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Valorization of Waste LDPE Using *Isoberlina* Wood Fillers: Mechanical Properties, Creep Resistance, and Dynamic Viscoelastic Behavior of Sustainable Composites

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ABSTRACT

In an effort to develop eco-conscious technologies for waste reduction, this study explores the potential of *Isoberlina* wood fibre (IWF) as a reinforcing agent in recycled low-density polyethylene (rLDPE) composites, aiming to enhance mechanical performance while promoting sustainable reuse of plastic waste. Using standardized mechanical testing, dynamic mechanical analysis (DMA), and creep evaluation, the influence of IWF on the composite's structural and viscoelastic properties was evaluated. At 20 wt% fibre content, the rLDPE composite exhibited significant improvements: tensile strength (11.5 MPa), elastic modulus (167 MPa), flexural strength (70.4 MPa), and Shore hardness (68). DMA results revealed a substantial increase in storage modulus from 330 MPa to 1.2 GPa, indicating enhanced load-bearing capacity. A decline in loss modulus with increasing temperature and frequency suggested reduced energy dissipation and improved stiffness. Creep analysis demonstrated a lower strain rate over time, with the reinforced composite reaching equilibrium at 38.1 minutes, outperforming the unreinforced rLDPE polymer and confirming improved resistance to long-term deformation. These results underscore the effectiveness of *Isoberlina* fibre in enhancing the mechanical, thermal and creep performance of rLDPE, offering a viable pathway for eco-friendly composite development.

Keywords: Waste valorization, *Isoberlina* fibre, Mechanical properties, Dynamic analysis, Wood and plastic waste.

1.0 INTRODUCTION

The widespread use of bottled and sachet-packaged water, though convenient, comes at a steep environmental cost (Yusuf *et al.,* 2024). The proliferation of plastic waste is predominantly driven by short-lived consumer products, particularly single-use plastics (Jacob, 2019). Among these, low-density polyethylene (LDPE) presents a notable concern due to its extensive utilization in packaging and disposable applications (Dokl *et al.,* 2024; Chelliah *et al.,* 2025). Packaging alone account for approximately 40% of global plastic production, positioning it as the primary contributor to plastic waste and a critical focus for mitigation strategies (Geyer, 2020). This is further driven by the relatively low recycling rate of post-consumer LDPE, estimated at just 35%, which has led to its persistent accumulation in terrestrial and aquatic environments (Romero-Gómez *et al.,* 2022). These trends highlight the urgent need for innovative valorization pathways for LDPE waste, particularly through its integration into polymer composites that offer enhanced performance and sustainability (Rumana-Hossain and Veena-Sahajwalla, 2025).

To respond to the recent surge in demand for environmentally responsible and recyclable materials, wood-plastic composites (WPCs) have emerged as promising alternatives (Fadipe *et al.,* 2025). These hybrid materials synergistically combine wood fibers with thermoplastic matrices such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), resulting in improved properties that cannot be achieved from either component alone (Samyn, 2024; Chawla, 2013). WPCs are widely used in both structural and non-structural applications, including decking, fencing, automobile parts, and interior furnishings, because of their ability to be extruded or injected into intricate geometries (Chen et al., 2018). Wood-plastic composites offer an excellent balance of mechanical stiffness, stable geometry, and resistance to moisture and biodegradation (Jacob, 2019; Musa *et al.,* 2024).

The integration of post-consumer or post-industrial plastic waste into WPC formulations not only improves material performance but also aligns with circular economy principles by reducing polymer waste and promoting resource efficiency (Chelliah *et al.,* 2025; Haba *et al.,* 2025; Jacob and Yusuf, 2023). Recent advances in WPC technology have focused on optimizing the use of recycled plastics and natural fibers to enhance sustainability and mechanical integrity. LDPE-based WPCs, in particular, have demonstrated improved stiffness and dimensional stability when reinforced with lignocellulosic fillers (Chen et al., 2018; Delgado-Alvarado *et al.,* 2019; Shinggu and Jacob, 2025). However, challenges such as poor interfacial adhesion and limited long-term

durability persist (Yusuf *et al.,* 2020; Khan *et al.,* 2025; Hao *et al.,* 2025).

Researchers have extensively studied ways to improve the strength of frequently used plastics through composite development. Khan et al. (2025) highlighted the influence of lignocellulosic particle content in modulating the structural properties of polyethylene composites, while Jubinville et al. (2024) explored compatibilization strategies to improve the recyclability and mechanical integrity of LDPE blends. Despite these advancements, limited attention has been given to the use of tropical hardwood species such as *Isoberlina* as fillers, which may offer unique advantages in terms of fiber morphology, thermal stability, and mechanical reinforcement. This gap presents an opportunity to investigate underutilized bioresources for composite development, particularly in the context of LDPE valorization.

This study investigates the valorization of waste LDPE through its reinforcement with *Isoberlina* wood fibers, a lignocellulosic filler derived from tropical hardwood species. By evaluating the mechanical properties, creep resistance, and dynamic viscoelastic behavior of the resulting composites, the research aims to elucidate the structure-property relationships that govern their performance. Particular emphasis is placed on the processing behavior and long-term durability of the materials under simulated service conditions. Through systematic characterization, this work contributes to the growing body of knowledge on sustainable composite technologies and supports the development of scalable solutions for polymer waste valorization.

2.0 METHODOLOGY

2.1 Sample Collection and Preparation

Post-consumer plastic waste from sachet-packaged water, composed of low-density polyethylene (LDPE, recycling code 4), was collected from refuse dumps located in and around the Federal University, Gusau, Nigeria. The collected samples were thoroughly washed with water to remove surface contaminants and subsequently air-dried. *Isoberlina* wood, locally referred to as *Kiriya* in Hausa and *Ayan* in Yoruba, was sourced from Hannu-Tara in Dansadau, Maru Local Government Area, Zamfara State, Nigeria. The logs were manually sectioned into smaller pieces and sun-dried for seven days to reduce moisture content. The dried wood was then pulverized using a mechanical grinder and sieved through a 100 µm mesh, following the procedure described by Jacob and Mamza (2021). To enhance interfacial compatibility between the hydrophilic wood fibers and the hydrophobic LDPE matrix, the sieved wood powder underwent alkali treatment using sodium hydroxide solution. This chemical modification was intended to remove surface impurities, reduce lignin and hemicellulose content, and improve fiber-matrix adhesion.

2.2 Composite Production

Post-consumer low-density polyethylene (LDPE) waste sourced from sachet-packaged water was reclaimed and designated as recycled LDPE (rLDPE). *Isoberlina* powder, serving as the lignocellulosic filler, was dried and sieved prior to compounding. Composite fabrication was carried out using a two-roll mill (Model No. 5183, New Jersey, USA) followed by compression molding. Initially, rLDPE was introduced into preheated rollers operating counterclockwise at 160 °C and mixed for 10 minutes to achieve a homogeneous melt. Subsequently, *Isoberlina* powder was manually incorporated into the molten matrix while maintaining a roller speed of 500 rpm to ensure uniform dispersion. Composite formulations were prepared with filler loadings ranging from 5 wt% to 25 wt%, with corresponding adjustments to the rLDPE content. The compounded materials were then transferred to a hydraulic press and cured at 170 °C under a compression pressure of 3 Pa for 10 minutes. Post-curing, the samples were cooled to ambient temperature, machined to standard dimensions, and conditioned prior to characterization. All procedures were conducted in accordance with established protocols (Jacob *et al.,* 2018; Jacob *et al.,* 2019).

2.3 Mechanical Property Test

2.3.1 Tensile test

Tensile properties of the polymer samples were evaluated in accordance with ASTM D638 (2014). Specimens were machined into a standard dumbbell geometry prior to testing. Mechanical characterization was performed using a computerized Instron Universal Testing Machine (Model 3369), which measured the elastic modulus and tensile strength of each sample.

2.3.2 Flexural strength

Flexural strength measurements were conducted following ASTM D790 (2015) using a universal testing machine configured for three-point bending. Tests were performed at a crosshead speed of 5 mm/min with a support span length of 40 mm.

The flexural strength (MPa) was calculated using equation (1): $\sigma = \frac{3Pl}{2bt^2}$

l = specimen span length between supports (mm)
P is the greatest deflection force (N).
b is the specimen's width (mm).
t = specimen thickness (mm)

2.3.3 Hardness test

The surface hardness of the composite samples was evaluated based on their resistance to indentation under a specified load, as described by Jacob et al. (2018). Shore A hardness was measured using a durometer on specimens with dimensions of 30 mm × 30 mm × 5 mm.

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Five measurements were taken at different locations on each sample, and the average value was reported as the representative hardness.

2.4 Thermal Properties

2.4.1 Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis was carried out using DMA 242 E machine in strength of materials Laboratory, Mechanical Engineering Department, ABU Zaria, in accordance with ASTM D7028 (2015). The test parameters, storage modulus (E′), loss modulus (E″), and damping factor (tan δ), were configured using Proteus software on a personal computer. The instrument was set to operate within a temperature range of 30 °C to 110 °C, with a dynamic load amplitude of 4 N and a frequency sweep from 1 to 10 Hz. A 3-point bending fixture was employed as the sample holder, and the heating rate was maintained at 3 K/min throughout the test to evaluate the thermomechanical behavior of the polymer samples.

3.0 RESULTS AND DISCUSSION

3.1 Physical properties

3.1.1 Tensile strength

Figure 1 illustrates how the tensile strength of *Isoberlina*-rLDPE composites varies with increasing fibre content. The strength increases between 5% and 20% fibre loading but drops at 25%. This initial improvement may be due to better interfacial bonding within the composite as the *Isoberlina*-rLDPE matrix becomes less dominant with higher reinforcement levels. Similar trends have been reported by other researchers (Jacob et al., 2018; Jacob & Mamza, 2021). Alegría-Torres, J. and Vallejo-Montesinos, J. (2023).

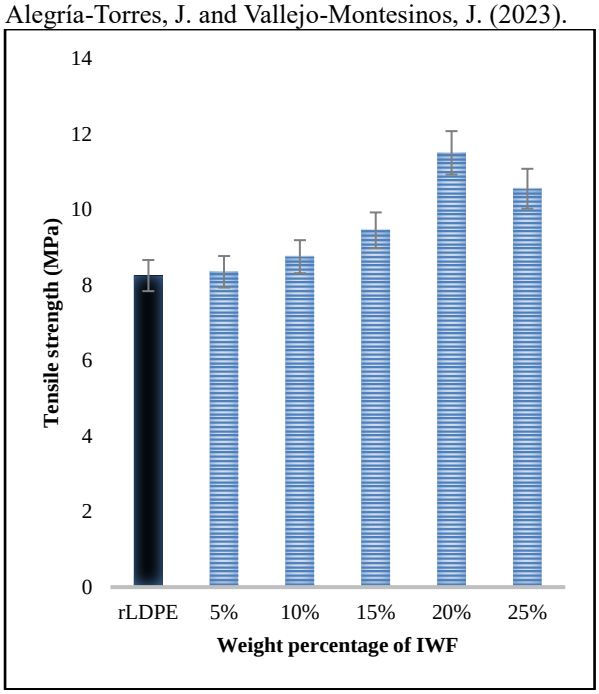

Figure 1: Effect of *Isoberlina* wood fibre on the tensile strength of rLDPE composites

3.1.2 Elastic modulus

Figure 2 demonstrates the variation in elastic modulus of *Isoberlina*-rLDPE composite as a function of fiber loading. A progressive enhancement in stiffness was recorded with increasing *Isoberlina* content, reaching a peak modulus of 167 MPa at 20 wt%. This improvement is likely due to enhanced interfacial bonding between the rLDPE matrix and the incorporated *Isoberlina* fibers. The observed trend aligns well with previous studies reported by Khalaf (2015), Jacob & Mamza (2021), and Rosas Orta et al. (2024).

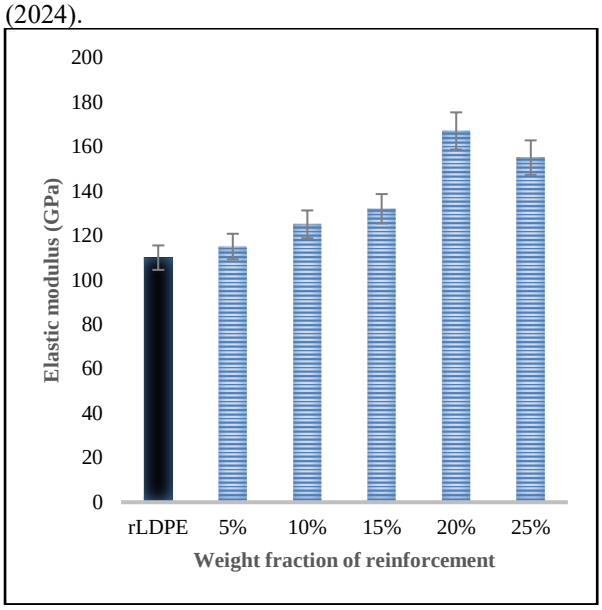

Figure 2: Effect of *Isoberlina* wood fibre on the elastic modulus of rLDPE composites

3.1.3 Flexural strength

Figure 3 presents the flexural strength behavior of recycled low-density polyethylene (rLDPE) composites reinforced with *Isoberlina* powder across varying weight fractions. An initial enhancement in flexural strength was observed with increasing fiber content, reaching a maximum value of 70.4 MPa at 20 wt%. This improvement is indicative of effective interfacial bonding and efficient stress transfer between the polymer matrix and the reinforcing particles. However, a subsequent decline in flexural strength at 25 wt% suggests the onset of interfacial debonding and suboptimal fiber-matrix adhesion, corroborating the findings of Yusuf (2024), and Shingu and Jacob (2025).

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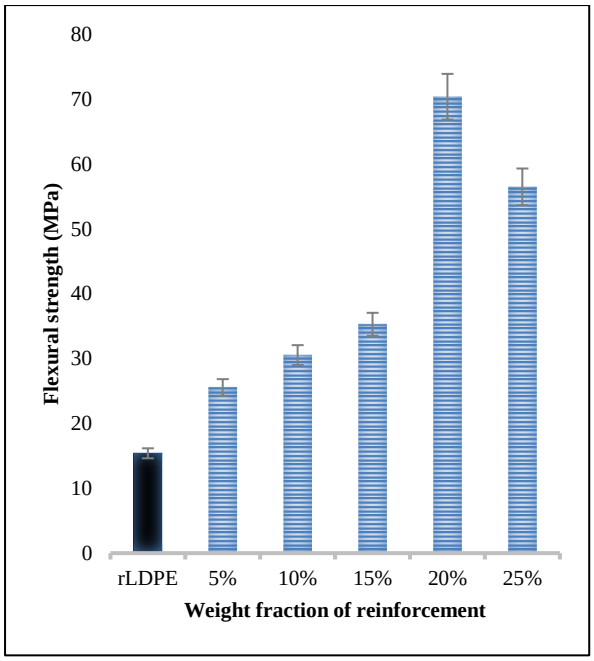

Figure 3: Effect of *Isoberlina* wood fibre on the flexural strength of rLDPE composites

3.1.4 Hardness

Hardness testing of the composite materials was performed in accordance with standard indentation-based protocols, which assess a material's resistance to localized plastic deformation under a defined load and indenter geometry (Jacob, 2019). Figure 4 presents the hardness values of *Isoberlina*-rLDPE composites across varying weight fractions. A gradual increase in hardness was observed with increasing reinforcement content, culminating in a maximum value of 68.0 Shores at the highest loading level. This enhancement is attributed to improved interfacial adhesion between the *Isoberlina* fibers and the rLDPE matrix, which facilitates more efficient stress distribution and resistance to surface deformation. These findings are in agreement with the work of Yusuf et al. (2020), who reported similar reinforcement-induced improvements in mechanical performance and creep resistance in polyvinyl chloride composites incorporating *Prosopis africana* wood fillers.

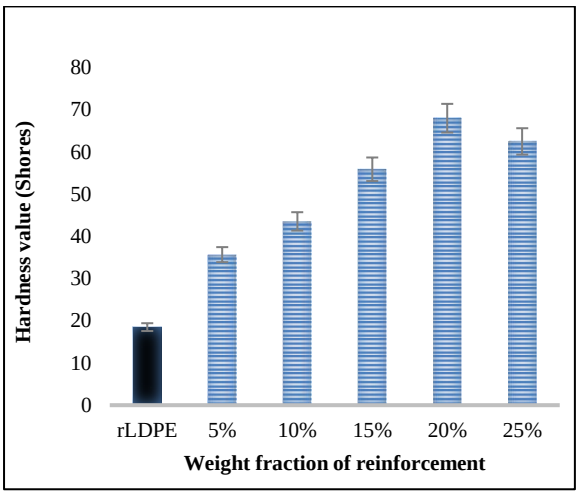

Figure 4: Effect of *Isoberlina* wood fibre on the hardness value of rLDPE composites

3.1.5 Thermal Properties

Storage modulus of unreinforced waste rLDPE (control sample)

The stiffness and energy storage capacity of a material is described by its storage modulus (Jacob *et al.,* 2018). Figure 5 shows the storage modulus of unreinforced rLDPE (control) at frequencies of 2.5, 5, and 10 Hz. The graph shows that the material is unstable at temperatures under 50 ℃ with a maximum rigidity of 0.033 GPa. The finding is consistent with the work of Jacob and Yusuf (2023) who reported the dynamic mechanical and morphological characterization of treated *Prosopis africana* wood fibre reinforced polyvinyl chloride composites and that made by Dan-asabe (2016), and Shinggu and Jacob (2025).

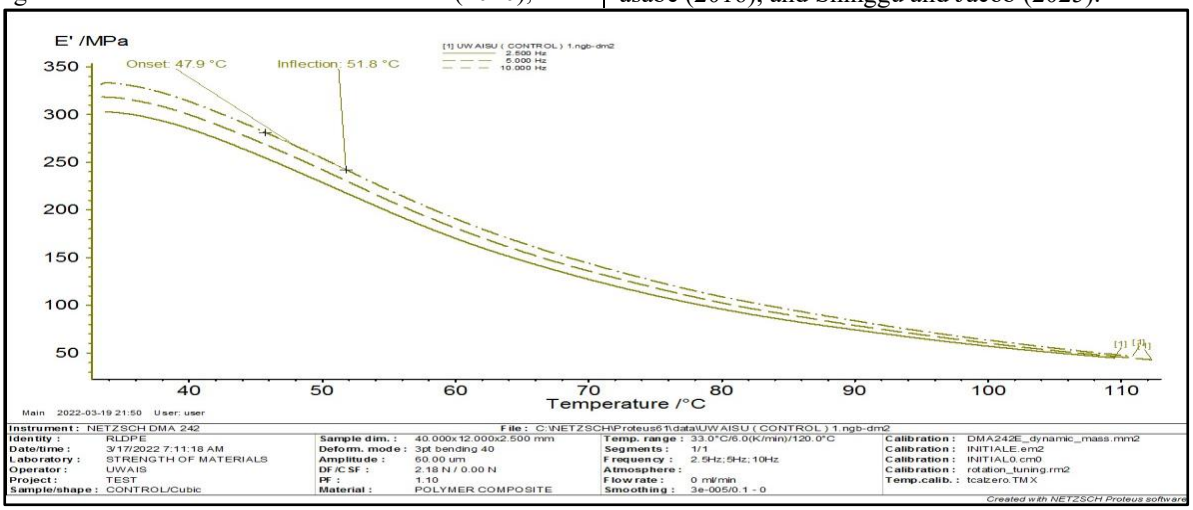

Figure 5: Storage modulus curve of unreinforced waste LDPE at 2.5, 5 and 10 Hz

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Storage modulus of 20 % IWF filled waste LDPE composites

Figures 6 depicts the storage modulus of 20 % IWF reinforced waste LDPE composites at 2.5 5, and 10 Hz, respectively. These result shows that the addition of IWF into waste LDPE increased the material's stiffness and energy storage capability (Shinggu and Jacob, 2025). This is because wLDPE's maximum stiffness stability increased from 0.33 GPa (control) to 1.2 GPa at 20 % weight of IWF (Figure 6). This could be attributed to the composites' strong fiber-matrix interaction (Jacob *et al.,* 2019; Shaikh *et al.,* 2023; Yusuf *et al.,* 2024). The results of an increase in storage modulus with a weight percentage of IWF fibres incorporated are also at par with the mechanical properties results (Dan-asabe, 2016; Yusuf *et al.,* 2020b).

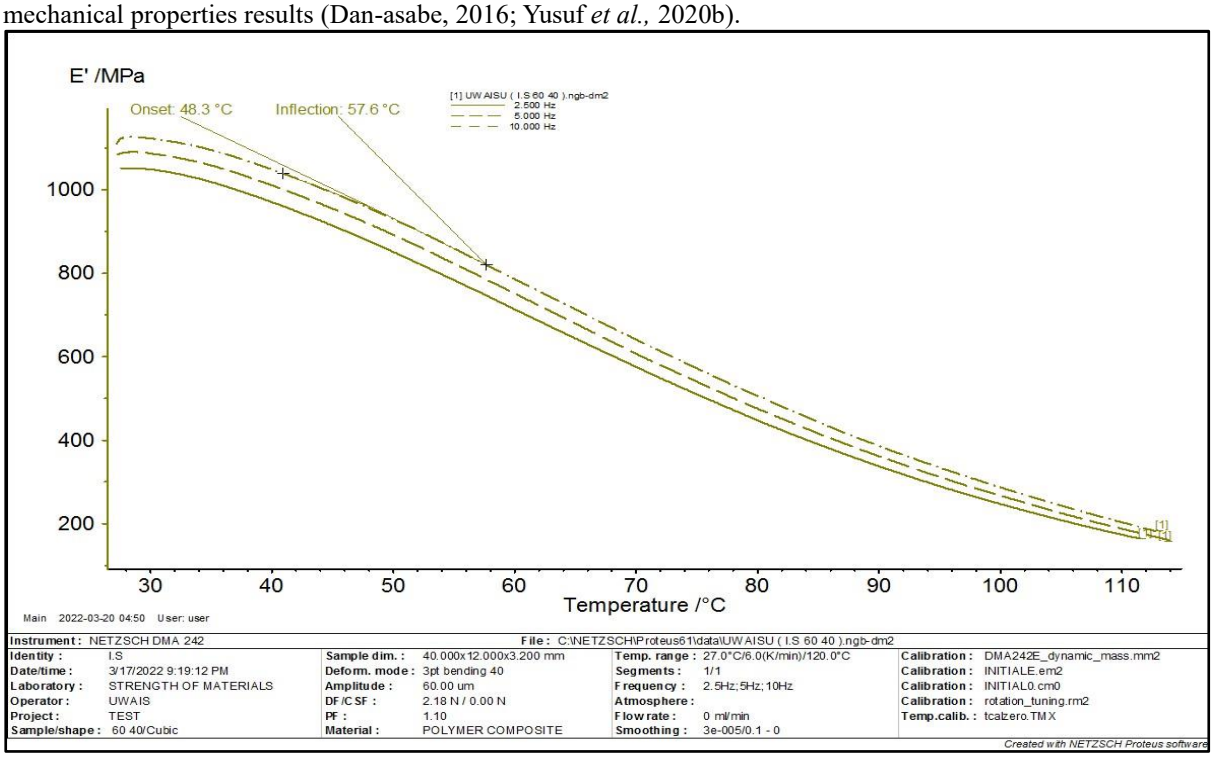

Figure 6: Storage modulus curve of IWF filled waste LDPE composites at 2.5, 5 and 10 Hz.

Loss modulus of 20 % IWF filled waste LDPE composites

Loss modulus (E") is defined as the maximum energy dissipated by composite materials during deformation (Jacob, 2019). The variation in loss modulus of unfilled waste LDPE and 20 % IWF reinforced waste LDPE composites as a function of temperature at 2.5, 5 and 10 Hz frequency is shown in figures 7 and 8. It was observed that the unreinforced composite (figure 7) has the highest loss modulus compared to that of the composites. This implies that the incorporation of IWF into rLDPE increases its thermal stability. However, the loss modulus was found to decrease with increase in temperature.

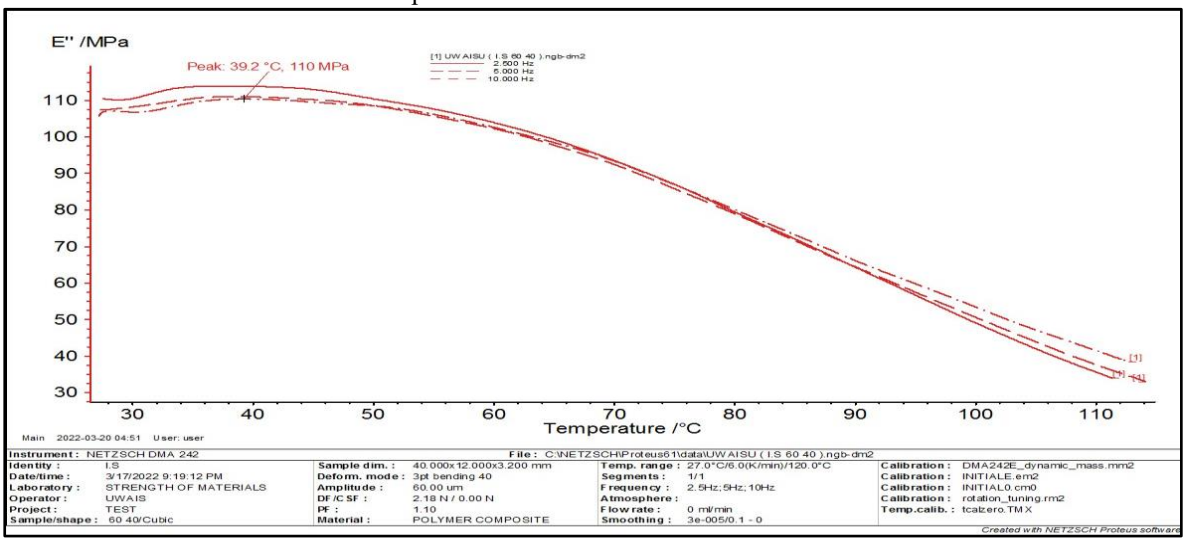

Figure 7*:* Loss modulus of unfilled waste LDPE at 2.5, 5 and 10 Hz.

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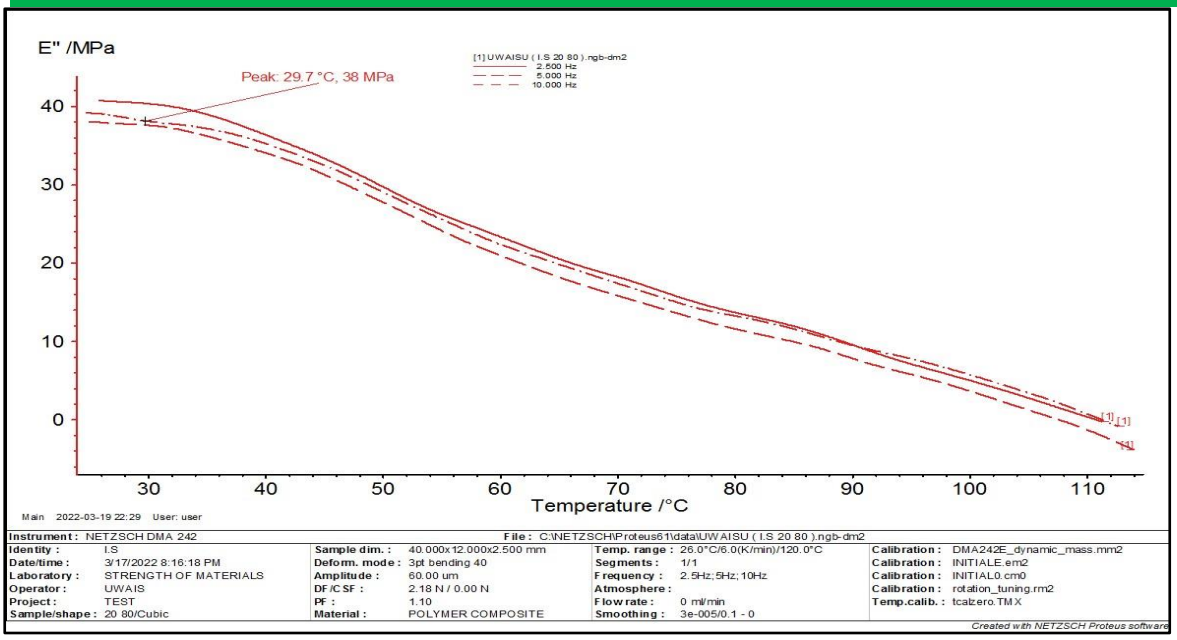

Figure 8*:* Loss modulus of 20 % IWF filled waste LDPE composites at 2.5, 5 and 10 Hz.

Damping parameter of unreinforced waste rLDPE (control sample)

Damping (Tan delta) is defined as the loss modulus divided by storage modulus. It is also known as the loss factor and is typically stated as a dimensionless number (Gupta, 2018; Jacob *et al.,* 2019). Figure 9 shows the temperature dependence of the tan ∂ (damping) of the unreinforced sample at different frequencies. A high tan ∂ value is indicative of a material that has a high, non-elastic strain component, while a low value indicates one that is more elastic. Therefore, improvement in interfacial bonding in composites occurs as observed by lowering in tan ∂ values (Jacob, 2019). The damping factor of the composite (figure 10) was observed to be lower than that of the control sample (figure 9). This could be due to better compatibility and reinforcing effect of IWF in the waste LDPE matrix. Lower value of damping shows the good load bearing capacity of the composites (Jacob, 2023).

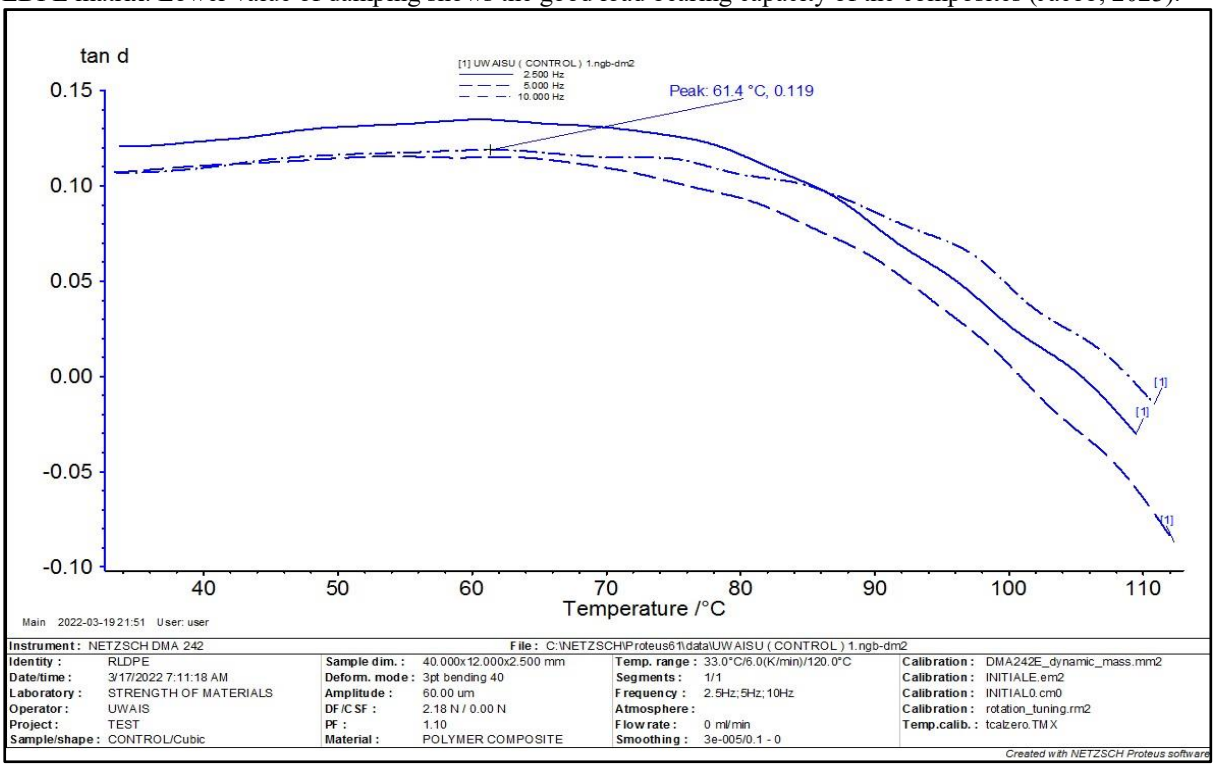

Figure 9: Damping parameter of unfilled waste LDPE at 2.5, 5 and 10 Hz.

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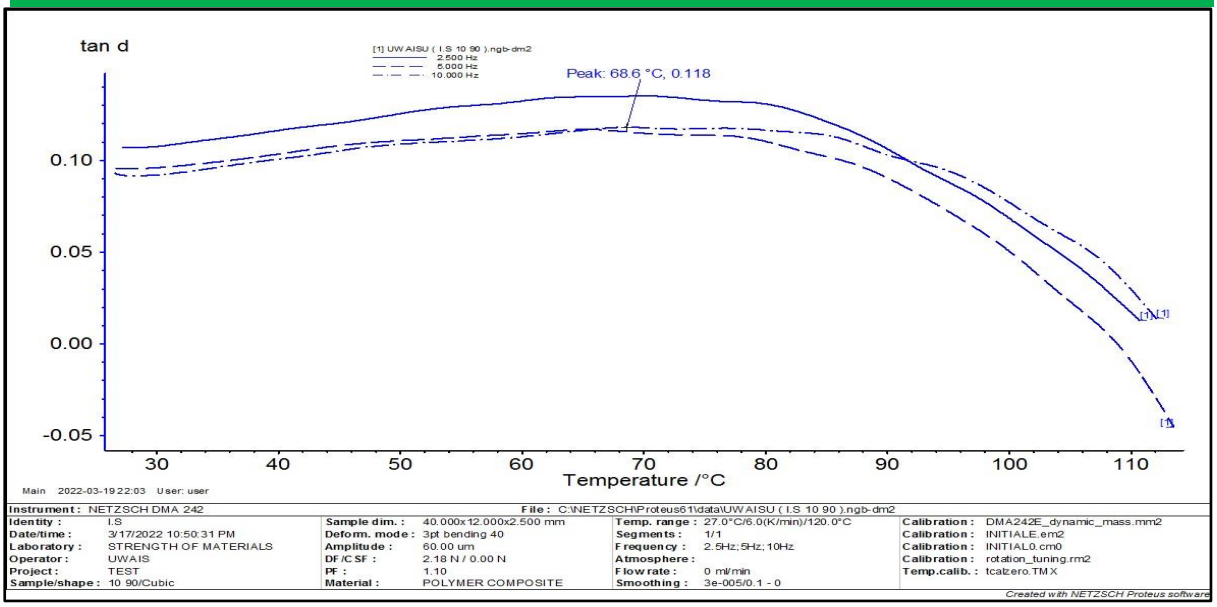

Figure 10: Damping parameter of 20 % IWF filled waste LDPE composites at 2.5, 5 and 10 Hz.

Creep

Creep is defined as the time-dependent deformation of materials under constant stress, depending on factors such as applied load, temperature, exposure duration, and the intrinsic properties of the material (Ganesh-Gupta *et al.,* 2021). Figure 11 presents the creep response of recycled low-density polyethylene (rLDPE) reinforced with 20 wt% *Isoberlina* wood fibre at 70 °C. A pronounced initial strain is observed upon loading, which progressively diminishes and stabilizes at approximately 38.1 minutes, marking the onset of the equilibrium strain rate. This phase corresponds to secondary creep, is critical in evaluating the load-bearing capacity of polymer composites. Comparable findings have been reported in previous studies (Yusuf *et al.,* 2020; Ganesh-Gupta *et al.,* 2021).

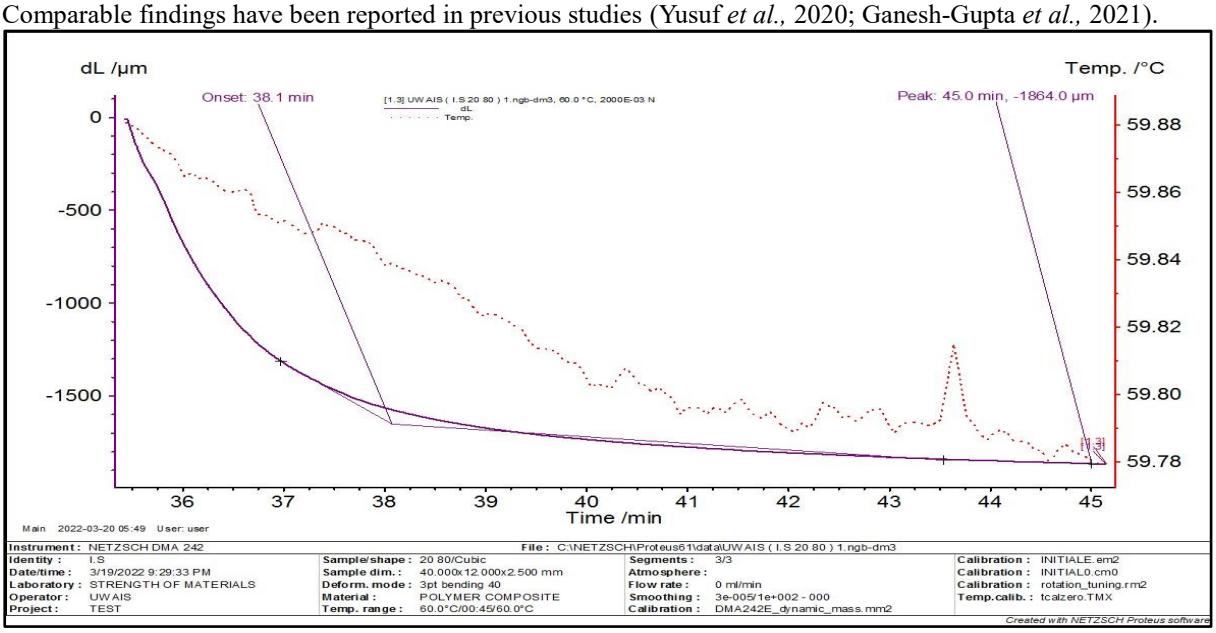

Figure 11: Creep curve of 20 % IWF filled waste LDPE composite at 70 ℃

Figure 12 shows the creep curve of the unreinforced rLDPE. The equilibrium strain rate occurred at 36.2 min which is lower than that of the composites. This is an indication of improvement in the load bearing capability of the IWF-rLDPE composites.

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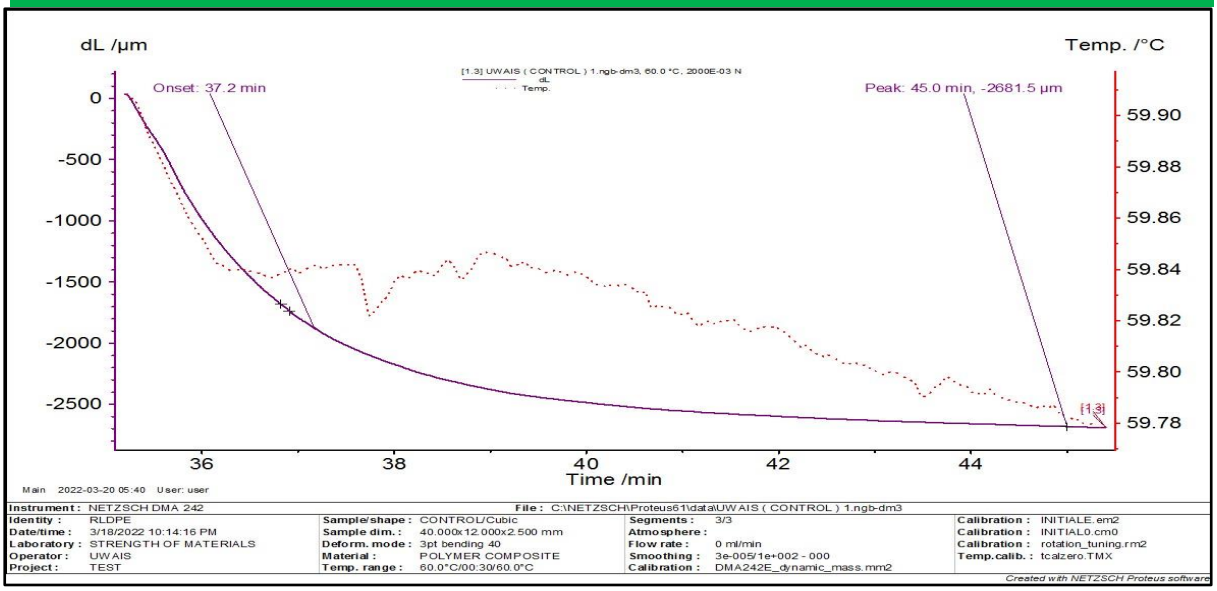

Figure 12: Creep curve of unfilled waste LDPE at 70 ℃

4.0 CONCLUSION

The valorization of waste low-density polyethylene (LDPE) through reinforcement with *Isoberlina* wood fillers (IWF) has yielded sustainable composites with significantly enhanced mechanical and viscoelastic properties. The incorporation of IWF into recycled LDPE (rLDPE) resulted in progressive improvements in tensile strength, elastic modulus, flexural strength, and Shore hardness, with optimal performance observed at 20 wt% filler content (11.5 MPa tensile strength, 167 MPa elastic modulus, 70.4 MPa flexural strength, and Shore hardness of 68). Dynamic mechanical analysis revealed a marked increase in storage modulus from 330 MPa to 1.2 GPa, indicating improved load-bearing capacity. The reduction in loss modulus with increasing temperature and frequency further suggests enhanced stiffness and lower energy dissipation. Creep resistance was notably improved, with the reinforced composite reaching equilibrium strain at 38.1 minutes, demonstrating superior resistance to long-term deformation compared to unreinforced rLDPE.

These findings confirm that integration of *Isoberlina* wood fillers into recycled LDPE not only enhances composite performance but also exemplifies a circular approach to polymer valorization. By leveraging bio-based fillers and post-consumer plastics, this work contributes to the development of sustainable materials with practical utility. Continued exploration of formulation strategies and processing optimization will be pivotal in advancing high-performance, eco-conscious polymer systems for scalable industrial adoption.

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