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Research Paper

# Uniaxial tensile response of coconut coir fiber-reinforced polyethylene Composites

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The roles of Composite materials in a variety of engineering applications have increased due to their enhanced strength and modulus, especially polymer-based composites which is one of the commercially available composites. The uniaxial tensile properties of polyethylene matrix reinforced with coconut coir fibers has been studied and the results from experiments and analytical models are presented. The compositional dependence of tensile strength, stiffness (elastic modulus), modulus of resilience and ductility are explored for different proportions of the constituent materials through experiments and analytical models. The results from experiments showed that the properties measured were greatly affected by the fiber mass fraction with optimized properties obtained at fiber content of 10 wt%.

## 1 Introduction

Composite materials are made up of multiple constituents which do not dissolve in each other. This class of material has developed over time and contributed to the advancement of modern materials [1]. Modern technological advances have necessitated the used of materials with unusual combinations of properties that are not obtainable from conventional metal, ceramics and polymers. Hence, composite materials were developed to provide specific intermediate properties from combination of materials [2]. One of such materials is fiber-reinforced polymers. Polymers such as polyethylene have relatively poor mechanical properties that renders them inadequate for most engineering applications [3]. They have large strain but with low strength and cannot stand the test of most structural application. These associated weaknesses of polymers can be enhanced by reinforcement with natural fibers [4].

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Fiber reinforced polymers have proven to be very important in engineering applications due to their high specific strength [5]. Thus, recent research interest has been shifting to natural fiber-reinforced polymeric materials. The natural fibers mostly used include sisal, banana, coir, kenaf and many others. They play substantial role in the advancement of biodegradable composites materials to resolve current ecological and environmental problems [6]. Natural fibers are chosen as reinforcement due to their ability to lessen tool wear when processing and serve as possible replacement for artificial fiber in composites [3]. Fiber-reinforced composites whose matrix phase is a polymeric material harbours high-strength fibers. The polymers used can either be thermoplastics or thermosetting. The former is predominantly used as matrices for natural fibers. They include polyethylene, polypropylene and poly vinyl chloride, while epoxy, polyester resins and phenolics are the commonly used thermosetting matrix materials [7]. On the other hand, fibers are classified into leaf, seed, fruit, wood and grasses [8].

Natural fiber-reinforced polymers are vastly influenced by the type of fiber and matrix used. A related study carried out by Jarukumjorn and Suppakarn, reported that polypropylene reinforced with glass fiber showed increased tensile and flexural properties, while, sisal fiber addition with glass fiber enhanced the water resistance and thermal properties of the composite [9]. In another study, the tensile and flexural strengths of natural fiber-reinforced polymer composites are highly affected by the aspect ratio, moisture absorption tendency and stability of the fibers used. It was also reported that these properties were slightly improved for chemically treated fiber composites [10].

This study presents the outcomes of combined experimental and analytical study of uniaxial tensile responses of coconut coir fiber-reinforced polyethylene composite. The effects of reinforcement with coconut coir fibers were elucidated using composite rule of mixture and short fiber theory. The measured and predicted properties from experiments and analytical models respectively are compared with those of unreinforced polyethylene. The consequences of the results are discussed for the design of a robust and sustainable material for domestic applications using recycled polymer.

## 2 Materials and Method

### *2.1 Raw Materials*

Thermoplastics polymers presently dominate as matrix materials for bio-fibers in fiber-reinforced polymeric composites and polyethylene is among the most frequently used thermoplastic matrix [7] while coconut fibers are extracts from the mesocarp of a coconut fruit known as Coir [11]. The polyethylene used as the matrix phase was collected directly from dump sites in Malete, Moro local government area of Kwara state, Nigeria. Specifically, sachet water packaging materials popularly known as pure water sachet was used. The polyethylene materials were washed vigorously in soap and water to remove the dirt attached to it because of its long stay on the dump sites. After being washed, it was sun-dried for about five hours to also remove moisture before it could be used for the sample preparation. Coconut coir fibers (reinforcing phase) were obtained from coconut fruit with diameter of the fibers ranging from 0.56 mm to 0.75 mm.

### *2.2 Matrix Preparation*

The polyethylene bags (pure water sachets) were cleaned with acetone to remove the paint on the body of the container. This is necessary because the chemical composition of the paint could alter that of the polyethylene itself, and there is a need for distinct chemical composition to ease processing of the polyethylene. After cleaning with acetone to get plain surfaced polyethylene material, the polymer was melted in toluene at about 140°C to get it in the molten form. While the toluene was boiling, shredded polyethylene was poured into the solvent and stirred vigorously until a molten and homogeneous polymer was obtained.

### *2.3 Composite Preparation*

Coconut coir fibers were chopped into smaller length using a pair of scissors so that a discontinuous and randomly oriented fibers is obtained. The critical length ($l_c$) of the fiber to be used was computed to be 10 mm and thus, they were cut into length greater than the critical length ($l \geq l_c$), at an average length of 11 mm (the fiber reinforcement becomes more effective). In this process, the fiber-polymer blend was prepared by first mixing the already chopped fibers with hot viscous polyethylene in toluene. Before mixing the fibers with the molten polyethylene, the solidification time of melted polyethylene was optimized and obtained to be 4 minutes. The fibers were vigorously and evenly mixed with the molten polyethylene. The fiber-polymer blend was then poured into a mould and allowed to solidify (Figure 1b).


(a)


(b)

***Fig 1 - (a) Mold used and (b) Composite mixture in the mold***

Coconut coir fiber-reinforced polymer composites were formed with different fiber composition in mass percentages from 0% to 15% as presented in Table 1. These mass percentages used were determined based on the mass fractions of the initial raw materials. For each sample, five specimens were made for the various mechanical tests carried out.

**Table 1 - Percentage composition by mass of matrix and fiber in the composite samples.**

| Composite | Sample I | Sample II | Sample III | Sample IV |
|---|---|---|---|---|
| Polyethylene (wt%) | 100 | 95 | 90 | 85 |
| Coconut coir fiber (wt%) | 0 | 5 | 10 | 15 |

## 3 Experimental Method

An Instron 3360 series (Norwood, MA, USA) with a 50 kN load cell was used for the determination of the tensile properties of the polymer-based composites. With average relative humidity of 65%, the samples were tested at room temperature. The tensile specimens were deformed at a loading rate of 2.0 N/s up to fracture by separation of specimens into two pieces. A curve of tensional load (kN) versus displacement (mm) was used to approximate the peak load, $F_A$. There are 5 samples for each fiber volume fraction and the average values obtained from those samples were determined. Samples with gauge length of 80 mm and cross-sectional area of $10 \times 6\ mm^2$ were used for the uniaxial tensile tests. The tensile strength was then estimated using equation 1:

$$\sigma = F_A / A_o \tag{1}$$

where $F_A$ is the peak load at the onset of fracture and $A_o$ is the initial cross-sectional area.

The degree of plastic deformation sustained at fracture (ductility) may be expressed as either percentage elongation (%EL) or percentage reduction in area (%AR). The former is the percentage of plastic strain at fracture given by [12]:

$$\%EL = \left( \frac{l_f - l_0}{l_0} \right) \times 100 \tag{2}$$

where $l_0$ and $l_f$ are the original gauge length and fracture length, respectively.

The modulus of resilience, $U_r$, is a measure of material's capacity to absorb energy during elastic deformation and then recover this energy completely upon unloading. It is obtained from the total area under the linear portion of a stress-strain curve and mathematically expressed as [12]:

$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon \tag{3}$$

this gives
$$U_r = \frac{1}{2}\sigma_y \varepsilon_y \tag{4}$$

In which $\varepsilon_y$ is the strain at yielding.

# 4 Analytical Models

### *4.1 Rule of Mixture (ROM)*

For a two-phase whisker/fiber-reinforced composite, the strength may be estimated from the rule of mixture model. The constant strain rule of mixture model assumes that the applied load is parallel to fiber direction. This gives [13]:

$$\sigma_c = V_m \sigma_m + V_f \sigma_f \tag{5}$$

where $V_m$ and $V_f$ are fractions of the matrix and fiber, respectively while $\sigma_m$ and $\sigma_f$ are matrix and fiber strengths, respectively.

### *4.2 Short fiber theory (SFT)*

In the case of short fibers/whiskers, average fiber stresses are less than those associated with long fibers. Under such condition, the average fiber stress is given by [14]:

$$\bar{\sigma}_f = (1/2)\sigma_f \left(l / l_c\right) \tag{6}$$

where the term $l/2l_c$ is known as the fiber efficiency factor $(\eta_f)$ for short fibers, and $l_c$ is the critical fiber length. The critical fiber length, $(l_c)$ is given by [13]:

$$l_c = \sigma_f d / 2\tau \tag{7}$$

where $\sigma_f$ is the fiber strength, d is fiber diameter and τ is the fiber-matrix bond strength. This expression for the average fiber strength can be substituted into the simple rule of mixture theory for short fiber lengths. Hence, the average fiber strength for short fibers is given by:

$$\bar{\sigma}_f = \left(l / 2l_c\right)\sigma_f = \eta_f \sigma_f \tag{8}$$

An additional parameter known as the orientation efficiency factor $(\eta_o)$ is needed to account for the decrease in composite strength due to random orientations of the fibers. When this is taken into consideration, the average fiber strength is now given by [14]:

$$\bar{\sigma}_f = \eta_o \eta_f \sigma_f \tag{9}$$

where $\eta_o$ have values of 0.375 and 0.2 for random two-dimensional and three-dimensional orientation, respectively [14]. Based on the short fiber theory, the composite strength and elastic modulus is given respectively by:

$$\sigma_c = V_m \sigma_m + V_f \sigma_f \eta_f \eta_o \tag{10}$$

$$E_c = V_m E_m + V_f E_f \eta_f \eta_o \tag{11}$$

where the parameters, $\eta_f$ corresponds to fiber length efficiency, while $\eta_o$ corresponds to the fiber orientation efficiency.

# 5 Results and Discussion

Optical images of the coconut coir fiber and coconut coir fiber-reinforced polyethylene composite are shown in Figure 2. The composite images show randomness in fiber orientations in the samples and clearly revealed polyethylene matrices in lesser quantities with higher fiber fraction. Also, the images of the composite sample reveal that the fibers are all well-bonded to the matrix material. Hence, the possibility of delamination at the interface of fiber and matrix is expected to be minimal.

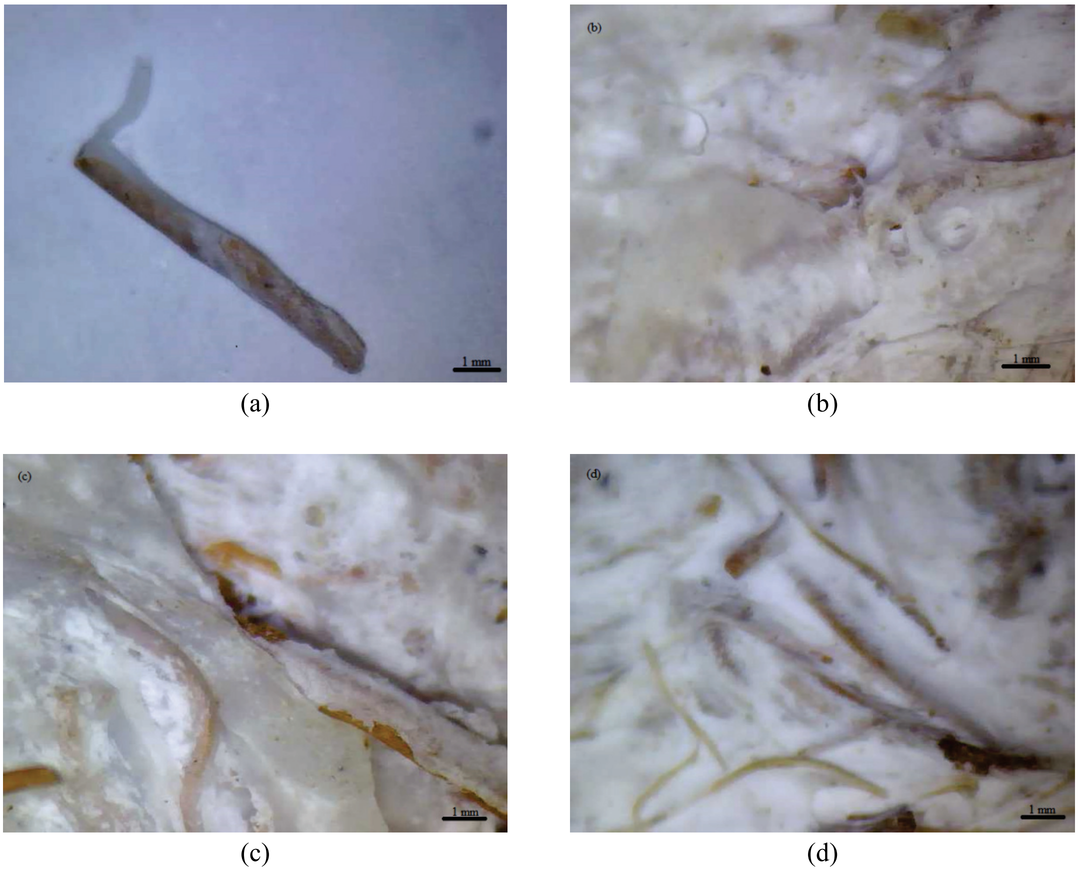


***Fig. 2 - Optical Micrographs of (a) Coconut coir fiber and Coconut Fiber Reinforced Polyethylene at (b) 5 wt% fibers, (c) 10 wt% fibers and (c) 15 wt% fibers.***

The mechanical properties of the raw materials used are presented in Table 2. The properties of the polyethylene were obtained from the tensile test results of the composite with 0% fiber content while those of the coconut coir fibers were obtained under an axial tension test using a Universal Testing Machine (Instron 3360 series, Norwood, MA, USA) equipped with a 1kN load cell. The tests were performed until the fiber fails. These results are needed for the estimation of the Tensile strength and Elastic Modulus of the composite using the analytical models presented in equations (10) and (11) respectively.

**Table 2 – Measured mechanical properties of raw materials used.**

| Materials | Tensile Strength (MPa | Elastic Modulus (MPa) | Elongation at Failure (%) |
|---|---|---|---|
| Polyethylene | 3.04 | 90.0 | 34.0 |
| Coconut coir fiber | 25.0 | 200.0 | 4.5 |

### *5.1 Tensile Strength*

Composite samples consisting of different mass fractions of fiber from 0 wt. % to 15 wt. % were subjected to a uniaxial tensile loading using a universal testing machine. Figure 3 shows the tensile strength for the composites with different fiber mass fraction. The introduction of coconut coir fiber to the polyethylene matrix showed enhanced tensile strength of the composite. Also, optimum tensile strength was achieved at a fiber mass fraction of 10 wt. %. For such fiber contents, the tensile strength was as high as 4.57 MPa. This increase in tensile strength from reinforcement with coconut coir fiber can be attributed to a collective effect of the ductility and high strength of the matrix fibers respectively. However, the tensile strength decreased at 15wt. % of fiber. This can be attributed to fiber interlock and the difficulty of an evenly mixed matrix and reinforcement phase at this composition.

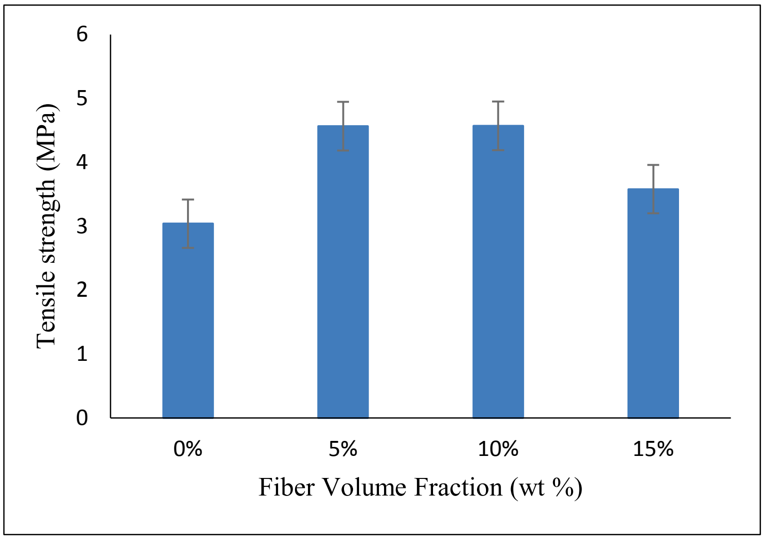


***Fig. 3 - Tensile strengths obtained for samples at different fiber mass fraction***

### *5.2 Modulus of Elasticity*

The elastic moduli of the composites at different fiber mass fractions were estimated from the linear portions of the stress-strain curve. It is the linear relationship between the tensile stress and tensile strain of the specimen under elastic condition. Figure 4 shows the elastic modulus of the coconut coir reinforced polyethylene at different mass fraction of fibers. The results indicate a rise in elastic modulus of composite with increased fiber percentage by mass. A maximum elastic modulus value was obtained at fiber content of about 10 wt% fraction.

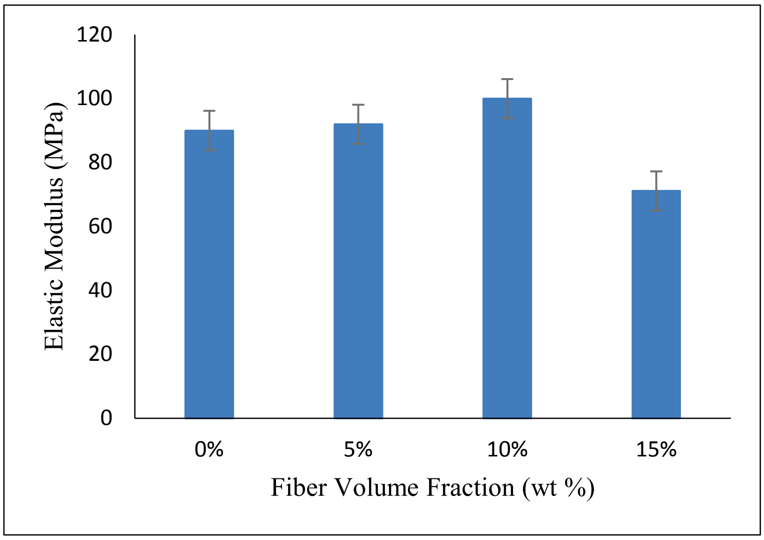


***Fig. 4 - Elastic Modulus obtained for samples at different fiber mass fraction***

### *5.3 Ductility*

Using the stress-strain relationship obtained from the tensile test, the ductility (in terms of %EL) of the composite was obtained using Equation 2. Figure 5 presents the ductility measurement for the composites at different fiber percentage by mass. The results indicate that the fiber-reinforced polyethylene is most ductile at fiber fraction of 10 wt %.

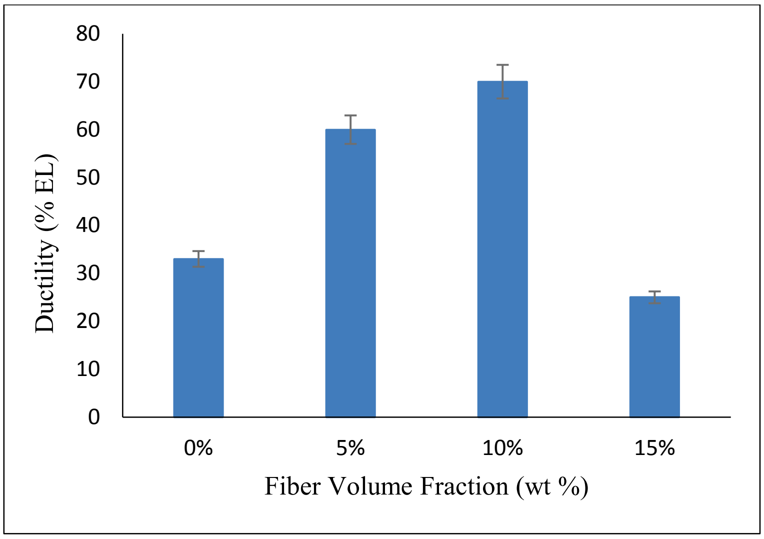


***Fig. 5 - Ductility of samples at different fiber mass fraction***

### *5.4 Resilience*

The modulus of resilience at fiber fractions of 0 wt%, 5 wt%, 10 wt%, and 15 wt% was estimated from the area under the elastic region of the stress-strain curve using Equation 4. From the results as shown in Figure 6, the resilience of the composites increases with increasing fiber mass fraction with optimum value obtained at about 5 - 10 wt% fiber contents.

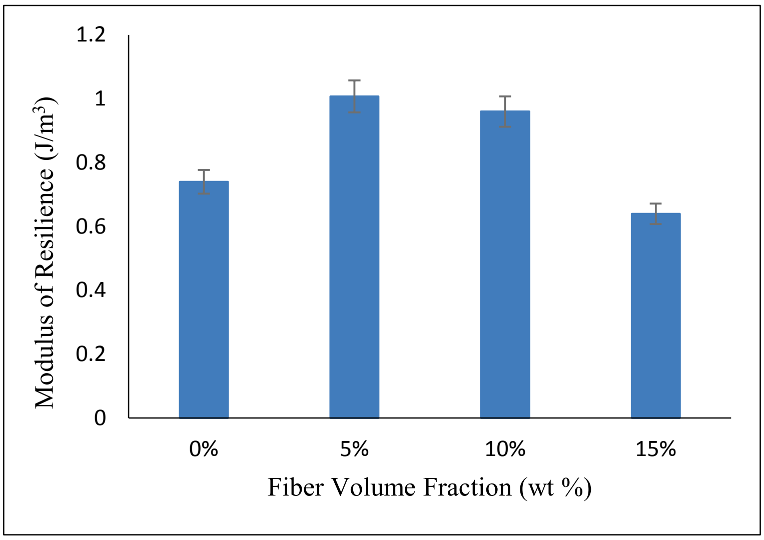


***Fig. 6 - Modulus of Resilience of samples at different fiber mass fraction***

### *5.5 Comparison of experimental and analytical results*

The results obtained from experiments were compared with predictions from mechanistic models for the tensile strength and modulus of elasticity of composite materials. Figures 7 and 8 shows comparison between results obtained from experiments and mechanistic models (ROMs and SFT). The results are consistent, affirming the effects of fiber and orientation efficiency factor in the prediction of composite mechanical properties. From the experimental results obtained, 90 wt% polyethylene and 10 wt% coconut coir fiber proved to be the optimized composition for the composite. At this value of fiber content, we have most outstanding enhancement in the uniaxial tensile properties of the composites measured.

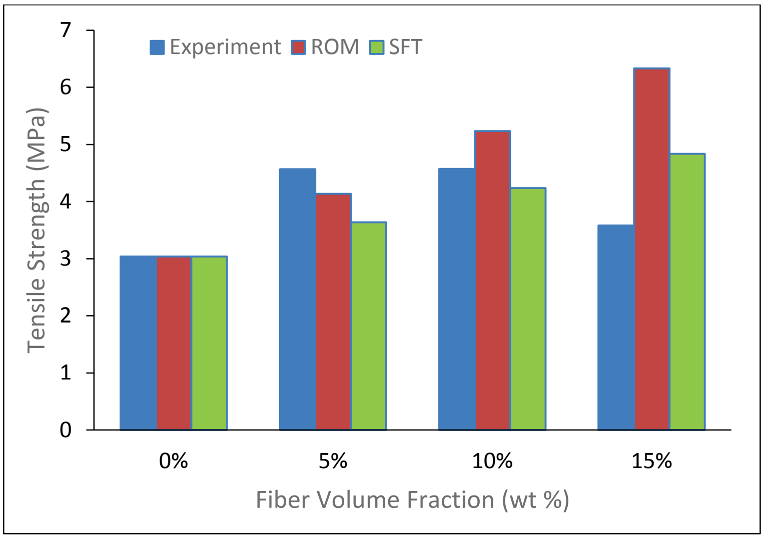


***Fig. 7 - Plot showing comparisons of experimental results and predictions of Tensile Strength form mechanistic models.***

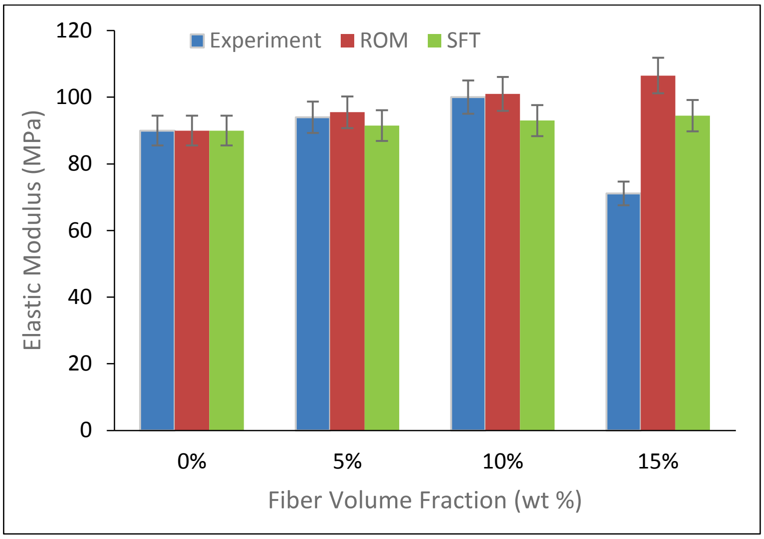


***Fig. 8 - Plot showing comparisons of experimental results and predictions of Elastic Modulus form mechanistic models.***

### *5.6 Implications*

The implications of this work are very significant for the design of coconut coir fiber-reinforced polyethylene composite for sustainable household applications. This work shows an improved mechanical property of polyethylene, when it is reinforced with coconut coir fiber. This is evident with the increase in composite mechanical properties as mass fractions of fibers are increased considerably. Also, the results from the test procedures in this study can help in micro-mechanical characterization and performance evaluation of polyethylene-based fiber-reinforced composites for sustainable engineering applications.

## 6 Summary and Concluding remarks

Composites consisting of polyethylene reinforced with coconut coir fibers at different mass fractions were produced. The uniaxial tensile properties of the different compositions were measured, and the results compared to determine the effects of reinforcement.

The fiber reinforcement resulted to an enhanced mechanical property up to an optimized fiber content of 10 wt%.

The measured tensile strength and elastic modulus from experiments are consistent with predictions from mechanistic models studied. The rule of mixture and short fiber theory predictions account for the effects of short fibers and randomness in orientation of the fibers to provide reasonable estimate of the properties measured.

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