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Finite Element Estimation of the Elastic Characteristics of Low-Density Polyethylene Reinforced with Rice Husk

Solomon C. MADU[1,2], Victor S. AIGBODION[1,2,3] and Cyril OCHERI[1,2*]

[1]*Department of Metallurgical and Materials Engineering, Faculty of Engineering, University of Nigeria, 410001 Nsukka, Nigeria*
[2]*African Centre for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria*
[3]*Faculty of Engineering and Built Environment, University of Johannesburg, P. O. Box 534 Auckland Park, South Africa*

Corresponding Author: cyril.ocheri@unn.edu.ng

Abstract
The need for evaluation of the elastic characteristic of biomass plastic composite (BPC) through finite element modelling is an essential approach towards accepting the adoption of BPC material in the industrial sector. The effective elastic properties of low-density polyethene reinforced with rice husk were determined through a finite element (FE) analysis conducted in COMSOL multiphysics. The study also included a comparison of the micromechanical model to evaluate the effectiveness in determining the unique properties of polymer composite comprised of rice husk fibre reinforced low-density polyethene composite. The results obtained from the FE analysis were compared to the effective properties derived from the micromechanical models. The elastic properties determined through finite element (FE) analysis align with the elastic properties calculated using various micromechanical models. There is no universal template that applies to all the elastic characteristics across different fibre volume fractions. Instead, it was unique to each specific elastic property and fibre volume fraction.

Keywords: *Composite, fibre, finite element, polyethylene, rice husk.*

1.0 Introduction

The new era of increasing demands of engineering materials for modern applications has necessitated the development of materials with enhanced properties. Therefore, there has been a great concern in building and developing a friendly and sustainable environment which has intrigued the interest of researchers worldwide cutting across all disciplines Callister, & Rethwisch, (2020). The quest for better performance of materials has led to the investigation of a new set of materials with enhanced properties. Engineering of materials, being the driving key for innovation and development plays a crucial role in building a reliable future by devising environmentally friendly materials with diverse engineering applications. Akadiri et al. (2012)
Sustainable materials alternatively known as eco-friendly materials are materials made from various combinations of other materials or locally sourced traditional materials, using a manufacturing methodology that causes no harm to the environment or eco-system at large. Popescu et al. (2024) Typically, they possess enhanced properties compared to traditional materials. These materials can be locally manufactured and obtained to minimize the adverse environmental impact, facilitating a balanced and sustainable environment. In addition, the use of these materials aids in reducing carbon emissions, mitigating the greenhouse effect, and contributing to ecosystem preservation. Kumar et al. (2021). The exceptional properties of these materials and the demand for a friendly and sustainable environment made these materials suitable for incorporation into different engineering fields. Aabid & Baig (2023).

Two or more materials can be combined to form a composite that can lead to the manufacturing of advanced engineering materials. Composite engineering materials have a distinct and separate constituent element which distinguishes them from metal alloys. The composite materials are characteristically unique because each constituent material maintains its unique physical and chemical properties. However, when these constituents are combined, they create a combination of qualities that cannot be achieved by any individual constituent on its own. Taj et al. (2007) Notably, the physical and chemical characteristics of composite material are improved as a result of synergistic combined qualities of the individual constituent material element. Babu & Balasubramanian (2018).

Composite materials comprise two phases: a continuous phase and a discontinuous phase. The matrix is an unbroken phase that maintains the positional orientation of the filler materials and transfers the load to the reinforced filler. The reinforcement is the load-bearing material, providing rigid and structural strength to

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support the load-bearing members. Malik et al. (2022 Composites are classified based on their reinforcement type as particle-reinforced, fibre-reinforced, or structural composites.

The adoption and inclusion of natural or synthetic fibre - particulates or flakes for reinforcement of polymer matrix have significantly increased the use of fibre across different industrial sectors; such as the aero-industry, automobile sector, infrastructure, electrical sector, and sports sector, as a result of their advantages over other reinforced composites. Chung (2018). High stiffness, toughness, good strength to low weight ratio, resistance to chemicals, corrosion and wear, and as well as, cost-effectiveness of composite material are the major properties that are more advantageous over other single materials. Srivastava & Pathak (2022). These materials can enhance the mechanical performance of components made from them by utilizing the distinct characteristics of their elements, microstructure, and the interactions among these elements. Based on the matrix type, composites can be classified as polymer, metal, ceramic, or carbon matrices. The most commonly used cutting-edge materials are fibre-reinforced polymer composite materials due to their low cost, eminent strength-to-weight ratio, and simple production processes Tripathy et al. (2022). Polymeric resins are either classified as thermoset or thermoplastic, and these resins can be reinforced with synthetic or natural fibre, flakes or particulate to form fibre-reinforced plastic (FRP) composites. AlShaafi (2017), Kumar & Sharma (2022). These reinforced polymeric materials can be shaped into various sizes and forms, providing excellent strength, stiffness, and resistance to corrosion. Bettini et al. (2010). These materials leverage the unique properties of their constituting materials, microstructure, and interactions between the constituting materials to enhance the physical features and mechanical behaviour of entities fashioned from these composites. Kuan et al. (2021)

Based on matrix type, composite materials are classified as metal, polymer, carbon or ceramic matrices. The commonly used advanced composites are polymer matrix composites owing to their cheap prices, high tensile ratio, and simple manufacturing principles. Valles-rosales et al. (2016). These composite materials are made up of a polymeric material (thermoplastic or thermosetting) backed by fibres (naturally occurring, carbon-made (artificial), or boron fibres). The aforementioned materials can be shaped into various forms and sizes, providing excellent strength, stiffness, and corrosion resistance Chawla (2022).

1.1 Background of the Study

The combination of fibre flakes that are embedded in a polymer matrix is referred to as reinforced polymer composite material. They have gained significant attention owing to their high strength and high modulus properties. Raju et al (2012). Fibre-reinforced polymer composites are extensively utilized in construction applications and are considered among the most important types of composites. The fibrous materials used as reinforces in polymer matrices are either natural or man-made in origin. Synthetic fibres are man-made through chemical processes, while naturally occurring fibres are obtained from a variety of plant and animal sources. With increasing environmental awareness and the need for sustainable production methods, naturally occurring fibres have attained recognition as potential replacements for synthetic fibres. Natural fibres are readily available in the surrounding environment, promoting a seemingly endless supply. Several types of natural fibres e.g. Rice husk, hemp, coir, banana stem and leaf, sisal, pine, and others, have been used to reinforce polymer matrices. Dayal et al. (2018) To reduce the environmental impact posed by materials like; rice husk fibre can be extracted from them and utilized as reinforcement in composite materials. However, when using natural fibres as reinforcement in polymer matrices, careful consideration must be given to the selection of the polymer matrix. Natural fibres present difficulties in processing owing to the slow reduction of the heat of cellulose cells [4]. Consequently, the chosen polymer matrix should have a melting temperature below the breakdown temperature levels of cellulose cells, which is approximately 200 degrees Celsius. Low-density polyethene is a suitable matrix for making fibre-reinforced polymer composites, meeting this temperature requirement. Sdrobi et al. (2012)

The purpose of this analysis is, therefore, to ascertain the elastic characteristics of rice husk fibre filler-reinforced low-density polyethene composite. In which micromechanical model, and finite element analysis of the composite was developed. The finite element result is validated with analytical results. The success or failure of a composite is often rated according to its mechanical behaviour. Good technical know-how of the elasticity of the composite material will aid in harnessing them to their highest potential so they can be utilized to their maximum strengths in their area of use. To determine the effective mechanical attributes of composite materials, various approaches have been employed, including experimental methods, numerical models, and analytical models. Experimentally estimating the properties of composites can be costly and challenging, particularly when evaluating properties in the longitude and transverse directions Yun et al. (2022) Analytical models can provide reasonable estimations for simple configurations of the constituent materials in natural fibre polymer composites (NFPCs). Singh et al. (2022). However, for more complex composite configurations, analytical models may not be suitable, and mathematical solutions are utilized as estimated solutions because they do not have geometric restrictions. Pal & Haseebuddin (2012). Finite element analysis (FEA) is widely applied in conducting virtual experiments and is considered the most popular numerical technique for analyzing composites Itu et al. (2024)

2.0 Finite Element Analysis (FEA) of Composites Materials

The FEA of composites follow the steps in Figure 1 shows the accuracy of the FEA depends on the assumptions made in the course of the study. Over time, several assumptions have been made to make the analysis easier. Assumptions made in FEA are:

- The matrix is free of void.
- The bond between the matrix and the fibre is perfect.
- The fibre materials are regularly spaced in the matrix mesh.
- The fibre particulate fillers are superbly accurately embedded in the polyethylene matrix.
- The composite is linearly elastic.
- The composite is stress-free at first.

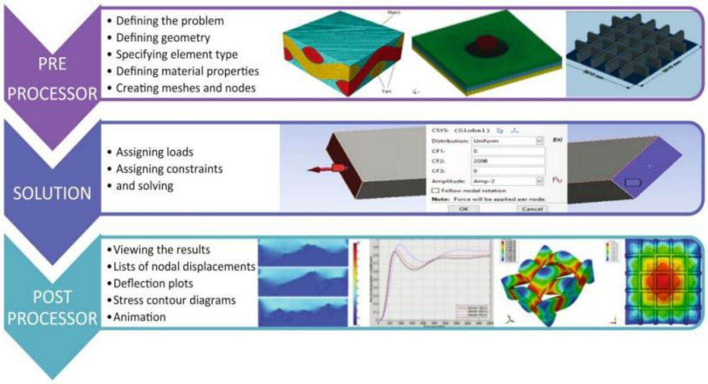


Figure 1: Steps in FEA Alhijazi *et al.* (2020)

While some assumptions made in finite element analysis (FEA) assume ideal behaviour, which may deviate from real-life situations, validating FEA results is necessary Chu et al. (2022). FEA can predict a broad range of properties and facilitate diverse methods for analysis, including multi-physics, electricity, buckling, electromagnetic, latent heat transfer, fluid dynamics, heat, structure, and sound property analyses. Sun et al., (2007). In the FEA of natural fibre-reinforced polymer composite materials, research is primarily focused on mechanical properties, particularly elastic properties Yang et al. (2018). For clearly superb results, 3-D models are highly recommended for Natural fibre analysis, if the loads are applied in a direction out of the plane Diana et al. (2021). The properties of the matrix mesh and naturally occurring fibres are enunciated in FEA based on the analysis type. For instance, studying mechanical properties requires defining parameters like; Young's modulus of elasticity, Poisson's ratio, elongation pre-break, tensile strength, and material density. Roozpeikar & Fattahi (2019). Analyzing thermal behaviour necessitates assigning thermal conductivity values to the constituent materials while inspecting electromagnetic sound wave absorption coefficient requires three-dimensional mechanical properties. Shnawa et al. (2011) "However, due to the difficulty in defining the exact three-dimensional properties of newly developed NFCs, for research purposes, students treat the sample materials as having the same value when measured in different directions i.e. isotropic.

The use of FEA in estimating composite material characteristics involves the accurate creation of the representative volume element (RVE), defined as the tiniest volume that yields a representative measurement of the entire cell. Chu et al. (2022). In the FEA of composites using RVEs, a periodic fibre arrangement in the polymer is assumed, and the isolated RVE has the same material properties as the composite at large. The performance of the mechanical characteristics of reinforced polymer composite materials depends on the fibre-matrix mechanical properties and microstructural features like fibre shape, packing sequence, and fibre volume fraction. Itu et al. (2024).

Numerous researches have been undertaken to approximate the effective properties of composites using FEA of RVEs, considering factors such as fibre geometry, packing sequence, volume fraction, aspect ratio, and fibre length distribution. These studies have shown that the elastic characteristics of composites are influenced owing to factors like fibre cross-section, geometry, volume fraction, and packing sequence, with good agreement between FEA results and experimental or analytical models . Sun et al. (2007). Researchers have also investigated the impact of factors like imperfect interfaces, nanotube curvature, and misalignment on the effective properties of composites using FEA and micromechanics techniques. These studies have revealed significant effects of these factors on properties like longitudinal moduli, shear moduli, transverse modulus, and Poisson's ratio, as well as the possibility of varying damage offset in the matrix mesh owing to varying interfacial properties. Chu et al., (2022), and Sun et al., (2007). Estimating the mechanical attributes of composite materials and other materials through non-degrading methods and Finite Element Analysis plays a crucial role in reading meaning into the behaviour of these composite materials. Katouzian et al., (2024) and Singh et al., (2022).

2.1 Mechanical characteristics of Natural Fibre filler-reinforced Polymer Composites

Mechanical attributes of composite materials describe how they react to applied loads and can be categorized as follows:

(i)Tensile properties: Tensile properties reveal a material's response when subjected to tensile (pulling) forces Sdrobi et al. (2012) and Das et al. (2021). They are determined through tensile tests, which produce a load-to-elongation curve that can be converted into an engineering stress-strain curve. Tensile properties provide information about tensile strength, Young's modulus of elasticity, Poisson's ratio, and shear modulus. The modulus of elasticity, that is the stress-strain ratio measures the material's stiffness. The Poisson's ratio quantifies deformation perpendicular to the loading direction. Tensile strength shows the maximum load a material can carry before it undergoes fracture.

(ii)Hardness: The hardness of a material refers to its ability to insulate deformation, as shown by a standard test measuring the surface's ability to insulate indentation.

(iii)Impact strength: This is the quantity of energy a sample material can hold in its lattice on the application of load. A near-instantaneous load application causes the material to absorb the impact energy.

2.2 Polyethylene Polymer

A polymer can be viewed as a large macro-molecule that constitutes many sub-components. They are usually formed during the process of polymerization. In this process, the individual elements of a polymer known as monomers join together to form polymer chains which form the bonds that hold a polymer together. Polymers are in existence everywhere, from our very own DNA which is naturally occurring and fundamental to biological structure and function, to synthetic polyethylene. Bongarde & Shinde (2014). Polyethylene also known as polythene is the most commonly used plastic in the world. It is a renowned member of the polymer family formed from the polymerization of ethylene. This indispensable polymer was first discovered by accident in 1898 by a German chemist known as Hans von Pechman while he was investigating diazomethane. Based on an extensive literature review, the specific combination of rice husk fibre filler and polyethylene matrix has not been previously studied using the finite element analysis method described. The results obtained from this research study will provide valuable insights and enable the maximum utilization of these composites within their respective fields of application.

3.0 Materials and Method

3.1 Materials

The biomass plastic composite (BPC) material being studied consists of a low-density polyethene as the polymeric matrix and is reinforced with rice husk fibre.

3.2 Methods

Both the low-density polyethene matrix and the rice husk fibre are assumed to be isotropic (having uniform properties in all directions) and homogeneous (uniform composition throughout). The mechanical attributes of the rice husk fibre with low-density polyethene resin applied in this modelling are shown in Table 1 below. A model considers the fibre fillers having circular cross-sections arranged periodically within the polyethene resin matrix. An indicator volume element (IVE) with a square-shaped filling arrangement of the fibre fillers was isolated for analysis. Parametric studies were conducted for fibre filler volume percentages of 10%, 20%, 30%, 40% and 50%.

Table 1: Mechanical characteristics of constituent elements [41]

Materials characteristics	Fibre	Polyethylene
Poisson's ratio	0.3	0.33
Density (g/cm^3)	0.75	1.2
Youngs' modulus (GPa)	30	3.1
Shear' modulus (GPa)	11.5384	1.1654

3.2.1 D constitutive equation

Discusses the 3D constitutive equation for composite materials. Composites can be considered anisotropic (material properties vary in all directions), three-dimensional, or isotropic. For the mainstream anisotropic tudy where properties differ in every direction at a given point, a 21 constant stiffness matrix is required to describe the material behaviour, as shown in the provided equations (1) and (2).

Recall, Hooke's law relates to stress and strain:

$$\sigma_{ij} = \mathrm{m}_{\mathrm{ij}}\varepsilon_{ij} \quad (1)$$

Where the stiffness matrix, (m_{ij}) contains the elastic constants and relates the stress, σ_{ij} and strainε_{ij}component vectors. For the full anisotropic case, the stiffness matrix, stress vector, and strain vector are related by the equations that follow in the original text.

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} & m_{16} \\ m_{12} & m_{22} & m_{23} & m_{24} & m_{25} & m_{26} \\ m_{13} & m_{23} & m_{33} & m_{34} & m_{35} & m_{36} \\ m_{14} & m_{24} & m_{34} & m_{44} & m_{45} & m_{46} \\ m_{15} & m_{25} & m_{35} & m_{45} & m_{55} & m_{56} \\ m_{16} & m_{26} & m_{36} & m_{46} & m_{56} & m_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} \quad (2)$$

Based on a similar assumption. Agwu et al., (2021) the composite will be considered to have a three-dimensional behaviour. For a transversely isotropic behaviour, the stiffness matrix is given in Equation. (3) and (4) elastic values that are independent are needed to explain its behaviour Barbero, (2013).

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{12} & 0 & 0 & 0 \\ m_{12} & m_{22} & m_{23} & 0 & 0 & 0 \\ m_{12} & m_{23} & m_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{m_{22}-m_{23}}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} \quad (3)$$

Both constituent phases of the composite will be assumed isotropic and the stiffness matrix is given in Equation (4)

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{12} & 0 & 0 & 0 \\ m_{12} & m_{11} & m_{12} & 0 & 0 & 0 \\ m_{12} & m_{12} & m_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{m_{11}-m_{12}}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{m_{11}-m_{12}}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{m_{11}-m_{12}}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} \quad (4)$$

Where σ_{ij} and ε_{ij} are the standard constituents of stress and strain. τ_{ij} and γ_{ij} are the shear constituents of stress and strain.

The needed material attributes of the PALF-reinforced composite material will be obtained from Equations (5) to (8) Barbero, (2013)

$$E_1 = m_{11} - \frac{2b_{12}^2}{(b_{22}+b_{23})} \quad (5)$$

$$E_2 = \frac{[m_{11}(m_{22}+m_{23})-2m_{12}^2](m_{22}-m_{23})}{(m_{11}m_{22}-m_{12}^2)} \quad (6)$$

$$\nu_{12} = \frac{m_{12}}{m_{22}+m_{23}} \quad (7)$$

$$G_{23} = \frac{1}{2}(m_{22} - m_{23}) \quad (8)$$

3.2.2 *Analytical models*

This discusses analytical models used to check the results of finite element analysis, which include: The Halpin-Tsai model, Chamis model, and mixtures calibration model (MCM). The mixtures calibration (MCM) model adopts the total density attributes of the fibre particulate filler and matrix constituents to describe the overall properties of a unidirectional fibre-reinforced composite. The Voigt ROM and inverse Reuss ROM provide upper and lower bounds, respectively, on the elastic properties of unidirectional composites. According to the ROM, when stress is applied parallel to the fibre direction, the deformation in the fibre and matrix is assumed to be equal (isostrain condition) since their original lengths are the same before loading. For transverse stresses perpendicular to the fibre, the load carried by the fibre fillers and the matrix was assumed to equal (isostress condition of the inverse ROM). The ROM model equations (9) to (12) give the predicted elastic properties of the composite based on these assumptions.

$$E_1 = E_f V_f + E_m V_m \quad (9)$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (10)$$

$$E_2 = \frac{E_m E_f}{E_m V_f + E_f V_m} \quad (11)$$

$$G_{23} = \frac{G_m G_f}{G_m V_f + G_f V_m} \quad (12)$$

In which; *G*, *ν*, and *E* are respectively the: shear modulus, Poisson's ratio, and Young's modulus, and as well as the subscripts *f* and *m* represent fibre and matrix respectively.

- Chamis modified the IROM in which he replaced the volume fraction of the fibrous component of the material with the value of its square root. The modification of IROM from Chamis is stated below; in equations (13), and (14).

$$E_2 = \frac{E_m}{1-\left\{\sqrt{V_f}\left[1-\left(\frac{E_m}{E_f}\right)\right]\right\}} \quad (13)$$

$$G_{23} = \frac{G_m}{1-\left\{\sqrt{V_f}\left[1-\left(\frac{G_m}{G_f}\right)\right]\right\}} \quad (14)$$

3.2.3 Finite Element analysis

To find the elastic attributes of the particulate-reinforced low-density polyethene composite material, finite element analysis (FEA) of the biomass plastic composite was performed with the use of software: 5.5 version of the COMSOL Multiphysics. The finite element modelling of composites in COMSOL follows the workflow outlined in Figure 2.

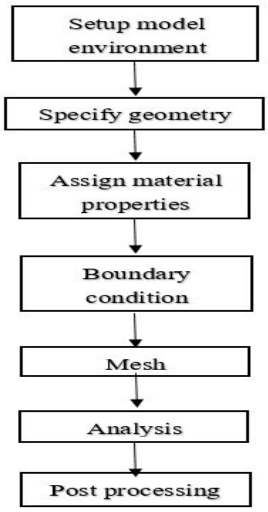


Figure 2: FEA workflow

To make the analysis easier, the following conditions were taken into account:

1. The low-density polyethylene matrix is free of void.
2. The bond between the rice husk fibre and the low-density polyethene polymer is perfect.
3. The rice husk fibres are regularly spaced in low-density polyethene.
4. The rice husk fibres are perfectly aligned in low-density polyethene.

- Geometry of the composite

  To accurately show the representative volume element (RVE) of the composite material, a square packing arrangement of the cylindrical rice husk fibre was considered. Figure 3 shows the micromechanical model of the composite that was developed based on this fibre packing geometry.

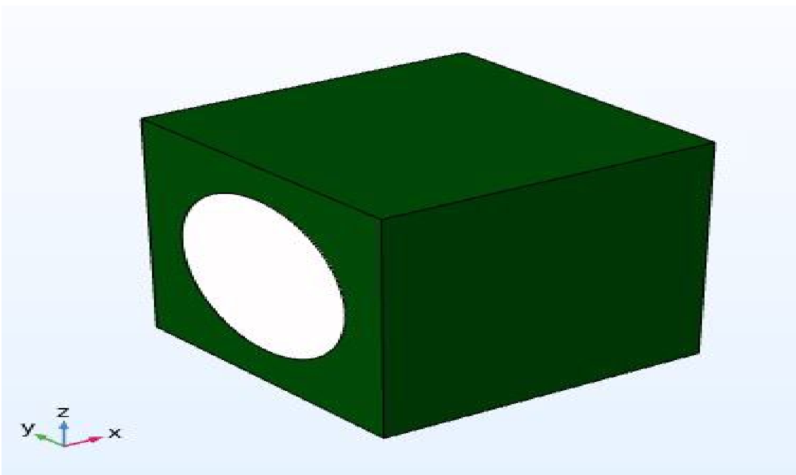


Figure 3: a micromechanical model of the composite

Let ax, ay and az represent the measurement constraints of the volume-element-representative (VER) through the axes of z, y, and x. Since the VER has a square geometry, ax = ay = az = 1 $x10^{-3}m$. The VER is put to a mean strain to calculate the biomass plastic composite material stiffness. Because, the arrangement of fibre filler is assumed as periodic, periodic boundary conditions have to be applied to ensure equivalent distortion across all VERs that form the biomass plastic composite material. The attributes of the applied strain are imposed on the VER by enforcing displacement constraints as shown below in Table 2. This allows the desired strain state to be achieved in the RVE model.

Table 2: Constraints boundary condition through the directions of x, z, and y

Characteristics	**Constraints**	**Boundary conditions**					
		Pair I boundary		Pair II boundary		Pair III boundary	
		$m_{1,5}$	$m_{11,12}$	m_2	m_{10}	m_3	m_4
E_1 and v_{12}	u	0	a_x	non-restricted	unrestricted	unrestricted	non-restricted
	v	non-restricted	non-restricted	0	unrestricted	unrestricted	non-restricted
	w	non-restricted	non-restricted	non-restricted	unrestricted	0	non-restricted
E_2	u	0	non-restricted	non-restricted	non-restricted	non-restricted	non-restricted
	v	non-restricted	non-restricted	0	a_y	non-restricted	non-restricted
	w	non-restricted	non-restricted	non-restricted	non-restricted	0	non-restricted
G_{23}	u	0	0	0	0	0	0
	v					0	a_z
	w			0	0		

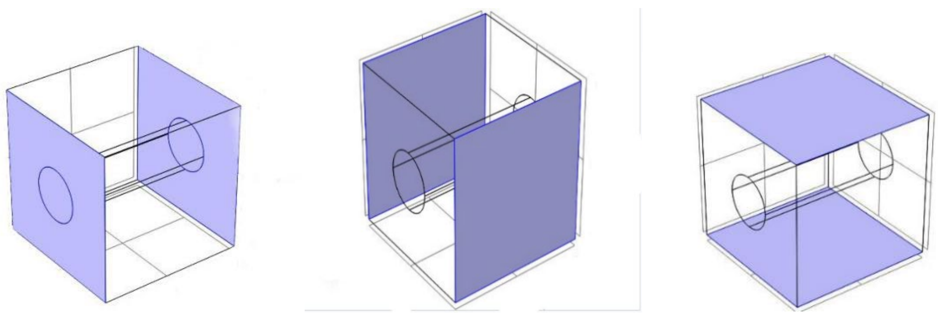
Figure 4 illustrates the various pairs of boundary surfaces that were defined to apply the boundary constraints in this study. On application of these boundary constraints, the equivalent analogous constants are permutated from equations (8), (9) provided in the original text. The desired elastic attributes of the composite material's RVE are then permutated using equations (15) through (16).

$$\overline{\sigma_{ij}} = \frac{1}{V}\int_V^1 \sigma_{ij}\, dV \quad (15)$$

$$\bar{\varepsilon}_{ij} = \frac{1}{V}\int_V^1 \varepsilon_{ij}\, dV \quad (16)$$

where $\overline{\sigma_{ij}}$, $\bar{\varepsilon}_{ij}$and V represent the mean stress, mean strain and the volume of the VER.

In COMSOL software, cell periodicity is defined for all distinct regions of the VER, and the periodic method is set to mean strain. This allows the desired strain state to be applied to the VER. For the mesh, boundaries 1 and 5 of the VER use a freely triangulating mesh system with 0.000018 mesh size. The remaining boundaries use a swept mesh method with a 0.0001 mesh size. Figure 5 shows a modeled mesh of the composite VER at a 0.1 fibre fraction of volume, after applying these mesh settings.



Pair I pair II Pair III

Figure 4**:** Boundary condition: pair I, II, and III correspondingly for 0.1 fibre volume fraction

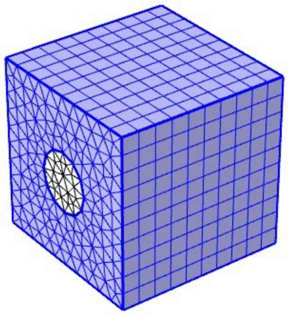


Figure 5: Meshed VER: The FEA results were validated using the selected analytical models.

4.0 Results and Discussion

To express the elastic characteristics effectiveness of the oyster shell fibre- reinforced low-density polyethylene composite, this study considered the consequence of the fibre volume fraction variations. Specifically, the elastic attributes were computed at volume fractions for fibre fillers of 0.1, 0.2, 0.3, 0.4 and 0.5 using Finite Element Analysis. The values obtained from this analysis at the different volume fractions are presented in Table 3 below.

Table 3: Elastic attributes of the oyster shell fibre reinforced polyethylene

Model	Fibre volume fraction	Elastic properties			
		E_1(GPa)	E_2 (GPa)	v_{12}	G_{23}(GPa)
FEM	0.1	5.7899	3.7309	0.3262	1.3531
	0.2	8.4801	4.4512	0.3227	1.6119
	0.3	11.170	5.3718	0.3193	1.9690
	0.4	13.860	6.5800	0.3161	2.4608
	0.5	16.550	8.1845	0.3130	3.1348
ROM	0.1	5.7900	3.4053	0.3270	1.2805
	0.2	8.4000	3.7774	0.3240	1.4209
	0.3	11.1700	4.2408	0.3210	1.5955
	0.4	13.8600	4.8337	0.3180	1.8198
	0.5	16.5500	5.6193	0.3250	2.1170
Chamis	0.1	5.7900	4.3269	0.3270	1.6283
	0.2	8.4000	5.1753	0.3240	1.9490
	0.3	11.1700	6.0919	0.3210	2.2959
	0.4	13.8600	7.1610	0.3180	2.7013
	0.5	16.5500	8.4708	0.3250	3.1989

4.1 Fibre volume fraction and the effect on longitudinal modulus

The ratio of applied stress parallel to the direction of fibre filler to the resulting strain in that direction is referred to as longitudinal modulus. Figure 6 depicts the distribution of stress within the VER under the applied strain loading, clearly indicating that the fibre is the primary load-bearing constituent. As seen in Figure 7, the biomass plastic composites' longitudinal modulus varies directly with that of the fibre filler volume fraction. A similar observation is obtainable between the finite element analysis (FEA) values and predictions from the analytical micromechanics models.

4.2 Fibre filler volume fraction and the effect on in-plane Poisson ratio

As described in Figure 8 Poisson's ratio of the biomass-reinforced composite material varies inversely with the volume fraction of the fibre filler. The trend occurs, because, as the stiffer reinforced fibre volume fraction is increased, it would result in less overall deformation of the composite under loading.

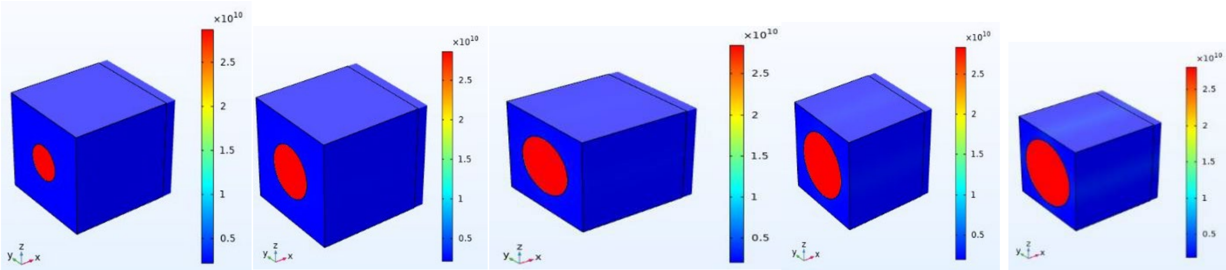


Figure 6 : stress distribution due to axial load

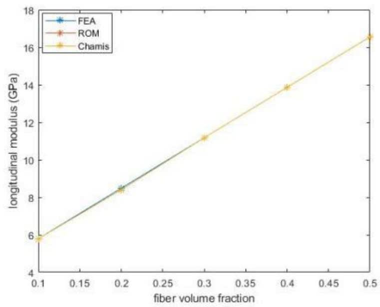


Figure 7: The graph of longitudinal modulus due to the effect of fibre loading.

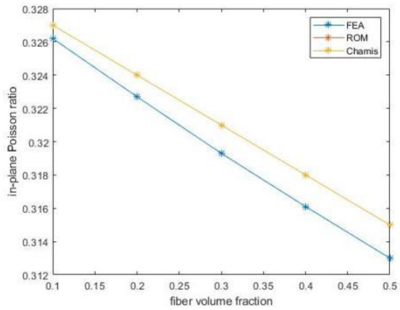


Figure 8: Effects observed when fibre is loaded on in-plane Poisson ratio

4.3 Effect of the fibre volume fraction on the transverse modulus

The transverse modulus is defined as the ratio of the applied stress perpendicular to the direction of fibre filler to the strain in that transverse direction. Figure 9 shows the stress distribution within the RVE at various fibre volume fractions when deformation is transversely applied. As observed in Figure 10, an increment in the fibre filler volume fraction results in an increment in the transverse modulus of the composite material. This is expected, as increasing the number of reinforcing fibres enhances the material's stiffness, even in the transverse plane to the fibre fillers' direction.

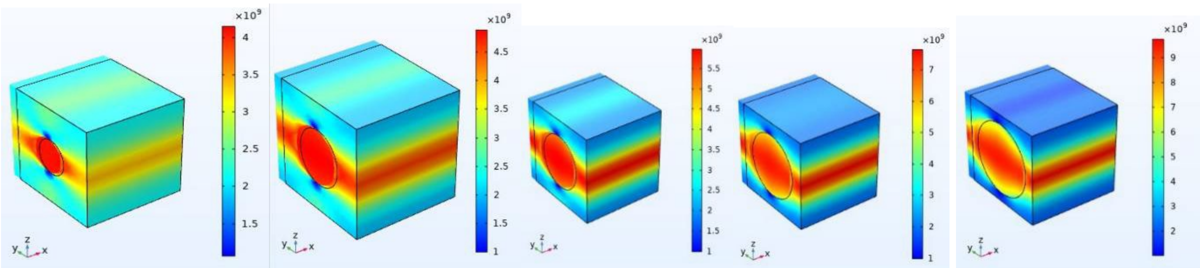


Figure 9: stress distribution due to load applied in the transverse direction

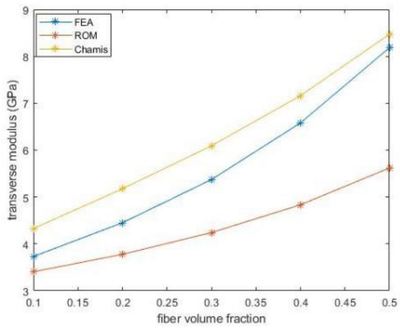


Figure 10: Fibre filler loading effect on in-plane Poisson ratio

4.4 Fibre filler volume fraction effect on shear modulus of the in-plane

The shear modulus values of the in-plane are related to the applied shear stress to the resultant shear strain. Figure 11 depicts the stress spread within the RVE for a host of fibre filler volume fractions when axial shear deformation is applied. In Figure 12, the in-plane shear modulus varies directly with the volume fraction of fibre. This occurs because incorporating more of the stiffer fibre reinforcement enhances the composite's resistance to shear deformation.

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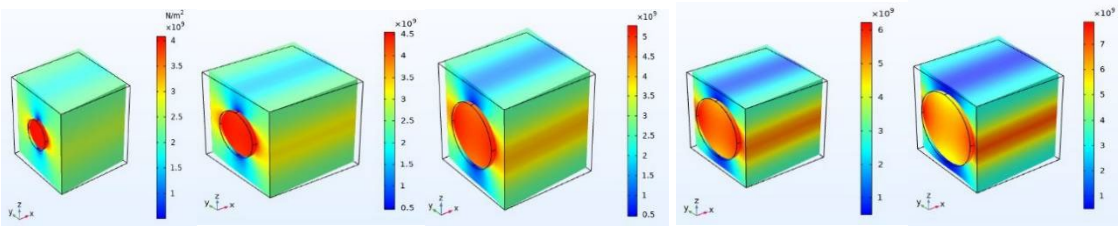

Figure 11**:** Stress distribution due to shear deformation

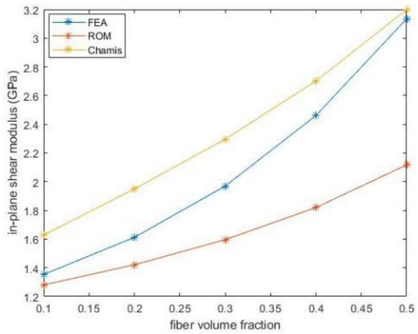

Figure 12: Fibre filler loading effect on in-plane shear modulus

5.0 Conclusion

Natural fibre fillers, which have a continuous renewable supply from nature, have gained attention as reinforcements for polymer composites to replace synthetic fibres. In this research, a micromechanical model of natural fibre filler reinforced polymer to develop biomass plastic composite (BPC) was developed using COMSOL Multiphysics Finite Element software to accurately depict the effective attributes of the composite material. Specifically, the fibre volume fraction effect on the elastic properties of this composite was investigated. The elastic properties analyzed were the longitudinal moduli, transverse moduli, in-plane Poisson's ratio, and in-plane shear moduli. The results showed that these properties are heavily dependent on the fibre volume fraction and cross-sectional geometry, which agrees with expected micromechanics and reinforcement mechanisms. The results from this research produce valuable insight into the mechanism of natural fibre filler-reinforced plastic composites to allow optimal utilization for varied applications. The numerical finite element predictions showed good agreement with selected analytical micromechanics models. Overall, this work demonstrates the capability to model and predict the influence of key parameters like the volume fraction of fibre on the effectual elastic attributes of natural fibre filler-reinforced polymer composite materials using finite element micromechanics techniques.

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Conflict of interest

The authors declare no conflict of interest.

Authors' Contribution Statement

Solomon C. Madu: Conceptualization, Methodology, Writing Original Draft, Validation, Funding acquisition review/editing; V.S. Aigbodion Writing original draft and methodology, Supervision; Ocheri C. Investigation, analysis and methodology.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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