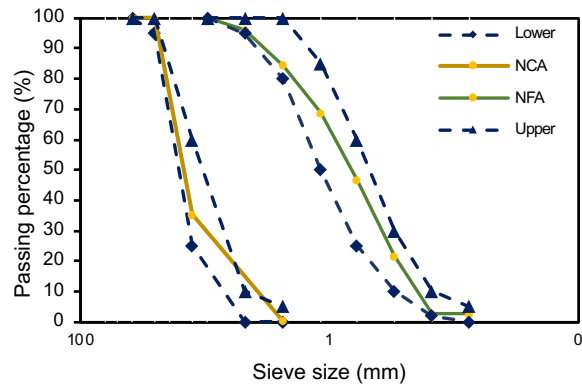


Figure 2. Particle size distribution of natural aggregates.

2.2.3 Aggregate Properties

NFA exhibited a moisture content of 0.6%, a density of 2,590 kg/m³, and a water absorption of 0.37%, with a fineness modulus of 2.8. Correspondingly, loose and compacted dry unit weights were 1,578 kg/m³ and 1,742 kg/m³, respectively. In comparison, NCA showed a moisture content of 0.34%, a density of 2,720 kg/m³, and a water absorption of 0.5%, with a nominal maximum size of 19.05 mm. Loose and compacted dry unit weights for the NCA were 1,402 kg/m³ and 1,550 kg/m³, respectively. Furthermore, the NCA demonstrated specific resistance values of 12.1% to magnesium sulfate and 23.7% to sodium sulfate, alongside an abrasion loss of 31.39%.

2.2.4 Design of Concrete Mixes

Concrete mixes were designed according to ACI 211 for severe exposure conditions (F1), with a target strength of 27.46 MPa. Chemical admixtures included Aimix 400 (air-entraining agent, 0.2 kg), Euco 37 (water-reducing agent, 3.3 kg), and Accelguard 100 (setting accelerator, 3.0 kg). Aggregates were graded by particle size before incorporation. The mixing process was conducted in a 0.25 m³ (9 ft³) rotary drum mixer for 5 min. Subsequently, *Opuntia ficus-indica* fibers were added in dosages ranging from 0.5 kg/m³ to 1.0 kg/m³, keeping all other components constant.

The aggregate distribution was optimized using 55.8% NCA (969 kg) and 44.2% NFA (731 kg) to maximize particle packing and mechanical performance. The base mix (EG₀) maintained a cement dosage of 367 kg, with a density of 2.85 g/cm³ and a water-cement (w/c) ratio of 0.50 (182 L of water). These parameters were uniformly applied across all experimental variations (EG₀ to EG₃). The systematic addition of chemical agents and the progressive fiber dosage (0 to 1.0 kg/m³) facilitated controlled workability, resulting in slump values between 81.28 mm

and 93.98 mm. Air content remained constant at 5% for all mixtures to ensure durability under freeze-thaw conditions (F1).

2.2.5 Specimen Preparation

To evaluate crack control, eight monolithic test panels (355 × 560 × 100 mm) were fabricated using 2.38 mm thick A36 grade hot-rolled carbon steel plate. Two panels were produced for each mixture group (EG₀–EG₃; n = 2 per group). Each panel incorporated two 32 ± 1 mm high restraints positioned 90 ± 2 mm from the edges, and a 63.5 ± 2 mm high central stress generator to promote controlled crack initiation.

Mold geometry, including nominal dimensions, tolerances, restraint locations, and crack-measurement points, is detailed in Figure 3a. Five ventilation chambers were constructed with cubic metallic frames (edge length ≈ 1 m), each with a capacity for two panels. During testing, four chambers operated simultaneously to host the four groups (EG₀–EG₃). Each chamber featured a base-mounted fan for upward unidirectional airflow, a monitoring pan and an evaporation-control pan (exposed surface area: 0.10 ± 0.01 m²), and sensors to monitor relative humidity (accuracy ± 1.0%) and air velocity (± 0.1 m/s). The sides and top were enclosed with transparent polypropylene sheets to ensure air containment.

The ventilation-chamber configuration, detailing airflow direction, support shelves, plastic covers, environmental sensors (located ≈ 1 m above the panels), and the evaporation-monitoring pan, is shown in Figure 3b. The panel tests followed a repeated-measures design; specifically, the same eight panels (two per group) were monitored at 1, 7, 14, and 28 days. No additional panels were fabricated for later ages, ensuring that the specimen count remained constant (n = 8). Consequently, temporal comparisons reflect only the effects of age and dosage on the same specimens.

2.2.6 Curing of Specimens

Panel specimens were subjected to curing periods of 1, 7, 14, and 28 days under controlled environmental conditions (36 ± 3 °C, 30 ± 10% relative humidity, and 4.7 m/s wind speed), in accordance with ASTM (2006b). Cylindrical and prismatic specimens were prepared following ASTM (2026). Additionally, core samples were extracted from cured material per ASTM (2006), while laboratory-prepared specimens complied with ASTM (2025). These specimens were cured under standardized conditions (23 ± 2 °C and 95 ± 2% relative humidity) until reaching the maximum testing age of 28 days.

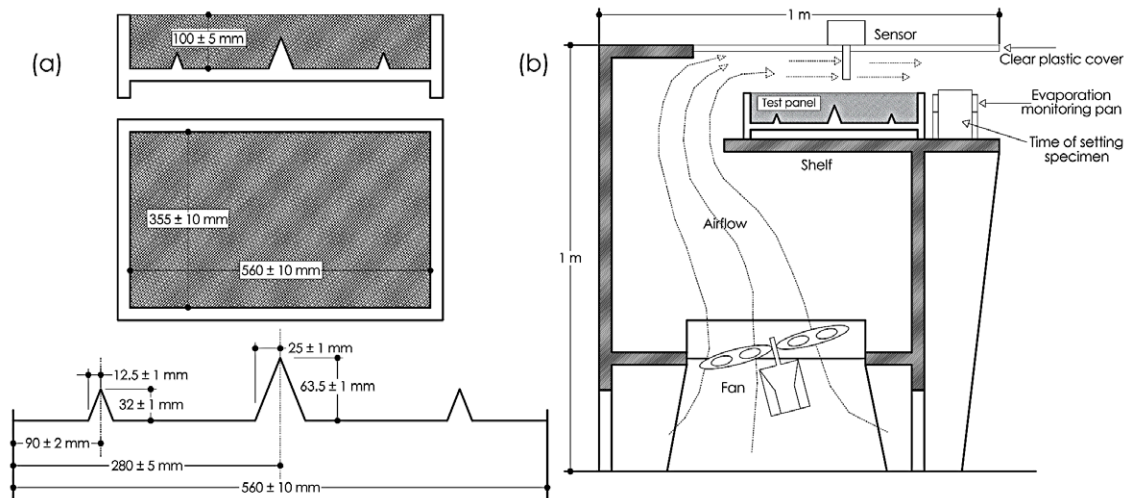


Figure 3. Mold geometry, including nominal dimensions, tolerances, and clamping locations (a). Ventilation chamber configuration showing airflow direction, sample holder, and evaporation control trays (b). Adapted from ASTM (2006b).

2.2.7 Crack Control (Time, Width, and Length)

Plastic shrinkage cracking was evaluated in accordance with ASTM (2006c). A systematic monitoring protocol was implemented, consisting of an initial inspection within the first 24 h (fresh state), followed by evaluations at 7, 14, and 28 days (hardened state). This schedule allowed for the documentation of crack evolution across the developmental stages of the concrete. Environmental conditions were monitored using calibrated instrumentation, including a digital anemometer, a thermohydrometer, and a digital thermometer. Crack width was measured via optical microscopy with a resolution of 0.05 mm, while crack length was determined using a digital caliper.

2.2.8 Compression and Flexural Strength Tests

Compressive strength was evaluated according to ASTM (2015a) using 152×305 mm cylinders cured for 7, 14, and 28 days. Tests were performed in a calibrated hydraulic machine at a loading rate of 0.25 ± 0.05 MPa/s until failure. Maximum load and failure patterns were recorded, and results are reported as the mean $\pm$ standard deviation (SD) of three specimens per group and age.

Flexural strength tests followed ASTM (2010) using $152 \times 152 \times 508$ mm beams under third-point loading. Specimens were seated using standardized protocols with a preload to ensure uniform contact, then loaded at 0.9–1.2 MPa/min until fracture occurred within the central third. Continuous load–displacement data were recorded, and results are presented as the mean $\pm$ SD of three specimens per group and age.

For mechanical characterization, a total of 96 specimens were cast (48 cylinders and 48 beams). For each mixture group and testing age, four specimens were produced: three were tested to determine average performance, while one was reserved as a backup.

3. Results and Discussion

3.1 Crack Control

3.1.1 Time of Crack Appearance

Data summarized in Table 1 characterize the temporal evolution of crack counts across the experimental groups. Observations at 1 day post-casting identified a total of 20 cracks, with the highest incidence in the control group ($EG_0 = 9$) compared to fiber-reinforced mixtures ($EG_1 = 4$, $EG_2 = 3$, $EG_3 = 4$). By day 7, the total count decreased to 17, reflecting a reduction in new crack formation across all dosages. A significant shift in performance occurred at 14 days, when total cracks dropped to 7; notably, dosages ≥ 0.75 kg/m³ (EG_2 and EG_3) achieved complete suppression of new cracking from this point forward. By the end of the 28-day evaluation period, the total count stabilized at 5 cracks, localized exclusively in EG_0 (4 units) and EG_1 (1 unit). While the control group maintained a dominant proportion of total cracks throughout the study—increasing from 45% at 1 day to 80% at 28 days—mixtures with higher fiber volume fractions demonstrated superior long-term stabilization of the cementitious matrix.

Table 1. Temporal distribution of crack counts

Mixture Groups	1 day		7 days		14 days		28 days	
	Unit	%	Unit	%	Unit	%	Unit	%
EG ₀	9	45	8	47.06	5	71.43	4	80
EG ₁	4	20	4	23.53	2	28.57	1	20
EG ₂	3	15	2	11.76	–	–	–	–
EG ₃	4	20	3	17.65	–	–	–	–
Totals	20	100	17	100	7	100	5	100

3.1.2 Width of Cracks

Data provided in Table 2 delineate the evolution of cumulative crack width across the evaluation period. Initial measurements at 1 day post-casting recorded a total cumulative width of 1.53 mm, with the control group accounting for 60.78% of the total (EG₀ = 0.93 mm). In contrast, fiber-reinforced mixtures exhibited significantly lower values, with EG₂ and EG₃ each contributing only 0.10 mm (6.54% each). By day 7, the total width decreased to 1.06 mm, where EG₀ and EG₁ showed reductions of 39.8% and 37.5%, respectively, while EG₃ experienced a marginal increase to 0.15 mm.

A substantial attenuation in cumulative width was observed at 14 days, falling to a total of 0.38 mm. At this stage, crack presence was completely eliminated in dosages ≥ 0.75 kg/m³ (EG₂ and EG₃), while EG₀ and EG₁ reduced their widths to 0.28 mm and 0.10 mm, respectively. By the conclusion of the 28-day period, the total cumulative width stabilized at 0.21 mm, localized in EG₀ (0.16 mm) and EG₁ (0.05 mm). These trends confirm that higher fiber volume fractions facilitate superior crack-bridging and shrinkage restraint, effectively neutralizing measurable crack widths in EG₂ and EG₃ from day 14 onward.

Table 2. Control of crack width.

Mixture Groups	1 day		7 days		14 days		28 days	
	mm	%	mm	%	mm	%	mm	%
EG ₀	.93	60.78	.56	52.83	.28	73.68	.16	76.19
EG ₁	.40	26.14	.25	23.58	.10	26.32	.05	23.81
EG ₂	.10	6.54	.10	9.43	–	–	–	–
EG ₃	.10	6.54	.15	14.15	–	–	–	–
Totals	1.53	100	1.06	100	.38	100	.21	100

3.1.3 Length of Cracks

Data summarized in Table 3 delineate the evolution of cumulative crack length across the testing period. Measurements at 1 day post-casting identified a total length

of 909 mm, with the control group representing 57.65% of the total (EG₀ = 524 mm) compared to fiber-reinforced mixtures (EG₁ = 175 mm, EG₂ = 109 mm, EG₃ = 101 mm). By day 7, a significant decline to a total of 260 mm occurred, reflecting an average reduction of 71.39% across all groups. At 14 days, the total length was measured at 115 mm, at which point crack propagation ceased in dosages ≥ 0.75 kg/m³ (EG₂ and EG₃). By the conclusion of the 28-day period, the total length reached 72 mm, localized in EG₀ (57 mm) and EG₁ (15 mm). These findings confirm a dosage-dependent mitigation of crack expansion through the incorporation of *Opuntia ficus-indica* fibers.

Table 3. Control of crack length.

Mixture Groups	1 day		7 days		14 days		28 days	
	mm	%	mm	%	mm	%	mm	%
EG ₀	524	57.65	160	61.54	68	59.13	57	79.17
EG ₁	175	19.25	35	13.46	47	40.87	15	20.83
EG ₂	109	11.99	35	13.46	–	–	–	–
EG ₃	101	11.11	30	11.54	–	–	–	–
Totals	909	100	260	100	115	100	72	100

The temporal evolution of cracking confirms a direct correlation between fiber volume fraction and mitigation efficiency. The complete suppression of new crack formation after 14 days in mixtures with dosages ≥ 0.75 kg/m³ (EG₂ and EG₃) aligns with the findings of Gamage et al. (2024), who reported shrinkage reductions between 5% and 30% using natural cellulose fibers. Such behavior supports the bridging and anchoring mechanisms characteristic of natural reinforcement, as documented by Ren et al. (2024).

The transition from macro- to micro-cracking upon *Opuntia* fiber addition is consistent with the observations of Huynh et al. (2023) regarding the influence of fiber geometry on crack control. Furthermore, the progressive reduction in cumulative crack width (from 1.53 to 0.21 mm) and length (from 909 to 72 mm) by day 28 indicates robust cracking restraint. These results exceed the performance reported for recycled plastic fibers at comparable volumes by Al-Alusi et al. (2024), highlighting the effectiveness of this natural reinforcement in cementitious matrices.

3.2 Compressive Strength

Compressive strength measurements at 7, 14, and 28 days are illustrated in Figure 4. A consistent upward trend in load capacity occurred across all experimental

groups as curing time progressed. In the control group (EG_0), strength values reached 22.01 ± 0.93 MPa, 23.89 ± 0.93 MPa, and 26.42 ± 0.72 MPa at the evaluated intervals. By comparison, fiber-reinforced mixtures exhibited enhanced performance, with EG_1 achieving 22.98 ± 0.86 MPa, 24.81 ± 1.07 MPa, and 28.67 ± 0.84 MPa. The peak mechanical response was identified in EG_2 (0.75 kg/m^3), recording 24.97 ± 0.83 MPa, 28.95 ± 0.56 MPa, and 33.58 ± 0.50 MPa. In EG_3 (1.0 kg/m^3), values were measured at 23.74 ± 0.87 MPa, 26.16 ± 1.03 MPa, and 29.21 ± 0.63 MPa. Overall, maximum strength values at 28 days ranged between 26.42 and 33.58 MPa.

The incorporation of *Opuntia* fibers significantly enhanced compressive strength (f'_c) relative to the control, with the optimum dosage established at 0.75 kg/m^3 (EG_2). The relative strength increments at 28 days reached 8.52% (EG_1), 27.12% (EG_2), and 10.56% (EG_3). The attenuation of gains observed at the 1.0 kg/m^3 dosage (EG_3) suggests potential fiber dispersion challenges or saturation effects within the cementitious matrix. Low standard deviations across all data points indicate high experimental repeatability and stringent quality control.

These increments are consistent with or superior to effects reported in the literature. For instance, Shi et al. (2020) reported a ~10% increase using hybrid fibers, while Amjad et al. (2023) and Michel et al. (2025) observed gains of 15.81% and 6%, respectively, with various natural fiber combinations. Similarly, Geremew et al. (2025) reported increases of 4.16% for wheat straw and 8.8% for bamboo. The enhancement in load capacity is attributed to the internal reinforcement and subsequent densification of the matrix. This mechanical optimization aligns with findings by Quispe-Vargas et al. (2026), confirming that controlled constituent management significantly improves bearing capacity compared to conventional concrete.

3.3 Flexural Strength

Flexural strength measurements at 7, 14, and 28 days are presented in Figure 5. In the control group (EG_0), recorded values reached 5.8 ± 0.14 MPa, 6.55 ± 0.22 MPa, and 7.11 ± 0.23 MPa at the evaluated intervals. Fiber-reinforced mixtures exhibited a superior flexural response, with EG_1 reaching 6.21 ± 0.21 MPa, 7.18 ± 0.47 MPa, and 7.69 ± 0.29 MPa. The peak performance was identified in EG_2 (0.75 kg/m^3), achieving 6.72 ± 0.22 MPa, 7.93 ± 0.39 MPa, and 8.72 ± 0.16 MPa. Conversely, EG_3 (1.0 kg/m^3) recorded values of 6.29 ± 0.23 MPa, 7.27 ± 0.44 MPa, and 7.77 ± 0.19 MPa. At the 28-day mark, flexural strength across all groups ranged between 7.11 and 8.72 MPa.

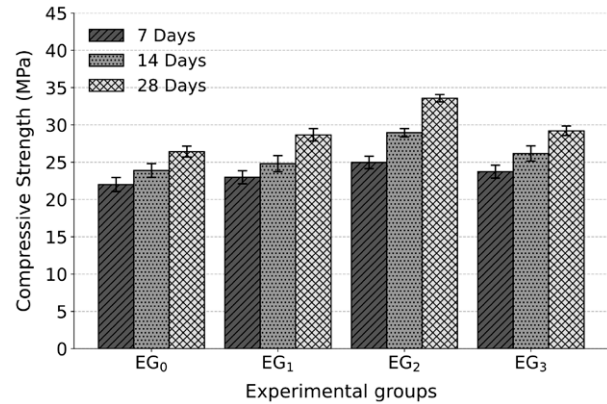


Figure 4. Compressive strength of concrete.

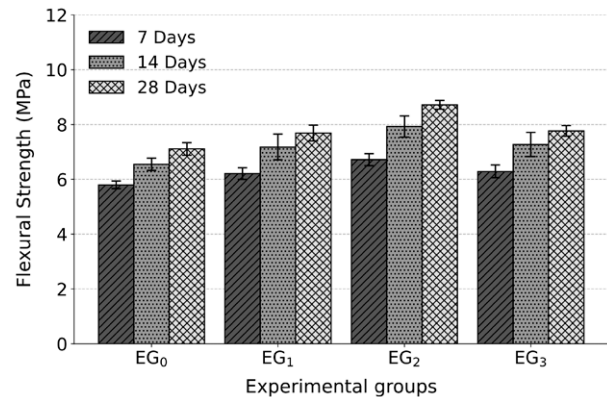


Figure 5. Flexural strength of concrete.

The flexural response improved concurrently with fiber content up to a threshold of 0.75 kg/m^3 (EG_2); however, the attenuated gains observed at 1.0 kg/m^3 (EG_3) indicate a practical upper limit for this reinforcement under the tested conditions. Regarding the modulus of rupture (Mr), EG_2 yielded the most significant increments—15.86%, 21.06%, and 22.64% at 7, 14, and 28 days, respectively—relative to EG_0 . These results are comparable to the findings of Shi et al. (2020), who reported gains exceeding 20%, and fall within the range observed by Rajkohila and Chandar (2024) for banana (54.49%) and coconut (47.96%) fibers. Additionally, these trends align with observations by Kurpińska et al. (2022) and Geremew et al. (2025), who reported improvements of 8% and 20.6% using ramie and wheat straw/bamboo combinations, respectively.

Variations in fiber type, processing, and curing conditions likely account for the differences in reported magnitudes. The enhanced flexural performance reinforces the viability of *Opuntia ficus-indica* as a sustainable reinforcing agent. Similar tendencies were documented

by Carrasco-Ahen and Monzon-Diaz (2025), demonstrating that the incorporation of recycled materials optimizes the toughness and tensile behavior of cementitious mixtures.

3.4 Statistical Analysis

Statistical significance was assessed across all experimental parameters. At each curing age, one-way analysis of variance (ANOVA) on groups EG_0 – EG_3 revealed that fiber dosage exerts a significant influence on crack-related metrics and mechanical strength ($p < .05$). These patterns, illustrated in Figures 4 and 5 via bar charts (mean $\pm$ SD), confirm significant inter-group variances ($p < .05$) in crack count, cumulative width, cumulative length, and compressive/flexural strength. Such data support a dose-dependent performance hierarchy, aligning with the observations reported by Bahja et al. (2021).

Evidence corroborates that *Opuntia ficus-indica* fibers constitute an effective, sustainable alternative for mitigating plastic-shrinkage cracking while enhancing mechanical properties, particularly at dosages ≥ 0.75 kg/m³. Nevertheless, vegetable fiber performance remains contingent upon alkaline durability within the Portland cement pore solution. The potential degradation of hemicellulose and lignin, followed by cellulose mineralization, may compromise tensile capacity and the fiber–matrix interfacial transition zone (ITZ) over time. Identified mitigation strategies include: (i) surface pretreatments to enhance mechanical interlocking; (ii) barrier coatings (e.g., silane-based) to inhibit alkaline hydrolysis; and (iii) binder optimization through supplementary cementitious materials (SCMs) to reduce $Ca(OH)_2$ concentrations.

Chemical and thermal data from *Opuntia* biocomposites (Alane et al., 2022) provide a basis for optimizing pretreatment selection. Furthermore, the behavior of black sugar palm fiber-reinforced concrete (Ferdiansyah & Abdul, 2011) contextualizes how natural fiber volume fractions govern matrix toughness and post-cracking response.

While findings are conclusive, the absence of SEM/EDS interfacial characterization and long-term alkalinity conditioning represents a scope for future inquiry. Subsequent research should integrate electron microscopy and accelerated aging protocols to quantify durability, alongside regression-based dose–response modeling. The 0.75 kg/m³ threshold serves as a practical benchmark for industrial-scale trials. Implementation necessitates standardized fiber preparation and dispersion protocols to prevent agglomeration. Priority applications target serviceability-governed elements, such as slabs and

overlays, whereas structural deployment requires further validation of fatigue resistance and long-term robustness under production-scale variability.

4. Conclusions

Evaluations of *Opuntia ficus-indica* fibers confirm their efficacy in mitigating plastic shrinkage cracking and enhancing the mechanical performance of concrete. Experimental data demonstrate that fiber incorporation is highly effective, particularly at dosages ≥ 0.75 kg/m³, where new crack formation was completely suppressed after 14 days. Throughout the 28-day evaluation period, progressive reductions in cumulative crack width (from 1.53 to 0.21 mm) and length (from 909 to 72 mm) occurred, validating the robust crack-bridging and shrinkage restraint mechanisms inherent to this natural reinforcement.

Mechanical performance improved consistently with curing age across all experimental groups. The 0.75 kg/m³ dosage (EG_2) yielded the highest measured strengths, achieving increments of 27.12% in compressive strength and 22.72% in flexural strength relative to the control group (EG_0) at 28 days. The attenuated strength gains observed at 1.0 kg/m³ (EG_3) indicate a practical performance plateau, suggesting that higher fiber volume fractions may lead to saturation effects or hindered compaction within the cementitious matrix.

While these findings highlight the potential for serviceability-governed elements, such as slabs and overlays, certain limitations persist. The absence of SEM/EDS microstructural evidence and long-term alkaline conditioning necessitates future integration of electron microscopy and accelerated aging protocols to quantify fiber–matrix adhesion and chemical durability. Furthermore, pilot-scale batching and regression-based dose–response modeling are required to assess robustness under production-scale variability and to refine the 0.75 kg/m³ benchmark.

Implementing this strategy aligns with sustainable construction paradigms by leveraging renewable, biodegradable fibers and reducing reliance on synthetic reinforcements. By fostering innovation in resilient infrastructure through local biomass utilization and circular economy models, these results contribute to United Nations Sustainable Development Goals 9 and 12. In regions where *Opuntia* is endemic, this technology offers a pragmatic and sustainable alternative for the construction industry, provided that standardized preparation and quality control protocols are rigorously implemented.

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Conflict of Interest

The authors declare they have no conflicts of interest to disclose.

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