Evaluation of the Mechanical Properties of Coconut-Fiber- and Plastic-Fiber-Reinforced Concrete

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ABSTRACT

The usage of natural and recycled fibers in order to reinforce concrete was driven by the search for sustainable building materials. This study performs a comparative evaluation of the mechanical behavior of concrete using coconut and Polyethylene Terephthalate (PET) fibers. The concrete is mixed and cured under consistent conditions and each fiber type is evaluated separately within the same standardized base mix formulation to eliminate design variables. The considered dosages (0.5% and 1% coconut and 2% PET) represent practical optimums, determined through workability limits and prior research with the same concrete formulation. A Control Mix (CM) (27.46 MPa, or approximately 280 kg/cm^2) was designed with fibers of different dosages acting as additional materials. The results suggest that coconut fibers are more effective than PET fibers as a reinforcing agent. Short Fibers (SFs) (100 mm) at a dosage of 1% exhibited the highest compressive strength, increasing it by 15.0%. In terms of flexural strength, Long coconut Fibers (LFs) (200 mm) at 1% were the most effective, increasing it by 13.7%. In contrast, PET fibers at 2% showed modest compression improvement (4.5%) and slight flexural strength reduction (–0.34%). The effectiveness of coconut fiber is due to its better adhesion to the cementitious matrix and its ability to act as a crack bridge, shifting the failure mode from brittle to cohesive with post-cracking structural integrity. These results show that coconut fiber can be used as a sustainable reinforcement material for nonstructural concrete applications and secondary elements.

Keywords-concrete; fiber-reinforced concrete; natural fibers; recycled PET; mechanical properties; sustainability; coconut fiber

I. INTRODUCTION

Concrete is the most widely used construction material, known for its high compressive strength and durability [1, 2]. However, its low tensile strength makes it prone to cracking [3, 4], so reinforcing steel or synthetic fibers are used, which are costly and have a significant environmental impact [5, 6]. Authors in [7-10] examined using natural fibers, whereas authors in [11-14] used recycled plastics, such as PET, and coconut fiber as more environmentally friendly reinforcement alternatives [15, 16]. Solid waste is an increasing environmental concern [17-19], with the Organization for Economic Cooperation and Development estimating that plastic waste could have tripled by 2060 [20]. PET is one of the most persistent polymers due to its low degradation rate [21, 22]. Conversely, coconut shells, which are abundant in tropical regions, generate large amounts of organic waste, much of which becomes an environmental liability [23, 24]. Reusing this waste in construction reduces emissions [25, 26], alleviates the burden on landfills, and promotes a circular economy [27].

Authors in [28] designed a concrete mixture with 2 kg/m³, 6 kg/m³, and 10 kg/m³ of recycled PET fibers and evaluated its compressive, flexural, and indirect tensile strengths. The 10 kg/m³ mixture performed better, showing a 39% increase in tenacity and a more stable and ductile response in flexural strength. However, it had a slight 9% decrease in compressive strength. Similarly, authors in [29] recorded compression and flexural strengths of 42.5 MPa and 7.0 MPa, respectively, after 28 days of using a mixture with 3.84 kg/m³ of PET fibers, surpassing the control mixture. Authors in [26] reviewed research on using PET in concrete, showing that the optimal addition range is between 0.2% and 1% PET, depending on whether it is used as a fiber or as a partial replacement for fine aggregates. Within this range, concrete exhibits increase in compressive strength ranging from 5% to 20%, improvements in indirect tensile strength ranging from 10% to 20%, and increases in flexural strength of up to 40% when some of the fine aggregate is replaced. However, when proportions exceeding 2% by volume or replacements greater than 10% of the aggregates are used, a progressive reduction in mechanical properties is observed. Additionally, all studies agree that using PET reduces concrete density due to plastic's lower specific gravity. Authors in [30] used industrial recycled PET fibers produced by extrusion that were 40 mm or 52 mm long and 0.7 mm or 1.1 mm in diameter. Using a dosage of 1%, they achieved an increase in compressive strength ranging from 22% to 35%, as well as significant improvements in initial crack resistance, ductility, and energy absorption capacity. Reinforcing concrete with coconut fiber significantly improves its mechanical properties. Authors in [31] conducted tests with fiber proportions between 0.5% and 2.0%, and fiber lengths ranging from 25 mm to 75 mm, concluding that the optimal mixture contained 1.5% fiber and 50 mm fiber lengths, resulting in 25% and 3% increases in compression and the modulus of rupture, respectively. Authors in [32] examined the usage of fibers of 2.5 cm, 5 cm, and 7.5 cm lengths into the mixture at proportions of 1%, 2%, 3%, and 5% relative to the cement weight, noting that the mixture with 5% fiber, 5 cm in length, achieved the best performance. Authors in [33] tested concrete by adding fibers ranging in length from 25 mm to 75 mm, some of which were treated with 1% NaOH for 30 min to improve adhesion. The researchers used coconut fiber percentages ranging from 0.5% to 2% relative to the weight of the cement. The results showed a 21% increase in compressive strength (the maximum reported) at 60 days. Authors in [34] showed that adding 3% fiber improved compressive and flexural strength, exceeding the standard sample of 23 MPa. Finally, authors in [35] included 40 mm LF in their mixture at 0.5% and 1% by weight of cement, showing that the mixture with 0.5% fiber had a 14.3% increase in compressive strength at 28 days. These variations in the literature, for both PET and coconut fiber, underscore the necessity of conducting comparative research under more suitable experimental conditions. This study's methodology was chosen in accordance with the United Nations' 2030 Agenda Sustainable Development Goals (SDGs) [36] (SDG9, SDG11, SDG 12, SDG 13), promoting alternative materials that improve sustainability in construction, proposing solutions that reduce the environmental impact of urbanization, using waste as a productive input, and reducing the carbon footprint of the concrete industry. The objective of this study was to compare the mechanical properties of concrete reinforced with coconut fiber and recycled PET by designing, manufacturing, and testing mixtures with different dosage levels. Through compression (ASTM C39) and flexural (ASTM C78) tests, the effectiveness of these materials as alternative reinforcements in structural concrete, was evaluated, allowing for an analysis of their technical and sustainable potential in construction applications.

II. MATERIALS AND METHODS

In this study, a comparative experimental approach was used to evaluate how incorporating natural (coconut) and synthetic (recycled PET) fibers, affects the mechanical properties of concrete. Two types of reinforcement were considered: chemically treated coconut fibers and recycled PET fibers in strips. The goal of this study is to provide sustainable solutions by using natural and recycled materials in the construction industry and developing more environmentally friendly and efficient concretes. The work was carried out in three stages: assessing the properties and characteristics of the materials, designing and mixing the reinforced concrete, and conducting strength tests, as shown in Figure 1.

Fig. 1. Research stages.

A. *Stage I: Assessing Material Properties and Characteristics*

Table I presents the characteristics of the conventional materials used in this study and the testing standards applied to evaluate them, whereas Table II describes the preparation, treatment, and incorporation state of the fibers used. Figure 2 depicts the material characterization.

TABLE I. CONVENTIONAL MATERIALS AND TEST STANDARDS

Material	Specification / source	Test standards
Cement	GU Portland (Holcim, Ecuador)	ASTM C150 [37]
Coarse aggregate	Local quarries	ASTM C127 [38], ASTM C136 [39], ASTM C29 [40], ASTM C566-19[41].
Fine aggregate	Local quarries	ASTM C128 [42], ASTM C136 [39], ASTM C29 [40], ASTM C566-19[41]
Water	Potable	ASTM C1602 [43]
Superplasticizer	Type F (Plastocrete DM Sika)	ASTM C-494 [44]

TABLE II. FIBER PREPARATION AND TREATMENT

Parameter	Coconut fiber	Recycled PET fiber
Source	Coconut husk	Recycled bottles
Preparation	Cut: 100 mm (short), 200 mm (long)	Cut into strips: 50 × 3 mm
Treatment	Ca $(OH)_2$ 10 g/L, 120 h, rinsed	Washed
State at incorporation	Moist	Dry

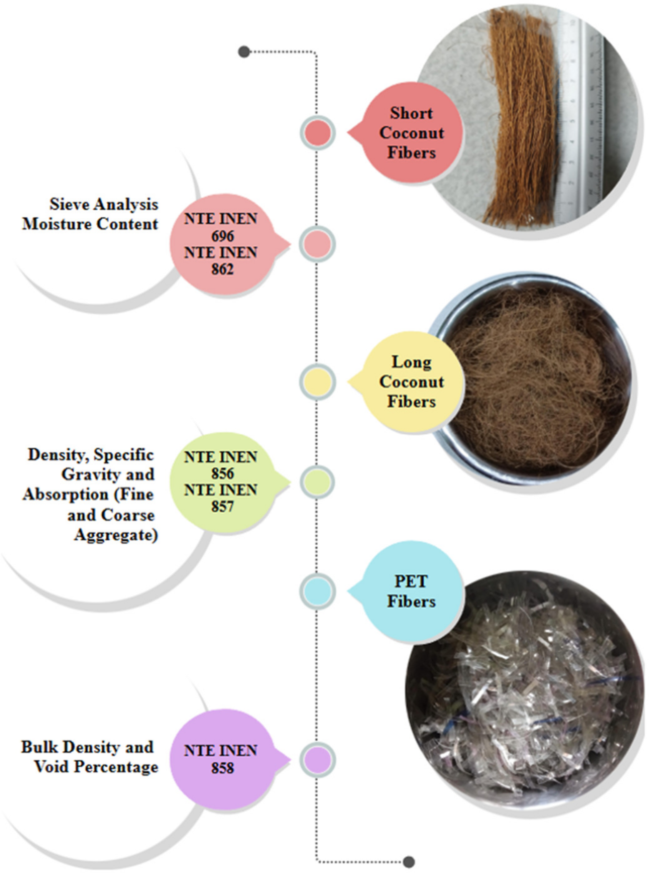

Fig. 2. Characterization of the materials and applied NTE INEN standards.

The coconut fibers underwent a chemical treatment involving a calcium hydroxide ($Ca(OH)_2$) solution at a concentration of 10 g/L for 120 h (5 days), followed by rinsing and oven drying for 24 h. The goal of this treatment was to reduce deterioration in the alkaline environment of concrete [45] and control interaction with the mixing water [13], thereby avoiding alterations in the water-cement ratio. A concentration of 10 g/L, used NaOH solutions at 1% by weight (approximately 10 g/L) to treat natural fibers [31, 32], adapting it to $Ca(OH)_2$ due to its lower aggressiveness and greater safety. The immersion time was determined based on preliminary tests with 2-, 5-, and 10-day periods (48-, 120-, and 240-h periods), and 5 days were selected as the treatment condition.

B. Stage II: Designing and Mixing Reinforced Concrete

The CM was designed according to ACI 211 [46] to have a strength of 27.46 MPa (approximately 280 kg/cm²), with the same dosage maintained in the reinforced variants. The experimental mixes were prepared with treated coconut fibers using 100 mm and 200 mm lengths (with the latter being the original uncut length) at percentages of 0.5% and 1%, relative to the cement weight and with 2% PET fibers. For this study, different dosages were selected for each fiber type based on two criteria. For PET fibers, the optimal dosage was selected based on [47], which used the same concrete base (cement, local aggregates, a water-to-cement ratio of 0.43, and a superplasticizer) to ensure methodological continuity. For coconut fiber, 1% was selected as the maximum viable dosage based on workability. Preliminary slump tests at a 1% dosage yielded values of approximately 40 mm. This reduction may be associated with the fibers' water absorption and their tendency to form mutual entanglements, which limited mixture flow. This differential approach (1% coconut fiber and 2% PET fiber) accounts for the distinct characteristics of each fiber while enabling a realistic comparison of their reinforcement potential within practical application ranges. Mixing was carried out in a concrete mixer: water with superplasticizer was added, followed by the first portion of coarse aggregate, cement, and sand that had been previously mixed with coconut fiber. After 90 sec, the remaining water was added, followed by the second portion of coarse aggregate. Mixing continued for 3 min-5 min until a homogeneous appearance was achieved.

C. Stage III: Resistance Tests

Cylinders measuring 150 mm × 300 mm were manufactured for compression tests, and prismatic beams measuring 150 mm × 150 mm × 500 mm were manufactured for flexural tests. The cylinder tests were performed in accordance with ASTM C39 [48] and INEN 1573 [49], and the beam tests were evaluated at 28 days using the three-point loading method according to ASTM C78 [50] and NTE INEN 2554 [51]. The results were then compared to those of the CM to analyze the influence of the fiber type and content on the mechanical behavior of concrete and to determine the technical feasibility of using it as an alternative reinforcement.

III. RESULTS

A. Stage I

The testing of the coarse aggregate indicated a nominal maximum size of 25.4 mm, a dry rodded unit weight of 1,377.81 kg/m³, a rodded unit weight of 1,546.72 kg/m³, a Saturated Surface-Dry (SSD) bulk specific gravity of 2,617.8 kg/m³, and an absorption of 1.94%. For the fine aggregate, the modulus of fineness was 2.05, with an SSD bulk specific gravity of 2,632 kg/m³, a dry rodded unit weight of 1,343 kg/m³, and an absorption rate of 2.61%. Finally, general use Portland cement (Holcim) was verified to meet all ASTM C150 requirements [37]. The water absorption of coconut fibers was measured according to ASTM D570 [52]. Treatment with $Ca(OH)_2$ significantly reduced this property, reaching a minimum of 31.83% after five days of curing, as shown in Table III. This period represents the optimal point of surface modification where removing soluble components reduces hydrophilicity without compromising fiber integrity, justifying the 120 h as treatment time.

TABLE III. WATER ABSORPTION OF COCONUT FIBERS WITH AND WITHOUT CHEMICAL TREATMENT

Fiber condition	Curing time with $Ca(OH)_2$	Water absorption (%)
Without chemical treatment	–	168.97
With chemical treatment	2 days	160.61
With chemical treatment	5 days	31.83
With chemical treatment	10 days	47.34

B. Stage II

The CM design for 1 m^3 of concrete (with a target strength of 280 kg/cm², equivalent to 27.46 MPa) was: 469.92 kg of cement, 1,098.11 kg of coarse aggregate, 557.27 kg of fine aggregate, 192.0 kg of water, and 1.99 kg of superplasticizer additive. This resulted in a water-to-cement ratio of 0.43 and a slump of 100 mm. This base dosage remained constant for all reinforced mixtures with fibers added as a non-replacing admixture. For the compressive strength tests, the coconut fiber mixtures were prepared in two series, resulting in a total of four cylinders per testing age (3 days, 7 days, and 28 days). PET mixtures and the CM were prepared in a single series with two cylinders per testing age. For the flexural tests, three beams were prepared for all mixtures at 28 days. The fibers were added as an extra material at percentages relative to the cement's weight. PET fibers were used at a dosage of 2% (0.88 kg), and two types of coconut fibers were used: short (SF, 10 cm) at a dosage of 1% (0.44 kg) and long (LF, 20 cm) at a dosage of 0.5% (0.22 kg). The workability of the mixtures decreased progressively with fiber incorporation; higher fiber content resulted in lower workability.

C. Stage III

Prior to mechanical strength testing, the specimens were cured according to ASTM C192 [53] under constant curing conditions. Compressive strength development was evaluated at 3 days and 7 days for quality control purposes. A definitive comparative evaluation was performed at 28 days in accordance with NTE INEN 1573 [49]. Flexural strength was evaluated using three specimens for all mixtures at 28 days, as established in NTE INEN 2554 [51]. The number of replicates per mixture was determined considering the study's exploratory and comparative nature: n = 4 for coconut fiber mixtures and n = 2 for PET fiber mixtures for compressive strength at each age and n = 3 for flexural strength. While this sample size allows identification of trends and representative percentage change magnitudes, it limits inferential statistical analysis. Therefore, the results should be considered as observed trends rather than statistically robust design values. This approach is common in initial studies of unconventional materials, where the objective is to assess feasibility before scaling up to more extensive testing. The average compressive and flexural strengths were calculated from tests conducted on corresponding specimens at 3 days, 7 days, and 28 days for each coconut- and PET-fiber-reinforced concrete mix. The values were then compared with those of the CM.

1) Compression Test

Table IV presents compressive strength development at early ages (3 days and 7 days). The values shown are the averages of the strength tests performed on each mixture, showing strength development consistent with that expected for concrete. The 28-day compressive strength results showed different behavior depending on the type and dosage of the fiber used in the CM, which had a compressive strength of 27.46 MPa (equivalent to 280 kg/cm²). Figure 3 displays the compressive strength values for all the mixtures that were evaluated, with the dashed horizontal line presenting the design strength that corresponds to the control mix.

TABLE IV. EARLY-AGE COMPRESSIVE STRENGTH (MPA)

Mixture	3 days (avg)	7 days (avg)
CM	12.06	17.85
2% PET	14.81	20.50
0.5% LF	7.26	14.91
1% LF	14.02	17.36
0.5% SF	12.26	15.99
1% SF	17.26	23.05

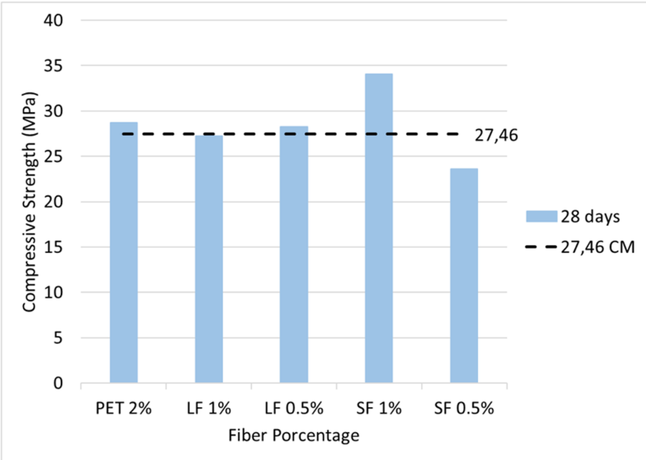

Fig. 3. Compressive strength at 28 days.

The mixture with 1% short coconut fiber (SF 1%) exhibited the greatest strength increase (+15.0%), which may indicate improved interfacial interaction and more effective stress transfer. The long coconut fiber at 0.5% (LF 0.5%) showed a slight increase of 3.0%, while the 1% long coconut fiber (LF 1%) remained close to the control value of -0.7%, and the 0.5% short coconut fiber (SF 0.5%) showed a notable reduction of -13.9%. Concrete with 2% PET fiber achieved a strength equivalent to 4.5% of the control mix. Figure 4 shows that the failure mode changed from brittle (the standard) to greater cohesion and residual strength in the reinforced mixtures. After initial cracking, the coconut fibers were particularly effective in bridging cracks and preventing the complete separation of fragments, suggesting an improvement in the composite's post-cracking behavior. The observed failure mode changed significantly between the CM and the fiber-reinforced mixtures.

(a) (b) (c)

Fig. 4. Cylinders after the compression test: (a) CM- brittle fracture, (b) PET mix - partially cohesive fragments, (c) coconut mix - structural integrity.

2) Flexural Test

The 1% LF mixture had the highest strength, increasing by 13.7% compared to the CM. Next was 0.5% LF, improving by +5.48%, followed by 1% SF, improving by +10.27%. In contrast, the mixture with 0.5% SF showed a moderate improvement of 1.71%, while the mixture with 2% PET showed a slight decrease of –0.34%. Figure 5 illustrates these results, where the dashed horizontal line represents the average strength of the CM (6.49 MPa).

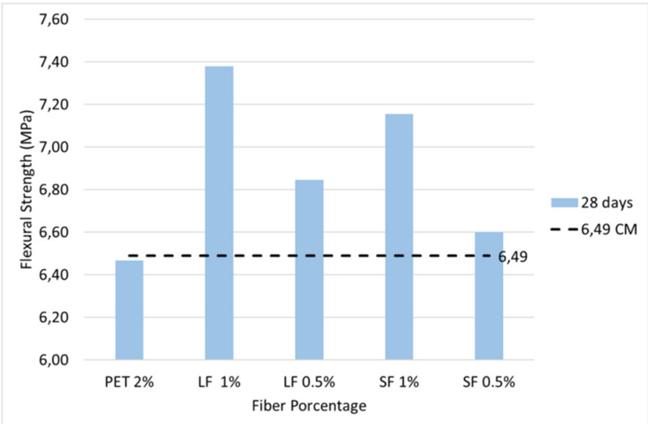

Fig. 5. Flexural strength (modulus of rupture) at 28 days.

As portrayed in Figure 6, the results confirm the effectiveness of coconut fibers, particularly the 1% LF, in improving the flexural strength of concrete. Table V summarizes the percentage changes in mechanical performance (compression and flexure) for each fiber-reinforced mixture compared to the CM.

TABLE V. MECHANICAL PERFORMANCE CHANGE AT 28 DAYS RELATIVE TO CONTROL MIX

Mixture	Compressive strength change (%)	Flexural strength change (%)
SF 0.5%	−13.9	+1.7
SF 1%	+15.0	+10.3
LF 0.5%	+3.0	+5.5
LF 1%	−0.7	+13.7
PET 2%	+4.5	−0.3

(a)

(b)

(c)

Fig. 6. Beams after the flexural test: (a) CM, (b) PET mix, (c) coconut mix.

IV. DISCUSSION AND CONCLUSIONS

The results of this study, when analyzed as representative trends and percentage changes, suggest that the nature and morphology of fibers influence concrete's mechanical performance. Adding coconut fibers, in particular, had a more favorable effect on compressive and flexural strength than adding recycled Polyethylene Terephthalate (PET) fibers. This is consistent with the change in failure mode, which shifted from brittle in the Control Mix (CM) to remarkable cohesion and crack-bridging capacity in the coconut fiber mixtures, suggesting a significant improvement in post-cracking structural integrity. This behavior is associated with the coconut fibers' rough surface and better adhesion to the cementitious matrix.

In terms of compressive strength, 1% short coconut fiber/Short Fiber (SF) produced the greatest increase (15.0%) compared to the CM. Concrete with 2% PET, on the other hand, showed a moderate improvement of 4.5%. Regarding flexural strength, concrete with coconut fibers exhibited superior performance. The mixture with 1% Long Fibers (LFs) exhibited the best performance with an increase of 13.7%, followed by 0.5% LFs (5.5%) and 1% SFs (10.3%). The effectiveness of LFs in improving flexural behavior aligns with the finding that longer fibers improve material performance. The consistent superior performance of LF (20 cm) over SF (10 cm) in flexure suggests that a longer fiber length is more effective in bridging cracks and redistributing stresses for this property. In contrast, the strength of the 2% PET mix did not exceed that of the CM (-0.3%), which differs from the results of [30], which report improvements in flexural strength with PET, using 40 mm industrial fibers and a dosage of 1%. This discrepancy could be explained by the geometry and nature of this study's fibers (manually cut 50 mm strips versus extruded fibers), as these factors affect anchoring and adhesion. The high internal friction of coconut and its ability to bridge cracks favor the material's ductility and post-cracking behavior, as reported in [54], which reinforced concrete with vegetable fibers. Overall, coconut fiber showed superior performance compared to PET under the experimental conditions of this study. The results suggest that 1% SF is optimal for compression and 1% LF is the best for flexure. PET offers advantages in durability and recyclability; however, its structural effectiveness depends on fiber dispersion and geometric optimization. These findings, when considered trends, support the potential of natural fibers and justify future large-scale research, including statistical analyses and long-term durability studies. The results provide preliminary evidence that coconut fiber has potential as a sustainable reinforcement material. PET, which has very low water absorption, was dosed at 2%. However, coconut fiber treated with $Ca(OH)_2$ presents water absorption problems at dosages above 1%, compromising workability. Thus, the selected dosages (1% coconut fiber and 2% PET) represent the optimal practical range for each material and allow for an evaluation of their true reinforcement potential. Future studies should examine fiber treatments that enable higher dosages without compromising workability.

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