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# Effect of Hybrid Castor Nutshell/Pineapple Leaf Fiber Loading on Creep Behavior of Epoxy Composites

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***Abstract.*** *Epoxy composites can undergo time-dependent deformation under sustained loading, limiting their dimensional stability, while agricultural residues offer potential as sustainable reinforcements. This study evaluated the effect of hybrid castor nutshell (CNS) and pineapple leaf fiber (PALF) powder loading on the displacement response and fracture-surface morphology of epoxy composites. CNS and PALF powders (75 µm) were combined at a 50:50 weight ratio and incorporated at total loadings of 0, 5, 10, 15 and 20wt%. The composites were fabricated by hand lay-up and evaluated using dynamic mechanical analysis (DMA)in three-point-bending mode at 100°C; scanning electron microscopy (SEM) was used to examine the tested specimens. The neat epoxy reached a displacement of approximately −103µm. The reinforced formulations showed loading-dependent responses, with reported later-stage displacements of approximately −63, −78 and −65µm for the 10, 15 and 20wt% composites, respectively; the 5wt% specimen showed a distinct change to approximately +12µm. SEM indicated the most homogeneous dispersion and lowest measured void and agglomerated areas in the 5wt% composite, whereas the 15wt% composite showed the greatest agglomeration and void content. These results indicate that hybrid CNS/PALF loading and dispersion influence the measured deformation response. However, because the study reports displacement rather than a normalized creep strain or compliance, and is limited to one temperature and a short test, further standardized creep testing is needed before drawing conclusions about long-term performance.*

***Keywords:*** *castor nutshell; pineapple leaf fibre; epoxy composites; creep behaviour; scanning electron microscopy.*

**Type of the Paper:** Regular Article.

## 1. Introduction

Growing environmental concerns, depletion of non-renewable resources, and increasingly stringent environmental regulations have accelerated the development of sustainable composite materials from renewable resources. Natural fiber reinforced polymer composites have attracted considerable attention as alternatives to conventional synthetic fiber composites because of their



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low density, renewability, biodegradability, cost-effectiveness, and favourable specific mechanical properties. These attributes have encouraged their application in automotive components, sporting goods, packaging, marine structures, and civil engineering applications. Recent advances in fiber treatment, composite processing, and hybrid reinforcement have further improved the performance of natural fiber composites, increasing their potential for structural and semi-structural applications [1–5].

Epoxy resins are widely used as thermosetting matrices because of their high stiffness and strength, low curing shrinkage, chemical resistance, dimensional stability, and strong adhesion to reinforcing materials. However, epoxy exhibits viscoelastic behaviour and can undergo time-dependent deformation under sustained loading, particularly at elevated temperatures. This behaviour can compromise dimensional stability and limit the service performance of epoxy-based composites. Incorporating natural fibers and bio-based particulate fillers into epoxy is therefore an attractive approach for improving stiffness, resistance to deformation, and sustainability while reducing dependence on synthetic reinforcements [1,3,4].

PALF is a promising lignocellulosic reinforcement owing to its relatively high cellulose content, low microfibrillar angle, tensile strength, and specific modulus. PALF is obtained from pineapple leaves, which are frequently discarded after harvesting, making its utilization attractive for agricultural waste valorization. Previous studies have demonstrated that PALF can improve the mechanical and thermal performance of polymer composites when adequate fiber-matrix adhesion and appropriate reinforcement loading are achieved. Surface modification and optimized fiber content can further improve interfacial bonding, stress transfer, and composite durability [4,5].

In parallel, agricultural waste-derived particulate fillers have received increasing attention as low-cost reinforcements for polymer matrices. Materials such as rice husk, coconut shell, walnut shell, groundnut shell, bamboo residues, and other lignocellulosic wastes have been investigated for their ability to modify stiffness, dimensional stability, hardness, and thermal behaviour. Their incorporation into polymer composites also provides an opportunity to convert agricultural residues into value-added materials, supporting waste reduction and circular-economy objectives [3,6,7].

CNS a lignocellulosic residue generated during castor seed processing, is a relatively underexplored agricultural waste for polymer composite applications. Its particulate form offers advantages for incorporation into thermosetting matrices, while its lignocellulosic structure provides potential for improving matrix stiffness and resistance to deformation. However, compared with more extensively studied agricultural fillers, limited attention has been paid to CNS as a reinforcement for epoxy composites, particularly when combined with natural fibers. This

provides an opportunity to explore CNS as a particulate component of a hybrid natural reinforcement system [8]. PALF provides structural strength, while CNS contribute waste valorization, cost efficiency, and environmental benefits.

Hybridization of fibers and particulate fillers provides a potential means of combining the complementary functions of different reinforcement forms. Fibers can contribute substantially to load bearing and crack bridging, whereas particulate fillers can modify matrix stiffness, dimensional stability, and deformation behaviour. The resulting performance depends hugely on reinforcement loading, dispersion, fiber-matrix adhesion, filler-matrix interaction, and the resulting stress-transfer mechanisms. Previous studies on hybrid natural fiber composites have recorded enhancements in mechanical and thermal properties at optimized reinforcement levels, while excessive loading may trigger agglomeration, poor wetting, void formation, and localized stress concentrations [3–5,9–14].

For structural and semi-structural applications, creep is an important consideration because polymer composites subjected to sustained loading undergo progressive time-dependent deformation. This behaviour becomes more pronounced at elevated temperatures as increased molecular mobility facilitates deformation of the polymer network. Consequently, characterization of creep behaviour is essential for evaluating the resistance of polymer composites to time-dependent deformation under specified service conditions [15,16].

DMA provides a useful approach to characterizing the viscoelastic response of polymer composites under controlled temperature and mechanical loading. Parameters obtained from DMA, including storage modulus, loss modulus, and damping behaviour, can provide information about the influence of reinforcement on polymer viscoelasticity. DMA can also be operated under creep modes to evaluate time-dependent deformation. Previous studies have reported improved creep resistance in natural fiber reinforced epoxy composites as a result of improved load transfer and restricted matrix deformation. However, the magnitude of this improvement is a function of reinforcement type, loading, dispersion, interfacial adhesion, and processing conditions [9,15].

An essential limitation observed in previous studies is that increasing reinforcement content does not necessarily produce continuous improvement in creep resistance. At an optimum loading, reinforcement can be sufficiently dispersed to enhance stress transfer and constrain matrix deformation. However, at higher contents reinforcement agglomeration, partial wetting, interfacial defects, and non-uniform stress distribution may increase tendency to deformation [9–14]. Knowing this loading-dependent behaviour is therefore crucial to optimizing hybrid natural fiber composites.

The key research gap addressed in this study is the continued reliance on synthetic fibers and petroleum-based resins, despite their significant environmental impact. Although natural fiber

composites have been widely studied, limited research exists on hybrid systems combining agro waste fibers using epoxy resin.

The specific contribution of this study is an initial evaluation of a hybrid CNS/PALF powder system in epoxy, with CNS and PALF held at a 50:50 weight ratio while total reinforcement loading is varied. The study relates the measured creep response to SEM observations across the five formulations. Because the available data cover a single reported temperature and test duration, the findings are interpreted as comparative performance under the stated laboratory conditions rather than as evidence of long-term service durability.

Although natural fiber and agricultural-waste fillers have been investigated in epoxy composites, the creep response of the particular CNS/PALF hybrid system considered here is not established by the studies cited in this manuscript. This study addresses that focused gap by comparing neat epoxy with four total hybrid reinforcement loadings and examining the associated fracture-surface morphology. The extent of novelty should be understood in relation to the literature review and references verified by the authors.

The objective of this study was to evaluate the effect of total CNS/PALF hybrid reinforcement loading on the creep response of epoxy composites. CNS particles and PALF powder were incorporated at a constant 50:50 weight ratio at total reinforcement loadings of 0, 5, 10, 15, and 20wt%.

Specifically, the study compares reported peak displacement and selected curve-derived times across the formulations and examines whether the SEM observations are consistent with the measured creep trends.

## 2. Materials and methods

### *2.1. Materials*

The castor nutshells and pineapple leaf fibers were obtained from agricultural farm in Awka Anambra State, Nigeria. Forward Response Technology Limited provided the epoxy resin (Epotech 2005004) and the hardener (Epotech 105003) and were used as received.

### *2.2 Preparation of CNS/PALF powder*

The castor nutshells and pineapple leaf fibers were thoroughly cleaned with distilled water several times to remove impurities, contaminants and subsequently sun-dried for 48 h as shown in Fig. 1 and 2. The castor nutshells and pineapple leaf fibers were then mechanically ground using a grinder and sieved to obtain a particle size of 75µm. The dried and sieved CNS/PALF powders were further oven-dried at 80°C for 24h to eliminate residual moisture. The prepared CNS/PALF powders were stored in sealed polyethylene containers until composite fabrication.



**Fig. 1.** castor nut shell



**Fig. 2.** Pineapple leaf fiber

*2.3 Fabrication of CNS/PALF/Epoxy Hybrid Composites*

CNS/PALF loadings were fabricated at an equal 50:50 weight ratio of castor nut shells to pineapple leaf fibers, at varying weight percentages of 0/0, 2.5/2.5, 5.0/5.0, 7.5/7.5, and 10.0/10.0 wt.%. The epoxy resin and hardener were mixed in the ratio 2:1 for 1 min, after which the required weight percentages of CNS/PALF powders were added and mechanically stirred to achieve uniform dispersion. The mixed CNS/PALF/epoxy/hardener composites were fabricated by hand lay-up and poured into a clean wooden mold of 180 x 180 x 5 mm, coated with poly (vinyl alcohol) as a mold release agent and room-temperature curing for 24 h. Thereafter, the fabricated composites were removed from the mold and cut into standard specimens for creep analysis as shown in Fig. 3.

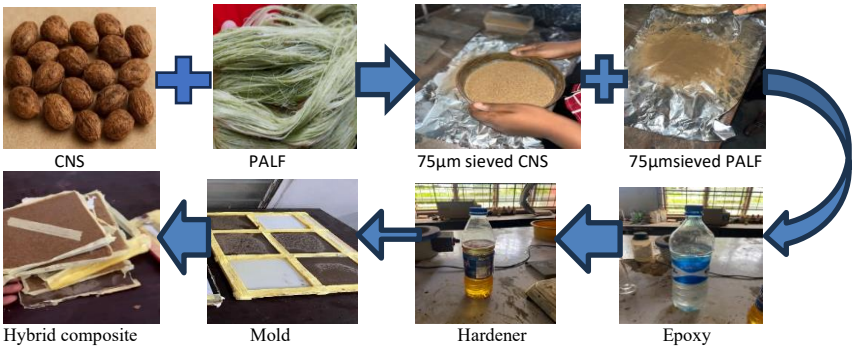



**Fig. 3.** CNS/PALF processing routes.

*2.4 Creep Testing Protocol*

Short-term creep testing of the CNS/PALF epoxy composites was performed using a NETZSCH DMA 242 instrument in a three-point-bending configuration. The specimens measured 40 × 6 × 6 mm and were tested over a support span of 36 mm at an elevated temperature under a nominal constant load of 0.001 N. The instrument software recorded displacement as a function of time, enabling the determination of characteristic response parameters, including onset time, inflection time, peak time, and peak displacement. The test was continued until specimen failure. The experimental procedure employed a three-point-bending configuration similar to that used in ASTM D790; however, the time-dependent measurements were used specifically to evaluate the short-term creep behaviour of the composites.

*2.5 Scanning Electron Microscopy (SEM)*

SEM (Phenom World Model Pro X) was used to examine the morphology of DMA-tested specimens for control and CNS/PALF reinforced composites at 5, 10, 15 and 20wt%. The supplied micrographs were obtained at an accelerating voltage of 15 kV using a BSD detector. The reported fields of view were 944 µm for 5wt%, 895 µm for 10wt%, 833 µm for 15wt% and 912 µm for 20wt%.

**Table 1.** Formulation for the composite fabrication

| Sample ID | Filler (wt.%) | CNS (wt.%) | PALF (wt.%) | Epoxy System (wt.%) | CNS (g) | PALF (g) | Epoxy Resin (g) | Hardener (g) | Total Mass (g) |
|---|---|---|---|---|---|---|---|---|---|
| Control | 0 | 0 | 0 | 100 | 0 | 0 | 133 | 67 | 200 |
| CNS/PALF5 | 5 | 2.5 | 2.5 | 95 | 5 | 5 | 127 | 63 | 200 |
| CNS/PALF10 | 10 | 5.0 | 5.0 | 90 | 10 | 10 | 120 | 60 | 200 |
| CNS/PALF15 | 15 | 7.5 | 7.5 | 85 | 15 | 15 | 113 | 57 | 200 |
| CNS/PALF20 | 20 | 10.0 | 10.0 | 80 | 20 | 20 | 107 | 53 | 200 |

For each formulation, the required mass of reinforcement was calculated from the selected percentage of the total 200g batch. The reinforcement mass was then divided equally between CNS and PALF. The remaining mass constituted the epoxy system, which was subsequently separated into epoxy resin and hardener in the 2:1 ratio. For example, at 10wt% reinforcement, the total reinforcement mass was 20g, comprising 10g CNS and 10g PALF, while the remaining 180g epoxy system consisted of 120g epoxy resin and 60g hardener.

## 3. Results and Discussion

*3.1. Creep Behavior of CNS/PALF/Epoxy Composites*

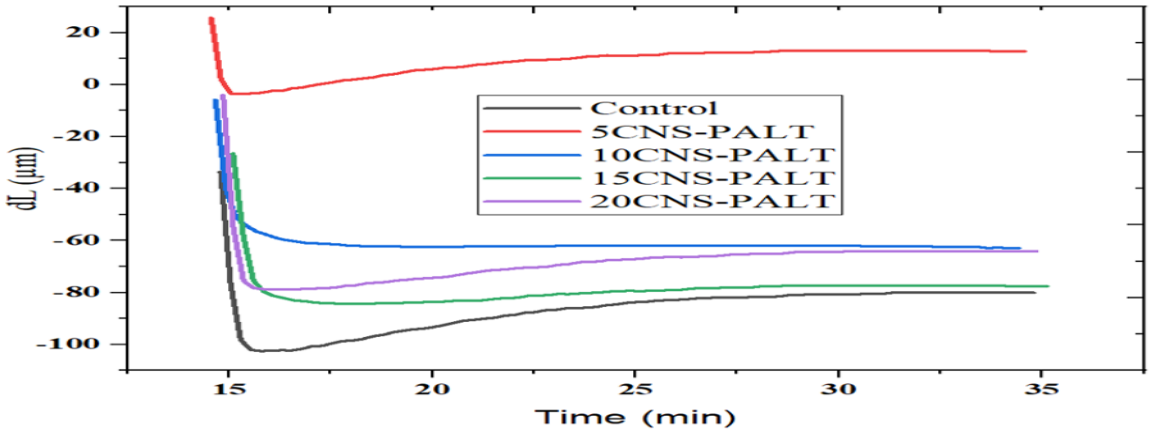



**Fig. 4.** Time-dependent deformation behavior of CNS/PALF reinforced epoxy composites

Fig. 4 shows the variation of dimensional change, dL, with time. Immediately after approximately 14-15 min, all compositions undergo a rapid dimensional change, followed by a slower recovery/stabilization period. The control (epoxy) shows the largest deformation, reaching approximately -103µm, before gradually recovering to approximately -80 µm. This indicates a

comparatively high susceptibility of the unreinforced epoxy to time-dependent deformation and stress relaxation.

The addition of CNS/PALF reinforcement loadings considerably modifies this response. The 10, 15 and 20wt% CNS/PALF composites reach approximately -63, -78 and -65µm, respectively, at later times, while the 5wt% CNS/PALF specimens show a distinctive response, changing from a small contraction to a positive dimensional change of approximately +12 µm. The reduction in deformation relative to the control can be attributed to the ability of CNS particles to restrict movement of the epoxy chains and redistribute applied stresses within the matrix. The PALF provides a continuous load-bearing phase, whereas the CNS particles can occupy spaces within the matrix and increase resistance to local matrix deformation.

Consequently, the hybrid reinforcement produces a more constrained polymer network. This interpretation is consistent with recent creep work on natural-fiber/epoxy composites, where fiber reinforcement reduced creep strain through restricted polymer-chain mobility and improved stress transfer. A study on palm-fiber/epoxy composites, for example, found progressively lower creep deformation with increasing fiber reinforcement and attributed the improvement to load transfer and restriction of matrix-chain mobility [17].

The result is also consistent with work specifically involving castor bean shell/epoxy composites. Ogah et al. [8] reported that castor bean shell loading improved tensile and flexural properties, with the best overall mechanical performance at 15wt% CNS, while higher loading produced reductions attributed to inefficient filler dispersion. SEM observations also indicated improved matrix-filler adhesion at 15wt%.

Thus, the creep/dimensional-change curves suggest that moderate CNS/PALF incorporation improves resistance to time-dependent deformation, while excessive filler loading does not necessarily provide further improvement.

All specimens exhibited a rapid initial deformation following application of the sustained load, followed by a gradual reduction in the rate of displacement, indicating the characteristic primary and secondary stages of viscoelastic creep. The control specimen exhibited the largest deformation, reaching approximately -103µm before recovering slightly and attaining a quasi-stable displacement of about -85µm. The incorporation of CNS/PALF considerably altered the creep response. In particular, the 10wt% CNS/PALF composite exhibited the lowest stabilized negative displacement of -63µm, indicating improved resistance to time-dependent deformation relative to the control. The 15 and 20wt% CNS/PALF specimens exhibited stabilized displacements of approximately -78µm and -65µm. The non-monotonic variation with reinforcement loading suggests that the creep response is influenced not only by the amount of reinforcement but also by its dispersion and interfacial interaction with the matrix. At an

appropriate reinforcement concentration, the CNS/PALF fibers can restrict matrix-chain mobility and facilitate stress transfer, thereby reducing creep deformation. At higher concentrations, however, fiber agglomeration, increased interfacial regions, or insufficient matrix encapsulation may reduce the effectiveness of stress transfer and consequently increase the observed creep deformation.

The neat epoxy showed the largest negative displacement in the present dataset (approximately −103 µm). The reinforced samples showed different responses rather than a monotonic improvement with loading. The 5wt% sample was distinctive, reaching approximately +12 µm, while the reported later-stage displacements for the 10, 15 and 20wt% samples were approximately −63, −78 and −65 µm, respectively. Because the 5wt% response crosses from negative to positive displacement, its interpretation as the lowest creep deformation requires confirmation of the displacement reference and sign convention.

Overall, the creep performance of the investigated composites followed the order: 5wt% CNS/PALF > 20wt% CNS/PALF > 10wt% CNS/PALF > 15wt% CNS/PALF > Control. The results clearly demonstrate that the creep resistance of epoxy composites is strongly dependent on reinforcement loading. Lower filler contents promoted effective filler dispersion, stronger filler-matrix interaction, and efficient stress transfer, whereas excessive reinforcement loading reduced creep performance because of agglomeration. These findings are consistent with numerous recent investigations on natural fiber reinforced polymer composites, which consistently report the existence of an optimum reinforcement level beyond which further filler addition no longer improves long-term viscoelastic performance [18–20]. The present result therefore confirms CNS/PALF provides an effective and sustainable approach for improving the creep resistance of epoxy composites intended for potential lightweight engineering and structural applications.

### *3.3. Analysis of Creep Parameters*

**Table 2.** The measured onset time, inflection point, peak time, and peak deformation

| Composite Samples (wt%) | Onset Time (min) | Inflection Time (min) | Peak Time (min) | Peak Deformation (dL /µm) | Creep Resistance | Interpretation |
|---|---|---|---|---|---|---|
| Control | 19.3 | 20.1 | 31.4 | -103 | Poor | High creep performance |
| CNS/PALF5 | 21.5 | 23.6 | 29.2 | +12 | Excellent | Optimum creep resistance |
| CNS/PALF10 | 18.1 | 18.0 | 20.3 | -63 | Good | Moderate improvement |
| CNS/PALF15 | 21.3 | 21.4 | 30.3 | -78 | Fair | Slight improvement |
| CNS/PALF20 | 21.3 | 22.9 | 31.6 | -65 | Very Good | Substantial improvement |

The creep onset time, inflection time, peak time, and maximum deformation extracted from the DMA curves provide further insight into the viscoelastic behaviour of the composites Table 2.

The reinforced specimens generally exhibited delayed creep onset and reduced maximum deformation compared with the neat epoxy, indicating that the hybrid reinforcement effectively delayed the initiation and propagation of time-dependent deformation. The superior performance of the 5wt% composite suggests that the hybrid reinforcement effectively constrained polymer chain movement while maintaining good matrix continuity. In contrast, the reduction in creep resistance observed at 15wt% indicates that increasing reinforcement content beyond the optimum level does not necessarily improve creep performance. Instead, reinforcement efficiency depends strongly on achieving uniform dispersion and effective interfacial stress transfer. Similar trends have been reported for hybrid natural fibre composites evaluated using DMA, where optimum reinforcement loadings produced superior viscoelastic performance compared with both lower and higher filler contents [21–23]. The results also demonstrate that CNS/PALF provides complementary reinforcement mechanisms. stop

*3.4. Scanning Electron Microscopy (SEM) Analysis*

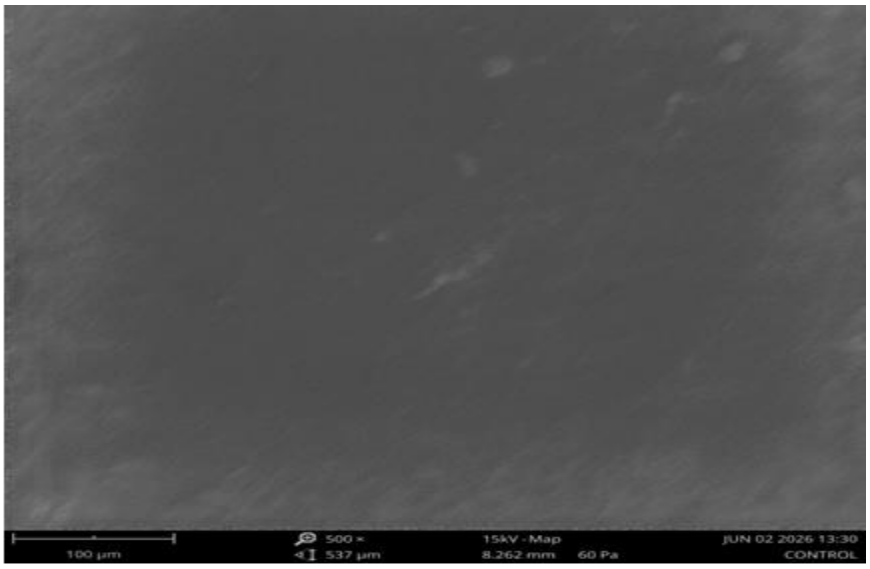



**Fig. 5.** (a) Control sample

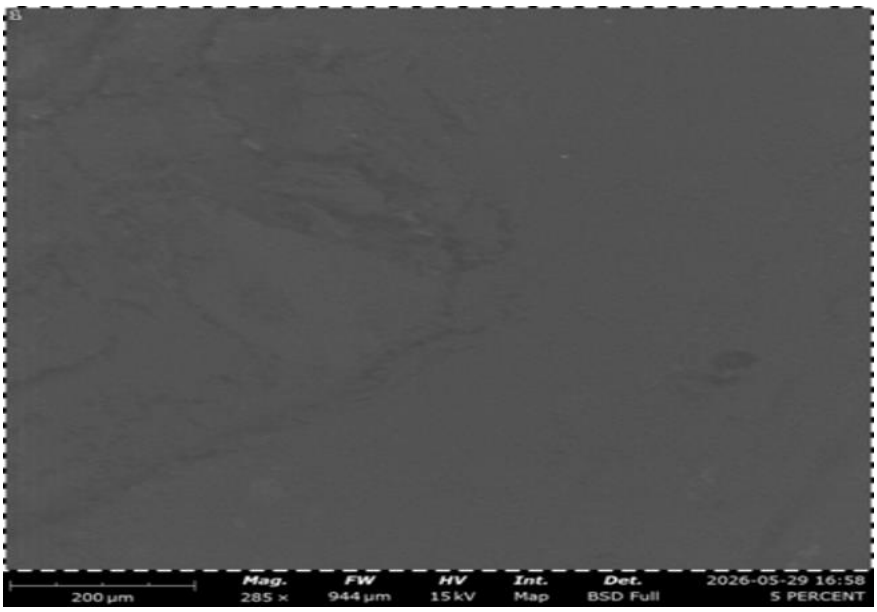



**Fig. 5 (b)** 5wt% CNS/PALF

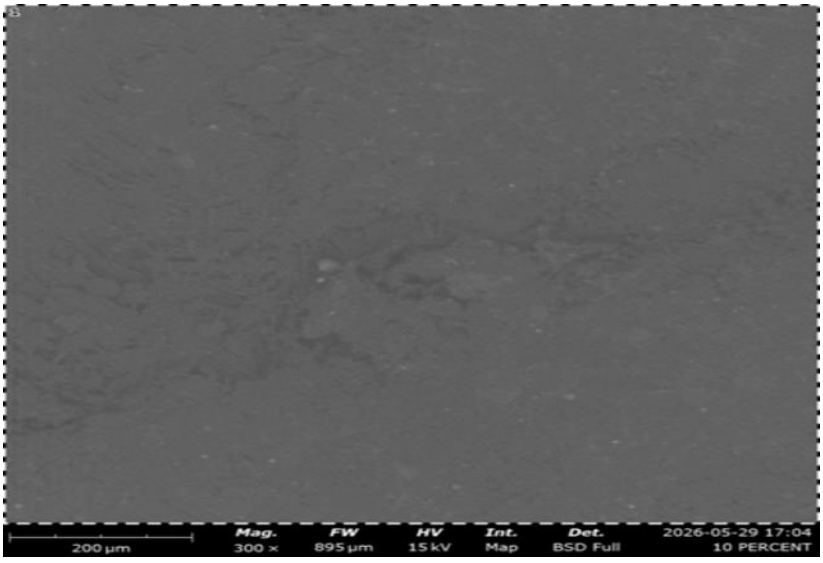



**Fig. 5 (c)** 10wt% CNS/PALF

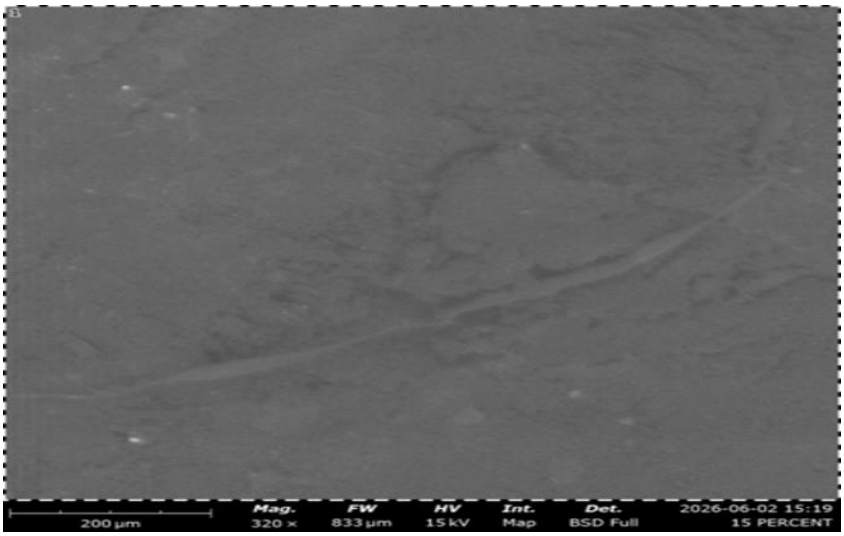



**Fig. 5 (d)** 15wt% CNS/PALF

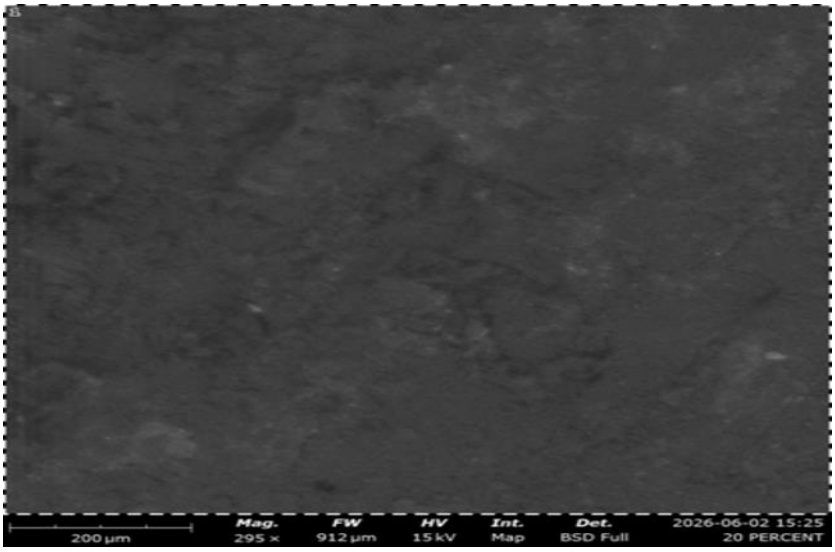



**Fig. 5 (e)** 20wt% CNS/PALF

**Fig. 5.** SEM micrographs of (a) control epoxy (b) 5wt.% CNS/PALF, (c) 10wt.% CNS/PALF, (d) 15wt.% CNS/PALF, and (e) 20wt.% CNS/PALF.

The DMA-tested specimens of the neat epoxy (control) exhibited a relatively smooth and homogeneous morphology with characteristic brittle fracture features and limited evidence of crack deflection Fig. 5a. The absence of reinforcing phases resulted in direct crack propagation through the epoxy matrix, indicating limited resistance to deformation under sustained loading. Similar fracture characteristics have been reported for neat epoxy systems, where the lack of reinforcement allows unrestricted crack propagation and greater polymer chain mobility, thereby contributing to poor creep resistance and dimensional stability [24].

The 5wt% CNS/PALF composite exhibited the most homogeneous microstructure among all the formulations investigated Fig. 5b. The CNS/PALF powder appeared to be uniformly distributed throughout the epoxy matrix with minimal agglomeration and good wetting by the resin. The micrograph displayed relatively few voids. The intimate contact between the reinforcement and the epoxy matrix suggests strong interfacial adhesion, which facilitates efficient stress transfer and minimizes localized stress concentrations. This microstructural feature is consistent with the superior creep resistance observed for the 5wt% composite.

The SEM micrograph of the 10wt% CNS/PALF composite Fig. 5c also showed relatively good dispersion of reinforcement particles, although isolated regions of particle clustering were observed. These localized agglomerates were accompanied by a small increase in micro void formation compared with the 5wt% composite. Nevertheless, the filler distribution remained sufficiently uniform to provide effective reinforcement, explaining the reduced creep deformation. Similar findings were reported by Anand et al. [25], who observed that moderate reinforcement loading improved creep resistance through increased matrix constraint, although slight agglomeration became evident as filler concentration increased.

A markedly different morphology was observed for the 15wt% CNS/PALF composite Fig. 5d. The SEM image revealed pronounced particle agglomeration. The poor dispersion observed at this reinforcement level corresponds well with the increased creep. Similar behaviour has been widely reported in natural fibre-reinforced polymer composites, where excessive filler loading promotes particle clustering and weak interfacial bonding, thereby reducing mechanical performance [26].

Although the 20wt% CNS/PALF composite Fig. 5e contained a higher concentration of reinforcement, the SEM micrograph suggested the formation of a more interconnected reinforcement network compared with the 15wt% formulation. While localized agglomeration remained visible, some regions exhibited continuous contact between neighbouring reinforcement particles, creating a rigid network capable of supporting the applied load. This interconnected structure likely contributed to the improved creep resistance observed for the 20wt% composite compared with the 15wt% specimen.

The correlation between the SEM observations and the DMA results demonstrate that creep resistance is strongly influenced by filler dispersion. Uniformly dispersed CNS/PALF particles effectively constrain the movement of epoxy molecular chains, thereby reducing viscoelastic deformation. Conversely, particle agglomeration increases local stress concentrations and restrict polymer chain mobility, resulting in greater creep deformation. This relationship has been consistently reported for natural fiber reinforced epoxy composites, where microstructural integrity governs long-term mechanical performance [27].

Overall, the SEM analysis confirms that the 5wt% CNS/PALF composite possessed the most favourable microstructure, characterized by homogeneous reinforcement dispersion, strong filler-matrix adhesion, and minimal agglomeration. These characteristics explain its superior creep resistance and dimensional stability observed during DMA testing. In contrast, higher reinforcement loadings introduced varying degrees of agglomeration and interfacial defects, reducing reinforcement efficiency despite the increased filler content. The combined SEM and DMA analyses therefore demonstrate that optimizing reinforcement loading is essential to achieving effective stress transfer, restricting polymer chain mobility, and enhancing the long-term viscoelastic performance of sustainable hybrid epoxy composites. These findings are consistent with recent studies on hybrid natural fiber composites, which emphasize that microstructural optimization is a key factor governing the durability and service performance of bio-based polymer composites [28].

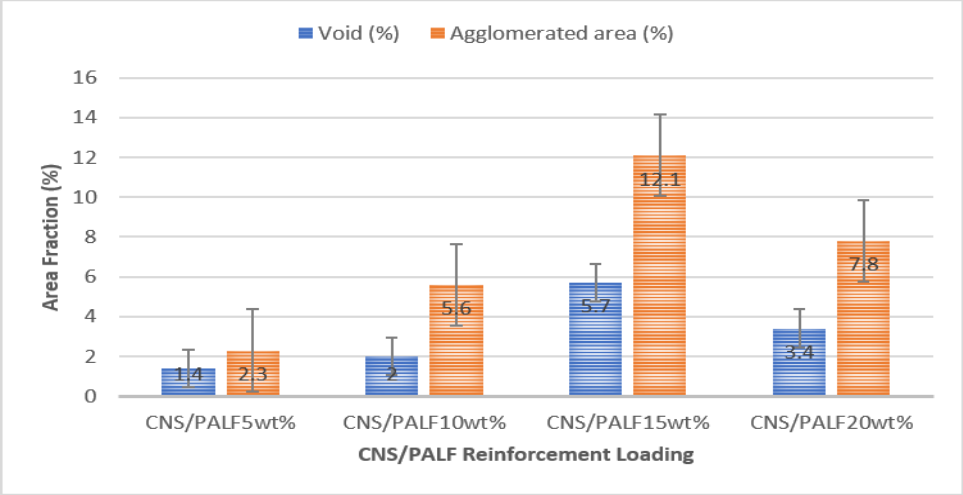



**Fig. 6.** Semi-quantitative void and agglomerated areas from SEM analysis.

Fig. 6 shows the semi-quantitative results obtained from J-Image software of the CNS/PALF composites. Void increased from 1.4% at 5wt% to 2.0% at 10wt% and reached 5.7% at 15wt%, before falling to 3.4% at 20wt%. The agglomerated area followed a similar pattern: 2.3, 5.6, 12.1 and 7.8% for the 5, 10, 15 and 20wt% composites. The 15wt% composite exhibited the highest measured voids and agglomerated areas, resulting in lowest creep resistance among the composites. These results provide direct support for the argument that reinforcement dispersion, void and agglomeration formation influenced the creep response [27,28]. The SEM observations provide a possible microstructural context for the loading-dependent responses. The 5wt% composite had the most homogeneous observed dispersion and the lowest measured void and agglomerated areas (1.4% and 2.3%, respectively), whereas the 15wt% composite had the highest values (5.7% voids and 12.1% agglomerated area).

*Comparison with previous studies and creep mechanisms*

Table 3 compares the present results with previous studies of natural-fiber and biofiller-reinforced epoxy composites. Across these systems, improved creep resistance is commonly associated with effective stress transfer, restricted matrix-chain mobility, and suitable reinforcement dispersion, although direct comparison is limited by differences in materials and test conditions. Overall, comparison with previous studies supports the importance of reinforcement dispersion and interfacial interaction, while the present results remain comparative because the test conditions and reported output differ across studies. The main contribution is an initial assessment of CNS/PALF hybrid loading alongside SEM observations.

**Table 3.** Comparison of the present study with recent investigations on creep behaviour of natural fiber reinforced epoxy composites.

| Study | Composite system | Major findings | Comparison with present study |
|---|---|---|---|
| Anand et al. [25] | PALF/epoxy composites | The study establishes 20wt% PALF as the optimal composition. | Dependence of composite performance on fiber loading. |

| | | | |
|---|---|---|---|
| Boukhlif et al. [17] | Creep behavior of palm fiber/epoxy composites | Palm fiber reinforcement enhances long-term creep resistance. | Consistent with improved creep resistance observed at 5wt% CNS/PALF. |
| Patel et al. [2] | Natural fiber/epoxy composites | Optimum reinforcement loading improved dimensional stability and mechanical properties. | The optimum 5wt% CNS/PALF loading produced the lowest creep deformation. |
| Present study | Hybrid CNS/PALF-reinforced epoxy | 5wt% hybrid reinforcement produced the highest creep resistance through improved filler-matrix interaction and restricted polymer chain mobility. | Demonstrates the potential of a novel CNS/PALF hybrid reinforcement for sustainable epoxy composites. |

## 4. Conclusions

This study evaluated the effect of hybrid castor nutshell (CNS)/pineapple leaf fibre (PALF) powder loading on the displacement response of epoxy composites and examined the tested fracture surfaces by SEM. Across the investigated formulations, the displacement response varied with reinforcement loading and was not monotonic: the neat epoxy reached approximately −103 µm, while the 10, 15 and 20wt% composites showed reported later-stage displacements of approximately −63, −78 and −65 µm, respectively; the 5wt% specimen showed a distinct response reaching approximately +12 µm. SEM showed the lowest measured void and agglomerated areas at 5wt% and the highest at 15wt%, indicating that reinforcement dispersion is an important microstructural factor. The study's measured contribution is the comparison of five CNS/PALF loading levels with displacement-curve features and semi-quantitative SEM observations. The principal limitation is that displacement was reported without normalized creep strain or compliance, and the test covered only one temperature and a short duration; the unusual sign change at 5wt% also requires confirmation of the displacement reference. Future work should verify the force-control and displacement settings, calculate strain or compliance where the required geometry and loading data are available, and conduct longer-duration creep and recovery tests at multiple temperatures with replicate specimens.

## Data availability statement

Data will be made available on request.

## CRediT authorship contribution statement

**Anselm Ogah Ogah**: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review and editing. **Melford Onyemaechi Chima**: Data curation, Funding acquisition, Resources, Supervision. **Uche Ibeneme Ibeneme**: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review and editing. **Ukeme James Timothy**: Formal analysis, Funding acquisition, Project administration, Resources.

**Uju Pauline Ojukwu**: Formal analysis, Funding acquisition, Project administration, Resources, Visualization. **Ferriawan Yudhanto**: Funding acquisition, Investigation, Resources, Software, Validation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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