Waste Polyethylene Reinforced with Coconut Fibers for Sustainable Construction: A Mechanical and Physical Property Evaluation Study

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ABSTRACT

This study evaluates the feasibility of using waste polyethylene as a construction material. To achieve this, a series of polymer composites were developed using waste Low-Density Polyethylene (LDPE) reinforced with coconut fiber (coir). The mechanical properties, including the tensile strength, flexural strength, impact strength, and elastic modulus, were assessed, along with the water absorption as a key physical property by following the ASTM standards. The composites were fabricated using the hand layup technique with varying coir-to-LDPE weight ratios and fiber lengths, followed by a hot-press machine manufacturing under controlled conditions. The results demonstrated that different fiber lengths and content levels influenced the mechanical properties, optimizing them at various configurations. A maximum tensile strength of 12.56 MPa was achieved using 40% coir content with 4 cm fiber length. The highest elastic modulus value of 0.46 GPa was achieved at 50% fiber content with 4 cm fibers. At 30% fiber content with 3 cm length, the maximum flexural strength value of 33.77 MPa was obtained. The impact strength reached its maximum value of 1.22 kJ/m² with 40% fiber content and 2 cm fiber length. The high water absorption exhibited by the composites, can be mitigated by applying waterproofing chemicals immediately after fabrication. It was found that the integration of fiber content and length affects the composite's properties. Depending on the required characteristics, appropriate fiber lengths and mix proportions can be selected, making these composites suitable for various applications in the construction industry. Additionally, proper waterproofing immediately after manufacturing the composite is proposed to enhance its performance as a construction material.

Keywords-waste polyethylene; coconut fiber; polymer composite; construction material; mechanical properties; physical properties

I. INTRODUCTION

Polyethylene is extensively utilized in different industries due to its lightweight and flexible behavior [1]. Humans and industries use polyethylene for different activities, and as a result, a considerable amount of waste polyethylene gathers daily in many countries. The traditional methods deployed to dispose of this polyethylene waste is landfilling and open burning, which create many environmental impacts and health issues due to polyethylene's non-biodegradable nature and the emission of hazardous air during burning. Therefore, different attempts have been made to solve these issues by reusing, reproducing, and recycling [2]. Another way to address these challenges is to replace decomposed plastics with alternatives that reduce plastic waste while having less of an adverse effect on the environment. In this context, reusing waste polyethylene as an alternative material in the construction industry is significant. The market share of natural lignocellulosic fiber has grown in many segments, such as packaging, furniture, building, and the automobile industries [3, 4]. Their low cost, environmental effect, and technical benefits over synthetic fiber have contributed to this growing trend [5]. Moreover, since they are readily available in a fibrous form and can be extracted at considerably low costs, they seem to be a promising alternative [6]. For these reasons, natural fibers are trusted over regular fibers. Among several natural fibers, coconut fiber has been given excessive attention due to its low bulk density and thermal conductivity. Compared to other natural fibers, coir fiber has a better lignin content with values between 41 and 45%, and a microfibrillar angle between 30 and 45 degrees, but lower cellulose with a percentage between 36 and 43%, and a hemicellulose value at 0.2% [7, 9]. Coir is a versatile lignocellulosic material that comprises hemicellulose and lignin as bonding materials [9, 10], which causes their relatively low elastic modulus, tensile strength, and elongation at break compared with other natural fibers. Despite these properties, yarn, rope, and mats traditionally use coir fiber [9, 11, 12]. In addition, the coir fiber could be used as an acoustic and thermal insulation material.

As an alternative to the synthetic fiber-reinforced composites, the development of coir fiber-reinforced composites is more significant in terms of energy and the environment [13-16]. Such composites have several benefits, including enhanced thermal and mechanical properties [17]. Thus, coconut fiber has often been used as a reinforcement material when developing polymer composites. The performance of Fiber-Reinforced Polymer Composites (FRPCs) strongly depends on the fiber content, length, and interfacial bonding between the fiber and the matrix material [18-22]. Defects, such as cavities and poor fiber alignment, can reduce the strength, while the water absorption through capillary action can degrade composites by causing fiber swelling and weakening of the fiber-matrix interface [23]. Despite the extensive research on FRPCs using different fibers and matrices, limited work has been carried out on composites developed with waste LDPE as the matrix and coir fiber as reinforcement.

Therefore, the current study investigates the potential of using waste LDPE reinforced with coir fiber to produce polymer composites suitable for construction applications. It additionally focuses on evaluating the influence of the fiber content and length on the mechanical properties of the composites, as well as their water absorption behavior, in order to assess the serviceability and practical applicability.

II. MATERIALS AND METHODS

Coir fiber served as the reinforcement, while waste LDPE was used as the matrix material and was collected from Rapid Creations (Pvt) Ltd., one of the largest polyethylene bag manufacturers in Colombo, Sri Lanka. This factory generates a considerable quantity of polyethylene waste during production, which was repurposed for this study. Coir fiber, obtained from coconut husks that are abundantly available in Sri Lanka after harvesting, was sourced from a local supplier in Colombo. To ensure consistency, all raw materials were collected in advance and stored under controlled conditions, minimizing the property variations throughout the study. Coir fiber is recognized for its durability, primarily due to its high lignin content, which provides longer lifespan compared to other natural fibers [24, 25]. It also exhibits superior resistance to moisture and salt compared to many other natural reinforcements [26]. Additional advantages include the resistance to fungal attack, biodegradation, and corrosion, as well as the favorable thermal and acoustic insulation properties [27]. These benefits, as well as the hardness, the non-toxic nature, and the resistance to microbial degradation, increase the coir fiber demand across various industries. Coir fiber also features low bulk density and thermal conductivity, making it particularly suitable for lightweight composite applications. LDPE, being a thermoplastic, undergoes reversible physical changes when exposed to heat [28] and is characterized by its high impact strength and recyclability, making it a sustainable choice for composite development [29].

A. *Preparation of Raw Materials*

Waste LDPE was first washed in potable water with washing powder to remove the contaminants and unwanted materials. It was dried at room temperature, and then it was shredded into small particles (Figure 1(a)). Coir fiber, purchased from a local supplier, was cut into five different lengths: 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm. The fibers were cleaned to remove the foreign particles and surface pith, followed by natural drying at room temperature (Figure 1(b)). To eliminate the residual moisture, the fibers were oven-dried at 50°C for 10-12 min.

B. *Preparation of Composite Samples*

Composite samples were fabricated by varying the fiber and LDPE weight ratios. The fiber content ranged from 10% to 50% at 10% increments for each fiber length (Table I). Then the hand lay-up method was used to prepare the samples. The shredded LDPE and cut fibers were carefully layered in a mold to ensure uniform distribution, and a hot press was then applied at 140 °C and 4 MPa for 6 min, followed by cooling. The resulting composite sheets were later cut and prepared for mechanical and physical testing according to ASTM standards.


(a) (b)

Fig. 1. Raw materials: (a) shredded polythene, (b) coir in different lengths.

TABLE I. MIX PROPORTIONS OF THE COMPOSITE SAMPLES

Sample no.	Coir wt. (%)	LDPE wt. (%)
A(i,j)	10	90
B(i,j)	20	80
C(i,j)	30	70
D(i,j)	40	60
E(i,j)	50	50

In Table I, i is the coir length in cm, with values from 1 to 5 with step 1, and j is the sample number with values from 1 to 7 with step 1. For example A(2,3) represent the 2 cm coir length 3rd sample .

C. *Experimental Procedure*

The mechanical and physical properties of the composites were evaluated for different fiber lengths and fiber weight percentages, according to the relevant standards Table II, where a is the number of the samples used for one set, b is the fiber length, and c is the coir weight percentage with values between 10 and 50% with step 10.

TABLE II. DETAILS OF THE PREPARED SAMPLES

Test	Sample sizes (mm)	Total number of samples N = a x b x c	Standards
Tensile	250×25×2.5	a=7, b=5, c= 5 (N= 175)	ASTM D3039 [30]
Flexural test	150×12.5× 3.2	a=6, b=5, c= 5 (N= 150)	ASTM D790 [31]
Impact	110×12.5× 3.0	a=5, b=5, c= 5 (N= 125)	ASTM D256 [32]

D. *Water Absorption Test*

Water absorption was measured according to [33]. Specimens were cut into bar shapes with dimensions of 76.2 × 25.4 × 3.2 mm, using a slow cutting speed to avoid overheating during sawing, and the edges were polished with fine sandpaper to ensure smooth, crack-free surfaces.

For each mix percentage at 3 cm fiber length, three specimens were tested. All samples were oven-dried at 50°C for 24 h, then conditioned in a desiccator, and subsequently they were fully immersed in distilled water at room temperature. At regular intervals, 24 h and beyond, the samples were removed, surface-dried with a cloth, weighed with a precision of three decimal places in grams, and returned to the water. Measurements continued until a stable weight was achieved. The water absorption (%) was calculated as the percentage weight gain relative to the dry weight.

Two sets of water absorption tests were carried out: Samples without waterproofing treatment and samples with waterproofing were applied to the cut edges. This comparison aimed to determine the influence of waterproofing on the water absorption and propose suitable measures to minimize the moisture uptake in the composites.

III. RESULTS AND DISCUSSION

A. *Tensile Strength*

The tensile strength tests were conducted according to ASTM standards and the results showed that the tensile strength initially increased with the fiber length but began to decrease beyond a certain point (Figure 2). The optimum performance was observed at a fiber length of 4 cm. At 40% fiber content, the maximum tensile strength reached 12.56 N/mm², while a similar trend was evident for 30% - 50% fiber content, where 4 cm also gave the highest values. Further increases in fiber length beyond 4 cm resulted in a reduction in the tensile strength. These findings indicate that the critical fiber length for achieving optimum tensile performance is 4 cm, particularly at 40% fiber content.

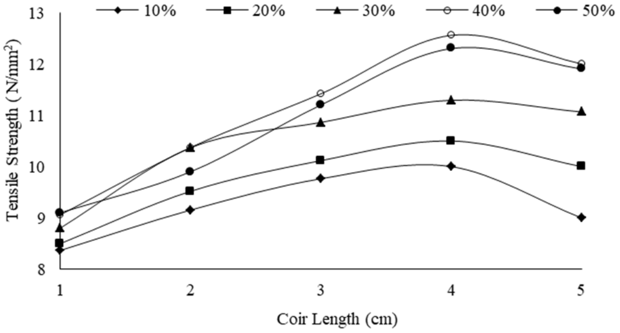

Fig. 2. Tensile strength variation with fiber length.

This variation can be explained by the interfacial bonding between the coir fibers and the LDPE matrix. As highlighted in [34], the transfer of load across the fiber-matrix interface plays a crucial role in determining the mechanical properties of the composites. At higher fiber contents, fiber agglomeration tends to occur, leaving insufficient matrix material between adjacent fibers, reducing the ability of the fibers to bond effectively with the matrix, thereby limiting the load transfer. As the fiber-fiber interaction increases, the likelihood of slippage or premature failure also rises [34].

The Scanning Electron Microscopy (SEM) images provide further insights into this behavior. Two cases occurred: Fiber detached from the matrix (Figure 3(a)) and fiber pull-out under applied loading (Figure 3(b)). These observations confirm the poor dispersion of the matrix within the fiber structure and demonstrate that the inadequate adhesion between the fiber and the matrix leads to weak interfacial bonding, which in turn dominates the failure mechanism of the composites.

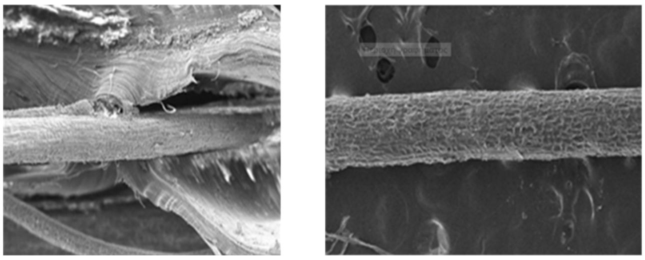
(a) (b)

Fig. 3. SEM images of the fractured surface: (a) fiber detached from the matrix, (b) fiber pull-out.

B. Elastic Modulus

The effect of the fiber length and fiber content on the elastic modulus of the composites was examined (Figure 4). The results show that the elastic modulus increased with a fiber length up to 4 cm, after which it declined with further increases, a trend that was observed in composites with lower fiber contents too, which exhibited lower elastic modulus values compared to those with higher fiber contents. The highest elastic modulus, 0.46 GPa, was achieved at a fiber length of 4 cm and 50% fiber content. These findings confirm that both the fiber length and fiber content play a significant role in determining the stiffness of the composites.

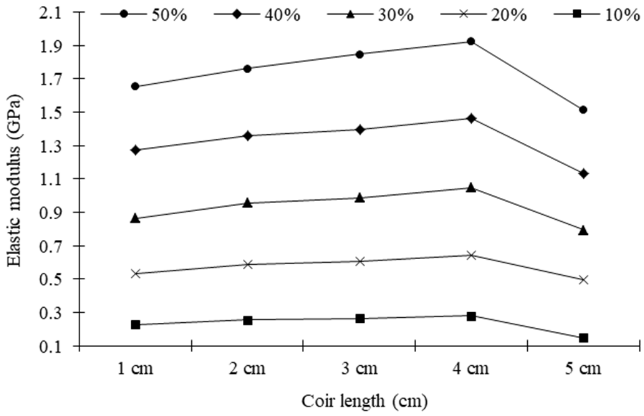

Fig. 4. Variation of elastic modulus with fiber length, at different weight percentages.

C. Flexural Strength

The influence of the fiber length and fiber content on the flexural strength of the coir fiber–reinforced polymer composites was also tested (Figure 5), and the results showed that the flexural strength increased with a fiber content up to 30%, reaching the maximum value of 33.77 MPa at a fiber length of 3 cm , after which it declined. This reduction at higher fiber contents is attributed to the poor interfacial bonding caused by the fiber agglomeration [35].

D. Impact Strength

The impact strength of FRPCs is determined mainly by the quality of the fiber-matrix interfacial bonding, as well as the type of fiber and polymer used [35]. Fibers contribute to the energy absorption, and this ability generally increases with the fiber content [36], however at higher fiber contents, poor interfacial bonding and fiber agglomeration can occur, leading to slippage between the fibers under impact loading and, consequently, a reduction in the absorbed energy. The results (Figure 6) of the test for the impact strength in relation to the fiber length and fiber content show that the impact strength increased with a fiber content up to 40%, after which it declined. The maximum value of 1.22 kJ/m² was obtained at 40% fiber content with a 2 cm fiber length. Considering all experimental outcomes, it is clear that the fiber length significantly influenced the tensile, flexural, and impact strength.

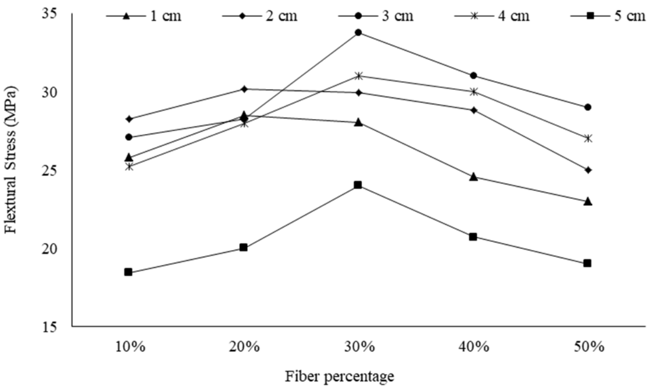

Fig. 5. Flexural strength variation with fiber percentage, at different fiber lengths.

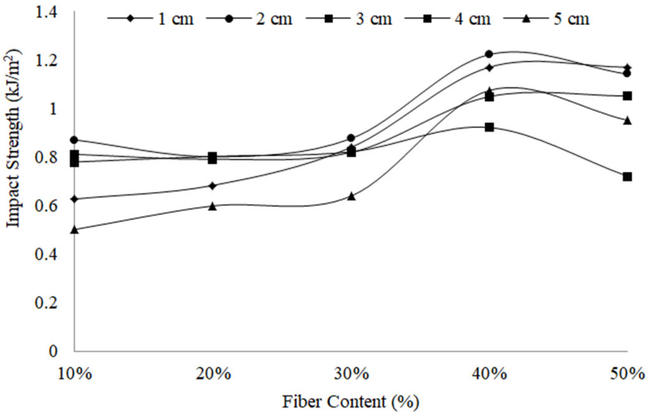

Fig. 6. Variation in impact strength of composites.

E. Critical Fiber Length

Authors in [37] explained that the load transfer capability of a fiber-reinforced polymer composite depends both on the inherent properties of the fiber and on the efficiency of the load transfer from the matrix to the fibers. The load transmission occurs through interfacial bonding, but this bond tends to weaken at the fiber ends, producing localized matrix deformation (Figure 7) indicating that no load is transferred at the fiber edges.

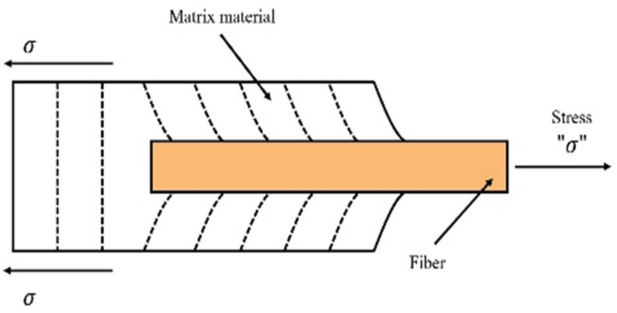

Fig. 7. Deformation of matrix material surrounding a fiber under the tensile force.

The concept of critical fiber length (l_c), derived from the rule of mixtures, defines the minimum length required for effective reinforcement and it is expressed by:

$$lc = \frac{\sigma^* d}{2\tau_c} \quad (1)$$

where σ^* is the ultimate tensile strength of the fiber, d is the fiber diameter, and τ_c is the interfacial shear strength between the fiber and the matrix.

Even though authors in [34] theoretically described the role of fiber in load transfer, the experimental validation remains essential. As shown in [37], when testing pineapple leaf fiber-polypropylene composites the theoretical predictions did not align with the experimental results. This discrepancy was attributed to factors, such as unidirectional fiber alignment and difficulties in achieving a uniform fiber distribution in practice. Therefore, experimental approaches are proposed to determine the critical fiber length and its effect on the mechanical properties [37].

Several researchers have studied the mechanical performance of composites using different fibers and matrix materials, and a number of representative results point to the existence of trends comparable to those of the current study (Table III). For instance, authors in [38] reported similar outcomes when using coir fiber with a different matrix, showing a consistent behavior in the tensile and flexural properties. However, a noticeable difference was observed in the impact resistance, suggesting that the matrix type significantly affects the impact performance. Further research is proposed to explore this relationship in greater detail.

TABLE III. MECHANICAL PROPERTIES OF DIFFERENT FIBER-REINFORCED POLYMER COMPOSITES

Composite material				Mechanical properties				Source
Fiber type	**Matrix material**	**Fiber length (mm)**	**Fiber content in wt. (%)**	**Max. tensile strength (MPa)**	**Max. elastic modulus (GPa)**	**Max. flexural strength (MPa)**	**Impact energy (KJ/m2)**	
Coir fiber	epoxy	12	15 %	24.71		29.43	13.54	[19]
		15	20 %		2.27			[19]
Banana	Epox (LY556)	5	12 %	16.39	0.652		2.23	[39, 40]
Oil palm fiber	Epoxy		30 %		1.342			[41]
Sisal fiber			20 %			22.3		
Coir fiber	Epoxy LY 556	30	30 %	13.05	2.064	35.42	17.5	[38]
Pineapple leaf fiber	Polypropylene		10.8 % by volume	37.28				[37]
Experimental results								
Coir fiber	Waste LDPE	40	40%	12.56				
		40	50%	12.00	0.46			
		30	30%	10.80	1.00	33.77	0.78	
		20	40%				1.22	

F. *Water Absorption*

The results of the water absorption tests indicated relatively low weight gain percentages across all composite samples, regardless of fiber content (Figure 8). This behavior can be attributed to the hydrophobic characteristics of both the coir fiber [42] and LDPE, which resist the water penetration. However, the composites with higher fiber loadings exhibited greater water absorption compared to those with lower fiber contents.

Among the tested samples, the composite containing 40 wt.% fiber exhibited the highest absorption rate, reaching 19.78%. In contrast, the composite reinforced with only 10 wt.% fiber showed the lowest weight gain. The results confirm that the water absorption rate is strongly influenced by the fiber weight fraction within the composite [43]. The absorption process stabilized after approximately 18 days, with all composites reaching equilibrium, and after that time it became negligible.

Notably, even at 40 wt.% fiber content, the composites developed in this study absorbed far less water than the commercially available wood particleboards [44], and the particleboards manufactured from sunflower stalks or poplar wood [45], in a percentage less than 70% and 52%, respectively [45]. This highlights the superior resistance of the coir-LDPE composites to water penetration.

To examine the effect of applying sealant to the cutting edges of the composites, more tests were conducted and the results demonstrated that the edge treatment significantly reduced the water absorption. However, even when the edges were properly sealed, the samples still absorbed small amounts of water through their surfaces. This suggests that, to achieve full water resistance, surface treatments in addition to edge sealing are necessary.

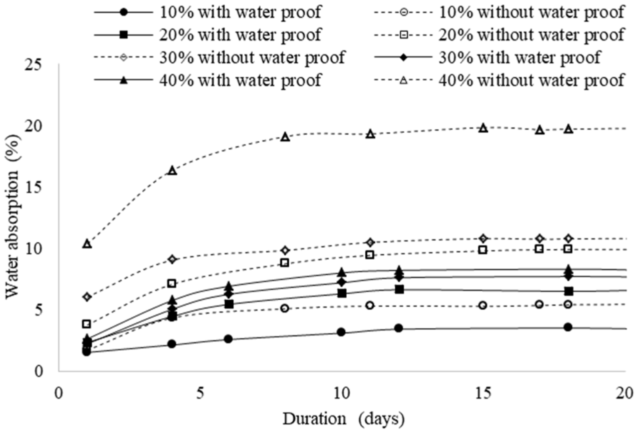

Fig. 8. Variation of water absorption.

IV. CONCLUSIONS

This study investigated the mechanical and physical behavior of coir fiber-reinforced Low-Density Polyethylene (LDPE) composites with varying fiber contents and lengths. The composites were manufactured using compression molding and the hand layup technique. The key findings are:

- The maximum tensile strength of 12.56 MPa was achieved with 40% fiber content and a 4 cm fiber length.
- The maximum elastic modulus of 0.46 GPa was obtained with 50% fiber content and 4 cm fiber length. Lower fiber contents generally exhibited lower modulus values.
- The maximum flexural strength of 33.77 MPa was observed at 30% fiber content with a 3 cm fiber length.
- The highest impact strength of 1.22 kJ/m² was recorded at 40% fiber content with a 2 cm fiber length.
- Water absorption is a critical limitation for these composites. The application of waterproofing agents immediately after fabrication is proposed to improve the performance.

Overall, the results demonstrate that both the fiber length and fiber content significantly influence the mechanical and physical properties of coir-fiber reinforced polymer composites. Depending on the intended application, appropriate fiber proportions and sizes can be selected to optimize performance.

Composites show potential for use in construction applications, such as ceilings, wall panels, partitioning walls, and floor tiles. However, further studies are needed to refine the mix proportions, improve durability, and evaluate the long-term behavior to ensure suitability for real-world construction scenarios.

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