Production and Characterization of Doum Palm Shell-Recycled Low-Density Polyethylene Composite as an Alternative Material for the Production of Crash Helmet

Abdullahi Usman Idris*, Abubakar Usman Babuje, Momoh Lamidi, Sunday Godwin Amon, and David Aman Nanlong

Abstract—The production of crash helmets is a critical aspect of ensuring the safety of individuals participating in various activities such as motorcycle riding, cycling, and extreme sports. Traditionally, helmets have been manufactured using materials that include polycarbonate, fiberglass, and carbon fiber. In recent years, there has been growing interest in exploring alternative materials for crash helmet production that are cost-effective and environmentally friendly. This study assessed the effects of integrating doum palm shell (DPS) particles into a composite material made from recycled low-density polyethylene (RLDPE). The study specifically addressed the impact, hardness, tensile, and flexural strength, and density of the particulate composite, and the influence of particle size and loading was also assessed. RLDPE and DPS particles were compounded using a two-roll mill and molded by compression molding to create the composites. Two particle sizes of DPS (150 µm and 300 µm) were used to prepare eight different composite formulations, which were tested to analyze their response to mechanical loads. The specimen with the optimum desirable mechanical properties for helmet application was found to be 95 wt% RLDPE and 5 wt% DPS (150 µm), with an impact strength of 66.67 kJ/m², flexural strength of 162.60 MPa, tensile strength of 18.4 MPa, hardness value of 16 HV, and density of 0.88 g/cm³. The results were compared with past literature and found to be considerably suitable.

Index Terms—doum palm shells, mechanical properties, polyethylene composites.

I. Introduction

The production of crash helmets is a critical aspect of ensuring the safety of individuals participating in various activities, such as motorcycle riding, cycling, and extreme sports. Traditionally, crash helmets have been manufactured using materials such as polycarbonate, fiberglass, and carbon fiber. While these materials offer excellent protection, they are often expensive and have significant environmental impacts due to their production and disposal processes [1].

In the past few years, there has been growing interest in exploring alternative materials for crash helmet production that are both cost-effective and environmentally friendly. One such material is a composite made from doum palm fibers and recycled low-density polyethylene. Plant fibers possess unique properties, such as low density and high tensile strength, making them suitable for reinforcement in composite materials [2].

Doum palm nuts and recycled low-density polyethylene waste have shown promise for use in lightweight structural applications, particularly when mixed in ideal proportions, exhibiting mechanical qualities that are optimal for such applications [3]. In another study, date palm fiber-reinforced epoxy composites were investigated for military helmet production; certain fiber-to-epoxy ratios showed promising results in terms of impact strength and hardness [4]. Furthermore, the use of crushed doum palm shell as a substitute for coarse aggregate in concrete has proven effective, satisfying the specifications for structural lightweight concrete at substitution levels of up to 10% [5]. Additionally, the use of date palm fiber-reinforced recycled polymer composites has resulted in improved mechanical properties, wherein fiber length and content directly influence hardness, impact resistance, and tensile strength [6]. These studies highlight the potential of natural fibers and recycled materials for producing sustainable alternatives for engineering applications, including protective equipment and construction materials.



Fig. 1. Doum palm shell waste.

A growing population has led to an increase in the volume of waste requiring disposal, contributing to a resurgence in the use

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of natural materials for various engineering applications, driven by the significant environmental concerns associated with the increasing use of synthetic polymers [7]. In addition, there has been a significant shift in attention toward natural fibers, both in the literature and in industry. Natural fibers offer several advantages over standard reinforcement fibers, including lower cost, lower density, higher biodegradability, and favorable specific properties. Low-density polyethylene (LDPE) is a significant thermoplastic owing to its favorable characteristics, such as fluidity, flexibility, transparency, light weight, and glossy surface, and is commonly used as a packaging material [8].

The doum palm, scientifically known as *Hyphaene thebaica*, is a species of palm tree native to parts of Africa and the Arabian Peninsula. It is also commonly known as the gingerbread tree [9].

The doum palm is a medium- to large-sized palm tree with a single trunk that can reach heights of up to 20 m (66 ft). The trunk is thick and covered in persistent leaf bases, which give it a distinctive appearance. The leaves are long and pinnate (feather-like), reaching lengths of up to 6 m (20 ft) [10].

II. Methodology

A. Materials

The materials used in this study were doum palm shell and recycled low-density polyethylene (RLDPE).

B. Equipment

The equipment used for composite preparation and characterization is presented in Table I.

TABLE I. EQUIPMENT AND SPECIFICATION

Equipment	Specification
Two-roll mill	Allen-Bradley two-roll mill, model 802T-WSIP
Tensile testing machine	Tensile testing machine
Hardness testing machine	Vickers hardness testing machine
Flexural testing machine	Universal materials testing machine, Cat. No. 261

C. Preparation of Doum Palm Shell Particles

The doum palm used in this study was sourced locally within Bauchi metropolis. Both the seed and the edible part of the fruit were removed, leaving only the shell. The shells were sun-dried for 10 days to ensure complete dryness, then crushed into smaller pieces and further ground into particulate form. A standard sieve of 150 µm and 300 µm sizes was used to obtain the powder. Fig. 2, Fig. 3, and Fig. 4 show the doum palm shells, crushed shells, and sieved particles, respectively.



Fig. 2. Doum palm shells.

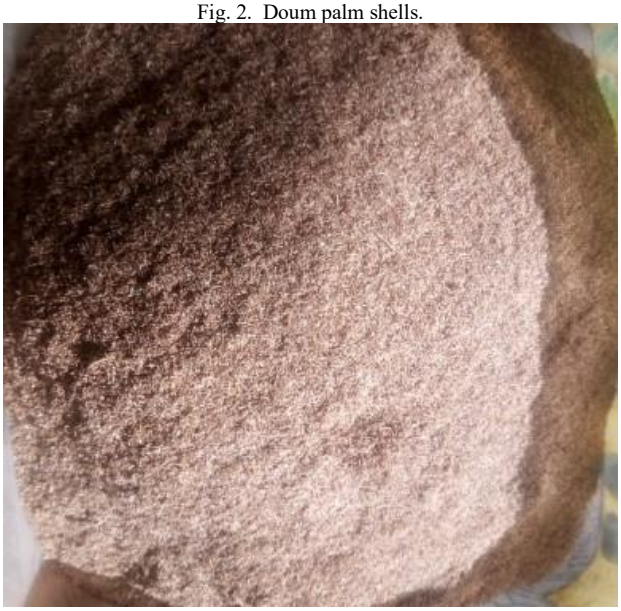

Fig. 3. Crushed doum palm shells.



Fig. 4. Sieved doum palm shell particles (150 µm).

D. Composite Preparation

1) Mold Preparation

A mold with dimensions 130 × 110 × 3 mm, shown in Fig. 5, was used to form the composite into a suitable shape for test-sample preparation.



Fig. 5. 130 × 110 × 3 mm mold.

2) Compounding

Compounding was carried out using a two-roll mill (Fig. 6) set at a temperature of 150 °C at the Polymer and Leather Research Institute, Zaria, Kaduna State, to obtain a homogeneous mixture. At 150 °C, the recycled low-density polyethylene (RLDPE) was fed into the space between the rolls, known as the nip. The reinforcement (doum palm shell particles) was added once the RLDPE was in molten form, and mixing continued for 10 minutes until a homogeneous mixture was attained. The composite designations and compositions used in this study are presented in Table II.



Fig. 6. Two-roll mill compounding of RLDPE.

TABLE II. COMPOSITE DESIGNATION AND COMPOSITION

Designation	Particle Size	Composition
A0	—	RLDPE (100%)
A1	150 µm 150 µm	RLDPE (95 wt%) + DPS (5 wt%)
A2	150 µm 150 µm	RLDPE (90 wt%) + DPS (10 wt%)
A3		RLDPE (85 wt%) + DPS (15 wt%)
A4		RLDPE (80 wt%) + DPS (20 wt%)
A5	300 µm 300 µm	RLDPE (95 wt%) + DPS (5 wt%)
A6	300 µm 300 µm	RLDPE (90 wt%) + DPS (10 wt%)
A7		RLDPE (85 wt%) + DPS (15 wt%)
A8		RLDPE (80 wt%) + DPS (20 wt%)

3) Compression Molding

The compounded composite was removed from the mill and placed in a metallic mold lined with foil paper to prevent it from burning during curing, then compressed using an electrically heated press under a pressure of 5 bar for 10 minutes to allow proper curing. After pressing, the composite was removed from the press and left to cool in air at ambient temperature. Fig. 7 and Fig. 8 show the sieved doum palm shell particles and the finished doum palm shell particle–RLDPE composite, respectively.



Fig. 7. Sieved doum palm shell particles.



Fig. 8. Finished doum palm shell particle–RLDPE composite.

E. Composite Characterization

1) Determination of Tensile Properties

Tensile strength is a measure of the maximum stress a material can withstand before failure or breakage. Samples for the tensile test were cut into a dumbbell shape and mounted in a tensile testing machine. Each sample was clamped between the two jaws of the machine, with one jaw fixed while the other was drawn away by hydraulic power. The machine is automated: as the free jaw continued to draw the material, readings were displayed on a computer every second for each increment of elongation until failure occurred.

2) Determination of Impact Properties

Impact strength is a measure of the work done to break a test sample, that is, the material's ability to withstand substantial stress loads. In practical applications where a material is expected to encounter dynamic forces such as shock, impact strength may be more important than tensile strength. The impact test was conducted using a Charpy impact testing machine, which measures the energy absorbed by the specimen to determine its resistance to the sudden impact load of a pendulum swung from a specific height. The machine has a capacity of 15 J to 25 J; an impact energy of 15 J was used for this test. The impact energy resisted per unit cross-sectional area is given by the impact energy minus the energy absorbed by the specimen, divided by the cross-sectional area, while the impact strength is calculated as

$$E = e / bh \quad (1)$$

where E is the impact strength, e is the impact energy absorbed by the specimen, b is the specimen width, and h is the specimen depth (thickness).

3) Determination of Hardness Properties

Hardness refers to a material's resistance to penetration by a pointed tool; it measures the material's capacity to withstand plastic deformation by indentation or abrasion. Samples were mounted in a plastic medium to prepare them for testing. Indentations were made as large as possible to optimize measurement resolution, since the measurement error increases as the indentation size decreases.

4) Determination of Flexural Properties

The flexural test was conducted using a universal testing machine operating on the three-point bending principle. A vertical load, driven by hydraulic power, was applied at the center of a 60 mm effective-length sample supported on two points on a horizontal rod. As the hydraulic press continued to apply load, the sample deformed under the resulting bending force, and a digital gauge attached to the machine recorded the corresponding deflection. Testing continued until the readings no longer changed with increasing bending, indicating internal failure of the material. The modulus of rupture, also known as flexural (bending) stress, was calculated as

$$\sigma = 3Fl / 2bd^2 \quad (2)$$

where F is the load (N), b is the specimen width (mm), d is the specimen depth or thickness (mm), and l is the working length or span (mm). The modulus of elasticity, also known as the flexural or bending modulus, is given by

$$E = Fl^3 / 4bd^3D \quad (3)$$

where D is the deflection (mm), given by the initial length minus the final length.

5) Determination of Physical Properties (Density)

The density of each sample was determined by weighing the composite using an analytical balance, while the volume was obtained by measuring its dimensions (length × width × thickness). Density was calculated as

$$\rho = m / V \quad (4)$$

where m is the mass (kg) and V is the volume (m^3).

III. Results and Discussion

A. Effect of Doum Palm Particle Loading and Size on Tensile Strength

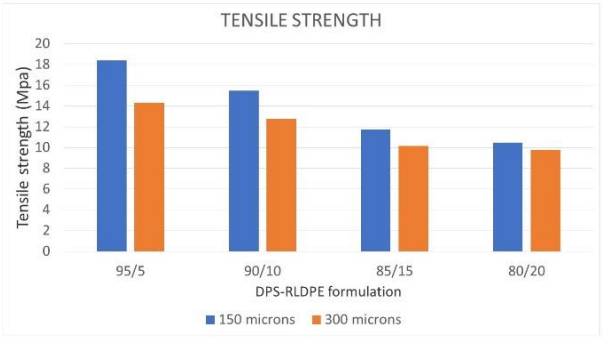

Fig. 9. Variation of tensile strength with doum palm shell particle loading and size.

Fig. 9 shows the effect of doum palm shell (DPS) particle loading on the tensile strength of the composite. For both particle sizes examined, tensile strength peaked at 5 wt% reinforcement and gradually decreased as particle loading increased. At equal weight fractions, the sample with 150 µm particle size exhibited higher tensile strength than the 300 µm sample, indicating that compatibility improves, and strength increases, as particle size decreases.

B. Effect of Doum Palm Particle Loading and Size on Impact Properties

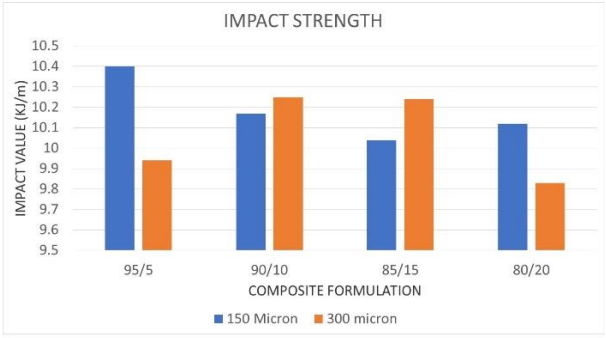

Fig. 10. Variation of impact strength with doum palm shell particle loading and size.

Fig. 10 presents the impact strength of the composites at each weight percentage of particle reinforcement. The results show a positive correlation between filler content and the material's capacity to absorb impact energy, thereby enhancing its resistance to fracture under sudden loading. The 300 µm particle size produced the best impact performance, with the highest impact strength recorded at 20 wt% filler loading.

C. Effect of Doum Palm Particle Loading and Size on Hardness Properties



Fig. 11. Variation of hardness value with doum palm shell particle loading and size.

Fig. 11 shows the hardness test results for the produced samples. For every weight percentage of particle reinforcement, hardness increased linearly with increasing DPS content. The 300 µm particle size produced the best hardness, with the highest value recorded at 20 wt% filler loading.

D. Effect of Doum Palm Particle Loading and Size on Flexural Properties

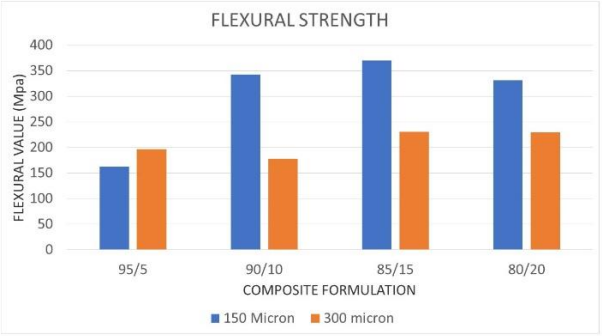

Fig. 12. Variation of flexural strength with doum palm shell particle loading and size.

Fig. 12 presents the flexural strength of the composites at each weight percentage of particle reinforcement. Flexural strength increased with increasing DPS content, indicating greater resistance to deformation, while a lower modulus of elasticity corresponds to reduced stiffness. Since ductility is an important requirement for crash-helmet applications, the lower flexural strength associated with the 150 µm particle size is favorable, as it indicates increased ductility. The best flexural strength was recorded at 95:5 wt% RLDPE–DPS with 150 µm particle size.

E. Effect of Doum Palm Particle Loading and Size on Density

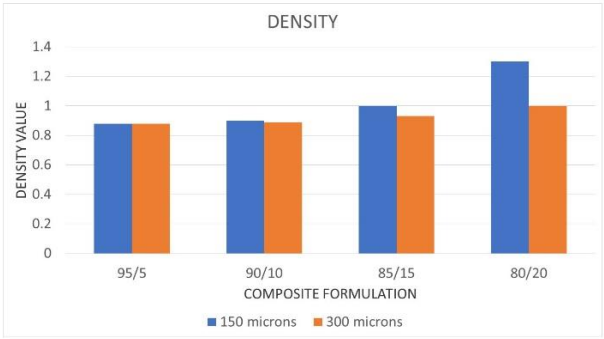

Fig. 13. Variation of density with doum palm shell particle loading and size.

Fig. 13 shows that the density of the composite increased with increasing reinforcement, indicating that greater DPS content also increases hardness, brittleness, and stiffness. For crash-helmet applications, a lower density is desirable to reduce weight and improve elasticity. The 95:5 wt% RLDPE–DPS formulation with 150 µm particle size was therefore found to be the most suitable composition.

IV. Conclusion

This study successfully demonstrated the production of doum palm shell–recycled low-density polyethylene composites, converting waste into a useful material of potential benefit to the populace and the economy. The mechanical properties of the composites — tensile strength, flexural strength, impact strength, and hardness — were found to be strongly influenced by the particle size and loading of the composite. As reinforcement increased, tensile strength decreased from 18.40 MPa to 9.77 MPa, while hardness increased from 16.00 HV to 41.70 HV, flexural strength increased from 162.60 MPa to 331 MPa, impact strength increased from 66.67 kJ/m² to 85.56 kJ/m², and density increased from 0.88 g/cm³ to 1.30 g/cm³. Particle size was also found to influence the mechanical properties of the composite, with smaller particle sizes producing the best mechanical properties and improved interfacial adhesion. Compared with previous work, the formulation with 150 µm particle size at 5 wt% DPS and 95 wt% RLDPE — having a tensile strength of 18.40 MPa, impact strength of 66.67 kJ/m², flexural strength of 162.60 MPa, hardness value of 16.00 HV, and density of 0.88 g/cm³ — was found suitable as an alternative material for crash-helmet production.

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