



Creep behavior of palm fiber reinforced epoxy composites: Experimental analysis and environmental implications

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ABSTRACT

This study investigates the combined effects of temperature and palm fiber reinforcement on the mechanical and creep behavior of epoxy-based composites. The viscoelastic response was evaluated from 20°C to 80°C, focusing on instantaneous strain, time-dependent deformation, and steady-state creep rate (min^{-1}). The incorporation of palm fibers increased the ultimate tensile strength from approximately 20 MPa for neat epoxy to 37 MPa and 55 MPa for composites reinforced with one and two palm fiber layers, respectively. Young's modulus also increased from 3.15 GPa for neat epoxy to 3.41 GPa for the two-layer composite, indicating an improvement of about 8.3%. The results show a strong thermo-activated creep mechanism, where increasing temperature enhances molecular mobility, reduces polymer viscosity, and increases deformation in neat epoxy. In contrast, palm fiber reinforcement markedly improves the mechanical stability and creep resistance of the epoxy matrix. Under a nominal dead-weight load of 1000 g (9.81 N), the maximum creep strain decreased from approximately 0.24 for neat epoxy to 0.205 and 0.165 for the one-layer and two-layer palm fiber composites, respectively. In addition, the two-layer composite reduced the maximum creep strain by approximately 37%, 34%, and 31% under applied loads of 400 g, 600 g, and 1000 g, respectively. These improvements are attributed to efficient stress transfer, restricted polymer-chain mobility, and the reinforcing effect of the fiber network. Overall, the results demonstrate that palm fiber reinforcement enhances both mechanical performance and long-term creep resistance, making these composites suitable for lightweight structural applications under moderate thermal environments.

1. Introduction

Composite materials consisting of a polymeric matrix reinforced with continuous or discontinuous fibers have emerged as foundational materials in advanced engineering applications due to their high specific strength, low density, superior corrosion resistance, and tunable mechanical properties. These characteristics have enabled their widespread adoption in sectors such as aerospace, automotive engineering, civil infrastructure, and renewable energy systems [1,2]. Recent studies have

also broadened composite research beyond constituent selection by showing that additive manufacturing routes, nanoparticle incorporation, and post-processing operations can strongly affect the final performance of hybrid polymer composites. For example, digital light processing (DLP)-printed polylactic acid (PLA)-based bio-composites containing ceramic nanoparticles and glass fiber/aluminum mesh (GF/Al-mesh) epoxy hybrids processed by conventional or abrasive water-jet drilling have shown that processing parameters, delamination, hole quality, and bearing strength are closely related to final composite

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performance [3–9]. In addition to mechanical performance, material selection is increasingly evaluated in relation to sustainability, environmental compatibility, service durability, and application-oriented design requirements [10–14]. Historically, synthetic fibers such as glass and carbon have dominated the reinforcement landscape thanks to their predictable performance, high modulus, and excellent fatigue resistance [15]. However, growing environmental concerns, strict regulations on carbon emissions, and the drive toward circular manufacturing have fostered significant interest in natural fiber-reinforced polymer composites (NFRCs) as more sustainable alternatives [16,17].

Natural fibers derived from plants including flax, jute, hemp, sisal, coir, and palm offer multiple advantages that align with ecological and economic sustainability goals, such as biodegradability, low cost, low density, reduced environmental footprint, and renewability [17,18]. These fibers are increasingly sourced from agricultural byproducts and waste streams, contributing to material valorization and circular economy practices [17,19]. Recent studies on palm-based lignocellulosic fibers further show that extraction and treatment routes, physico-chemical composition, fiber loading, and water-absorption behavior strongly influence their suitability for sustainable structural biocomposites [20,21]. In parallel, residue-based and biomass/palm-fiber hybrid systems have demonstrated that eco-efficient processing, thermal stability, phase/structural behavior, and thermochemical valorization are key parameters for advancing sustainable polymer engineering applications [22–24]. Among them, palm fibers stand out as an abundant byproduct of date and oil palm industries, with reported mechanical attributes including specific stiffness values between 4 and 25 GPa and densities of 1.2–1.6 g/cm³ [25]. Such properties make palm fibers promising candidates for lightweight structural applications in transportation, construction, and consumer products, while reducing reliance on fossil fuel derived reinforcement materials. Despite their potential, the long term mechanical performance of NFRCs remains a critical challenge that limits wider industrial adoption. In particular, creep, the time-dependent deformation under sustained loading, is of paramount importance for components subjected to static or cyclic stresses over extended service lives. Creep deformation in polymer composites arises from the intrinsic viscoelasticity of polymer matrices and the complex interaction between matrix and fibers, especially when fibers are hydrophilic and exhibit weak interfacial adhesion with hydrophobic resins such as epoxy [26,27]. This complexity can lead to irreversible strain accumulation, reduced stiffness over time, and premature failure when exposed to sustained mechanical and thermal loading [26,28]. To date, a significant portion of the literature has focused on the instantaneous mechanical responses of NFRCs, including tensile, flexural, and impact behaviors [15,18,25]. Such studies consistently demonstrate that fiber type, orientation, volume fraction, and surface treatments critically influence static mechanical performance [17,26]. However, comprehensive investigations of creep behavior particularly in relation to varying temperatures, stress levels, and fiber treatments remain comparatively scarce. Most creep research has traditionally focused on synthetic fiber composites or hybrid systems, with limited application to natural fiber composites, and even fewer studies specifically addressing palm fiber reinforced epoxy systems [27,29]. Existing work on natural fiber composite creep indicates the importance of procedures such as time temperature and time stress superposition for long term predictions, yet experimental datasets that systematically explore real service relevant conditions are lacking [29]. Furthermore, there is limited understanding of how palm fiber microstructure, interfacial bonding, and thermal sensitivity collectively influence creep mechanisms and failure modes in NFRCs. Accordingly, the main research question of this study is whether increasing palm fiber reinforcement can simultaneously improve tensile performance and suppress creep deformation in epoxy composites under combined mechanical and thermal loading. To address this question, this study experimentally evaluates the tensile and creep behavior of palm fiber

reinforced epoxy composites under different loading and temperature conditions. Compared with previous studies that mainly focused on static mechanical properties or isolated creep responses, this research expands the subject area by linking fiber content with both load-dependent and temperature-dependent creep behavior. The main novelty of this work lies in the combined assessment of tensile properties, mechanical creep response, and thermal creep sensitivity within a single experimental framework. By analyzing the interplay between fiber content, thermal environment, and mechanical performance, this work provides critical insights for advancing NFRCs toward reliable and sustainable structural applications.

2. Viscoelastic framework for interpreting stress relaxation and creep recovery behavior

The viscoelastic behavior of materials, commonly observed in polymers, composites, and biomaterials, is characterized by the time dependent evolution of stress (σ) and strain (ϵ) when subjected to constant mechanical loading. This response combines immediate elastic deformation with delayed viscous flow, which cannot be accurately described using classical linear elasticity. Stress relaxation and creep recovery tests are therefore fundamental experimental protocols used to quantify these phenomena and to validate rheological models capable of representing the time dependent response of materials.

In a stress relaxation test, the material is subjected to an imposed strain ϵ_0 at the initial time $t = 0$, which is then maintained constant throughout the test (Fig. 1). The resulting stress $\sigma(t)$ gradually decreases over time and asymptotically approaches a final value due to the redistribution of internal viscoelastic stresses [30,31]. This phenomenon reflects the ability of viscous elements within the material to progressively dissipate energy and reduce internal resistance under a constant applied strain.

Conversely, during a creep recovery test, the material is subjected to a constant stress σ_0 at $t = 0$, which is removed at time $t = t_1$ (Fig. 2). Under the applied constant stress, the strain $\epsilon(t)$ evolves as a combination of three contributions instantaneous elastic, delayed viscoelastic, and permanent viscous strain. Ideal elastic springs and viscous dashpots in rheological models such as the Burgers model or the generalized standard linear solid model conveniently represent these mechanisms.

The material is subjected to the applied stress σ_0 at time $t = 0$, which is then released at time $t = t_1$.

The total strain under constant applied stress σ_0 can be expressed as:

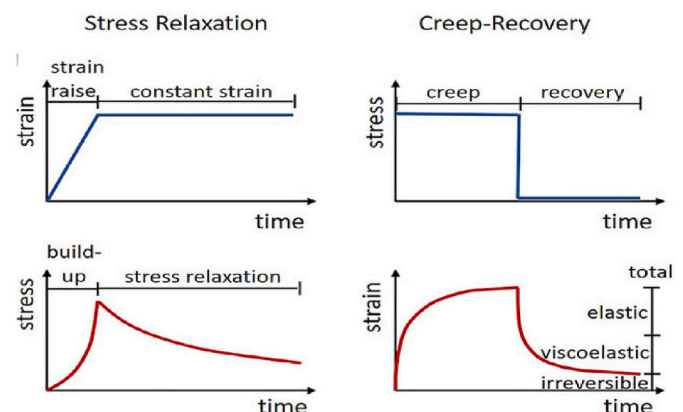


Fig. 1. Schematic representation of the material behavior during a stress relaxation test: (a) The material is subjected to an initial strain ϵ_0 at time $t = 0$, which is then held constant. (b) Stress response of a linear viscoelastic material under the applied strain. The stress gradually decreases throughout the test and asymptotically approaches a final value.

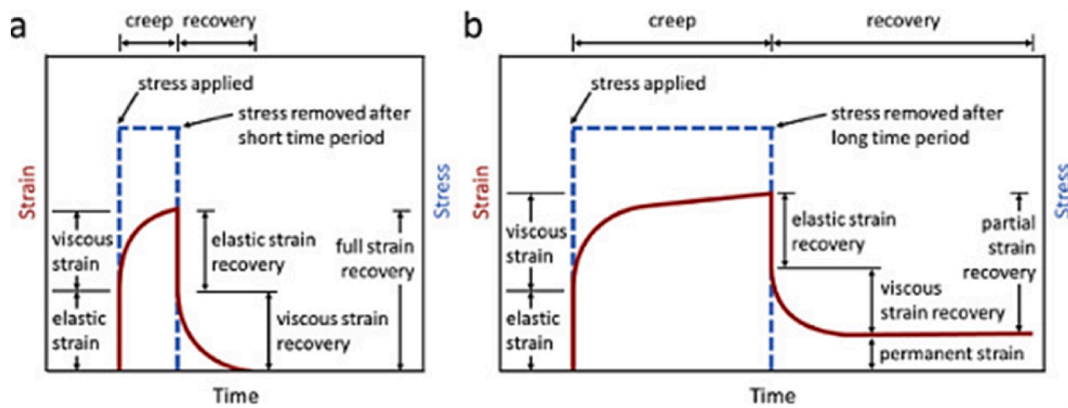


Fig. 2. Schematic representation of the material behavior during a creep recovery test.

$$\varepsilon(t) = \sigma_0 / E_1 + \sigma_0 / E_2 \left(1 - e^{-E_2 t / \eta_2} \right) + \sigma_0 t / \eta_1 \quad (1)$$

Where E_1 and E_2 are the elastic moduli associated with the Maxwell and Kelvin elements, respectively, and η_1 and η_2 are the viscosities of the corresponding dashpots. This formulation captures:

The instantaneous elastic strain (σ_0/E_1), corresponding to immediate deformation, the delayed viscoelastic strain ($\sigma_0/E_2 (1 - e^{-E_2 t / \eta_2})$), associated with time dependent relaxation processes, and the steady viscous flow ($\sigma_0 t / \eta_1$), which increases linearly with time.

Typical creep curves (Fig. 3) show an increase in strain rate with increasing temperature or stress level, demonstrating the thermo-mechanical sensitivity of internal viscous mobility [32]. These responses are associated with molecular rearrangements and thermally activated diffusion processes that dominate long term deformation under constant loading.

Rheological models such as the Standard Linear Solid (SLS), also known as the Zener model, provide a robust analytical framework for combining creep, relaxation, and recovery phenomena, outperforming the Maxwell and Kelvin models when considered separately. In this study, Equation (1) is used to support the physical interpretation of the creep stages rather than to perform full constitutive parameter identification. Therefore, the experimental discussion focuses on the relative changes in instantaneous deformation, steady-state creep tendency, and tertiary-stage development among EP, EP + 1 PF, and EP + 2 PF. Furthermore, recent formulations improve predictive accuracy by incorporating finite loading rates observed in real experiments, thereby reducing errors associated with the assumption of instantaneous loading traditionally used in analytical creep and relaxation solutions.

In the present study, these viscoelastic concepts are used as an

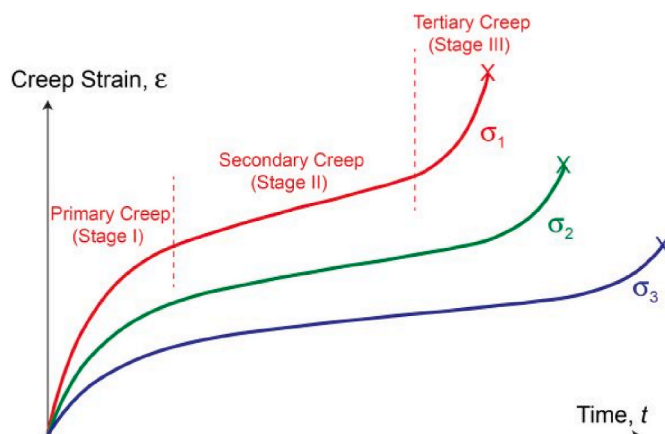


Fig. 3. Creep curves for increasing temperatures or applied stresses.

interpretive framework for evaluating the experimental creep curves rather than as an independent constitutive modelling section. Accordingly, the instantaneous elastic response, delayed viscoelastic deformation, and progressive viscous strain components provide the basis for discussing the primary, secondary, and tertiary creep stages observed in the palm fiber/epoxy composites.

3. Experimental methodology

3.1. Preparation of palm fibers

Untreated palm fibers were extracted from palm trees, oven-dried to remove moisture, and cut to the desired length. Due to natural variability in fiber diameter and flexibility, a manual alignment technique was employed; fibers were laid parallel in the mold and temporarily fixed at both ends with adhesive tape to maintain unidirectional orientation. After resin infusion, the tape was removed to obtain unidirectional reinforced specimens, a method shown to improve fiber alignment in natural fiber composites [33]. The same fiber preparation procedure was applied to all reinforced specimens to minimize variability associated with fiber orientation and handling. In this experimental design, reinforcement was controlled as a discrete unidirectional fiber-layer configuration rather than as a continuously varied fiber volume fraction. Therefore, EP + 1 PF and EP + 2 PF represent nominal reinforcement architectures used for comparative evaluation of tensile and creep performance.

3.2. Epoxy matrix preparation and specimen fabrication

An epoxy resin with an amine hardener was used as the polymer matrix. The mixture was stirred at 200–300 rpm for 3–5 min, followed by vacuum degassing at 25–50 mbar for 10–15 min to remove entrapped air bubbles and improve fiber wetting [34,35].

The degassed resin was poured into silicone molds containing the aligned fibers. Polymerization was carried out at room temperature (21°C) for 24 h to obtain fully cured neat epoxy and palm fiber reinforced composite specimens. Hereafter, neat epoxy, the composite reinforced with one palm fiber layer, and the composite reinforced with two palm fiber layers are denoted as EP, EP + 1 PF, and EP + 2 PF, respectively. The raw palm fiber reference is denoted as PF. Neat epoxy specimens were fabricated under the same curing and processing conditions and used as the reference control group. After curing, the specimens were demolded, and their width and thickness were measured using a digital caliper (tolerance: ± 0.1 mm) to verify dimensional conformity in accordance with ASTM International (ASTM) D618 [36].

3.3. Conditioning and surface inspection

After demolding, specimens were conditioned at 20°C and 50% relative humidity (RH) to achieve moisture equilibrium. Visual inspection under axial lighting was performed to detect surface imperfections, including voids or cracks. Ensuring accurate dimensions and surface quality was critical for reliable creep testing.

3.4. Experimental procedure

3.4.1. Specimen preparation

Miniature tensile specimens were machined from cured epoxy laminates. All coupons were cut from the same laminate and prepared under identical conditions to minimize geometrical bias. The specimen geometry (Fig. 4) consisted of a narrow gauge section extending between two wider grip sections. This design ensured that failure would occur in the gauge zone rather than at the grips. Both unreinforced epoxy and natural-fiber-reinforced composite specimens were fabricated with the same dimensions and processing to allow direct comparison. This geometry was used for unidirectional specimens to reduce the risk of premature grip failures [37,38]. By machining flat rectangular coupons in this manner, the specimen preparation followed the principle that ASTM D3039 specimens are flat and rectangular [39] with a constant cross-section [40], which minimizes bending and shear failures during gripping.

3.4.2. Tensile testing

Tensile tests were conducted on a 100 kN servo-hydraulic testing machine (Model BED-100) under displacement control. The specimen dimensions are shown in Fig. 4. For the raw palm fiber reference, a single untreated technical palm fiber strand was tested separately without epoxy impregnation, using a nominal gauge length of 25 mm for strain calculation. Fillets with radii R14 and R25 joined the wider grips to the narrower gauge section. A tapered transition was thus formed to avoid sudden stress concentrations at the shoulders. Notably, the gauge width is smaller than the grip width, which creates a controlled stress gradient that helps ensure fracture occurs centrally within the gauge length rather than near the grips. The inclusion of large-radius fillets (R25) further reduces edge stresses at the transitions, a practice that is important when testing brittle fiber-reinforced composites [37,38]. After tensile testing, the fractured specimens were also examined at the macro-scale to compare the dominant post-failure appearance of EP, EP + 1 PF, and EP + 2 PF. This observation was used to support the interpretation of brittle matrix cracking, fiber bridging, and progressive damage development.

3.4.3. Creep testing

Creep behavior was measured on an SM1006 creep frame with constant load and thermal control, following ASTM D2990-17 [41,42]. Creep specimens had a rectangular geometry.

Creep tests were run under uniaxial tension. The applied dead weights were converted into equivalent nominal tensile stresses using $\sigma = F/A$, where F is the applied force and A is the nominal gauge cross-sectional area of the creep specimen. Based on the gauge dimensions shown in Fig. 5, the nominal cross-sectional area was taken as 5 mm². Table 1 shows the conversion of the main analyzed dead weights into force and equivalent nominal tensile stress values used in the creep tests.

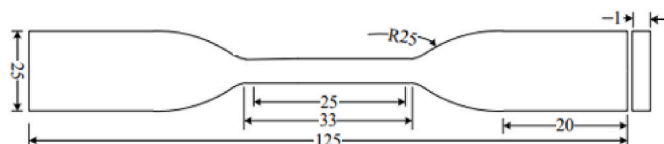


Fig. 4. Dimensions of tensile test specimens.

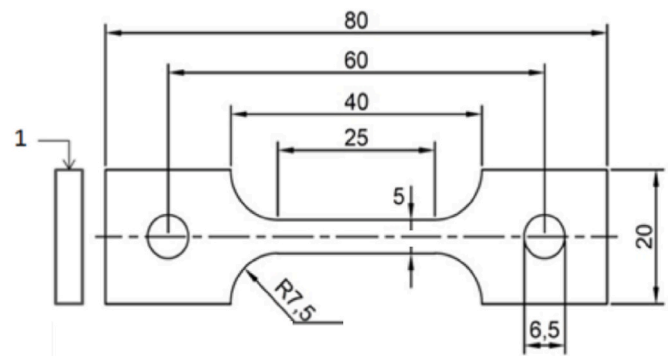


Fig. 5. Dimensions of creep test specimens.

Table 1

Conversion of applied dead weights into equivalent nominal tensile stresses for creep testing.

Applied mass (g)	Applied force (N)	Nominal cross-sectional area (mm ²)	Nominal tensile stress (MPa)
400	3.92	5.00	0.785
600	5.89	5.00	1.177
1000	9.81	5.00	1.962

After pre-aligning each specimen to ensure coaxial loading, the load was applied in controlled increments using calibrated dead weights in the range of 300–1000 g [41]. The creep results discussed in this study are therefore interpreted as nominal load-dependent creep strain responses. Since all specimens were prepared using the same nominal geometry and dimensional inspection procedure, the comparison focuses on relative creep resistance rather than true cross-sectional creep compliance. This incremental loading procedure helps avoid an instantaneous jump in stress that could induce transient viscoelastic relaxation. Throughout the test, temperature was monitored with a thermocouple and held within $\pm 1^\circ\text{C}$ of the setpoint to minimize temperature fluctuations [42]. Specimen strain was measured using a displacement transducer, and strain values were calculated from the recorded displacement data based on the initial gauge length. Tests were continued until rupture or until a preset maximum time was reached.

3.4.4. Time-dependent deformation measurement and data analysis

Time-dependent strain during creep and the stress–strain response during tensile tests were recorded digitally at high resolution (displacement resolution = 0.01 mm). Temperature and environmental conditions were logged to verify stability throughout each test. The experimental program was designed to systematically compare short-term tensile behavior and long-term creep of neat epoxy and natural-fiber composites under identical conditions. These methodological controls, including identical curing, conditioning, dimensional inspection, coaxial alignment, loading procedure, and thermal regulation, were used to reduce variability related to geometry, moisture content, loading eccentricity, and environmental fluctuations.

Creep strain versus time data were analyzed to identify the classical three-stage creep behavior: an initial primary creep with decreasing strain rate, a secondary steady-state creep, and a tertiary creep with accelerating strain leading to failure. These stages and the corresponding rates were quantified for each material. The combination of precise instrumentation and carefully controlled test conditions ensured reproducibility and reliable extraction of viscoelastic parameters. This integrated experimental approach, combining tensile and creep tests, provided a robust dataset for characterizing the mechanical performance and time-dependent deformation of the fiber-reinforced epoxy systems.

4. Results and discussion

4.1. Tensile mechanical behavior of palm fiber-reinforced epoxy composites

The tensile stress–strain responses of EP, EP + 1 PF, EP + 2 PF, and PF are presented in Fig. 6. The obtained curves reveal a significant enhancement in the mechanical performance of the epoxy matrix after the incorporation of natural palm fibers. Similar trends have been widely reported for lignocellulosic fiber-reinforced thermoset composites, where the fibers act as effective stress-transfer constituents and crack-arresting mechanisms [43,44].

The stress–strain curves reveal three characteristic mechanical regions: an initial quasi-linear elastic domain corresponding to reversible deformation, followed by a nonlinear region associated with progressive damage evolution, and finally a fracture region characterized by matrix cracking and fiber failure. The evolution of these mechanical stages with increasing palm fiber content highlights the significant reinforcing effect of the natural fibers on the composite structure. Indeed, the incorporation of palm fibers enhances the stiffness and load-transfer capability of the epoxy matrix, while also modifying the damage propagation mechanisms during deformation.

4.1.1. Mechanical response of neat epoxy resin

The neat epoxy resin exhibits a predominantly brittle mechanical behavior, which is characteristic of highly crosslinked thermosetting polymers. The material shows an approximately linear elastic response at low strain levels, followed by a limited nonlinear region prior to fracture. The maximum tensile stress reaches approximately 20 MPa at a strain close to 0.021 mm/mm.

Beyond the peak stress, a rapid stress drop is observed, indicating unstable crack propagation and catastrophic failure. This behavior is mainly attributed to the limited molecular mobility of the epoxy network and the absence of energy-dissipating mechanisms within the matrix structure. Similar brittle responses for unreinforced epoxy systems have been reported by Jawaid et al. [43] and Fiore et al. [45].

The relatively low strain-to-failure confirms the poor ductility and low fracture toughness of the neat epoxy matrix.

4.1.2. Effect of one palm fiber reinforcement

The incorporation of a single palm fiber significantly modifies the tensile response of the epoxy matrix. The stress–strain curve shifts upward compared with neat epoxy, indicating a clear improvement in load-bearing capacity. The ultimate tensile strength increases to

approximately 37 MPa, which corresponds to an enhancement of nearly 85% relative to the unreinforced epoxy resin. This substantial improvement confirms the effectiveness of palm fiber as a reinforcing agent within the brittle polymer matrix.

In addition to strength enhancement, the reinforced composite exhibits a slight increase in strain-to-failure as well as a more gradual post-peak stress. This behavior suggests a transition from brittle fracture toward a more progressive failure mode. The palm fiber plays a crucial role in delaying crack initiation and slowing crack propagation by acting as a crack-bridging element within the matrix.

The observed improvement in tensile performance can be mainly attributed to several synergistic mechanisms, including effective stress transfer between the epoxy matrix and the fiber, partial restriction of matrix deformation under loading, redistribution of local stresses within the composite structure, and energy dissipation mechanisms such as interfacial debonding and fiber pull-out. These mechanisms collectively contribute to enhancing the overall mechanical integrity of the material.

The smoother stress reduction after the maximum load indicates the activation of damage-tolerant mechanisms that are absent in neat epoxy. Instead of sudden catastrophic failure, the presence of the fiber promotes a more controlled and progressive failure process. According to Pickering et al. [46], natural fibers are particularly effective in improving the toughness of polymer matrices by transforming brittle fracture into a more gradual energy-dissipating failure mode, thereby increasing the structural reliability of the composite system.

4.1.3. Effect of two palm fibers reinforcement

The composite reinforced with two palm fibers exhibits the highest mechanical performance among all investigated systems. The maximum tensile stress reaches approximately 55 MPa at a strain of about 0.025 mm/mm, corresponding to an improvement of nearly 175% compared with neat epoxy resin. This significant enhancement confirms the strong reinforcing efficiency of palm fibers in improving the load-carrying capacity of the epoxy matrix, in agreement with previously reported behavior in natural fiber composites [43,44].

The stress–strain response of this composite becomes more nonlinear and progressive, indicating improved energy absorption capability and superior resistance to crack propagation. In addition, the material maintains a stable load-bearing capacity even at relatively high strain levels, reflecting enhanced structural integrity and delayed failure during damage evolution.

This mechanical improvement is mainly attributed to several synergistic mechanisms, including increased fiber reinforcement content, improved stress redistribution within the matrix, higher resistance to microcrack initiation and propagation, and more efficient load transfer between fibers and epoxy matrix. These mechanisms collectively contribute to the improved toughness and damage tolerance of the composite system.

However, the mechanical performance does not increase proportionally with fiber content, indicating a nonlinear reinforcement effect. This limitation can be explained by interfacial inefficiencies such as imperfect fiber–matrix adhesion, stress concentration at fiber ends, localized fiber agglomeration, formation of matrix-rich zones, and premature interfacial debonding. Such behaviors are commonly observed in natural fiber-reinforced polymer composites due to the intrinsic hydrophilic nature of lignocellulosic fibers and the hydrophobic character of epoxy matrices, which reduce interfacial compatibility and stress transfer efficiency [46,47]. Therefore, the observed non-proportional strength improvement can be reasonably interpreted in relation to interfacial stress transfer efficiency, local damage development, and reinforcement distribution within the epoxy matrix.

4.1.4. Mechanical behavior, strength hierarchy, and failure mechanisms of palm fiber and epoxy composites

The raw palm fiber exhibits the highest tensile strength among all investigated materials, reaching approximately 80 MPa. Its nearly linear

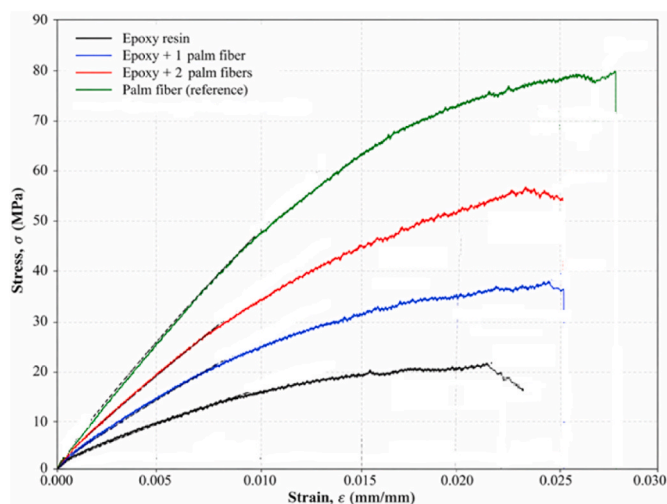


Fig. 6. Tensile stress–strain curves of EP, EP + 1 PF, EP + 2 PF, and PF reference tested as a single untreated technical fiber strand.

stress–strain response up to fracture reflects a stiff, cellulose-dominated microstructure with limited plastic deformation, governed by the alignment of lignocellulosic microfibrils and its semi-crystalline nature. These intrinsic features are responsible for the excellent mechanical performance of the isolated fiber.

However, the mechanical response of the composite systems remains significantly lower than that of the raw fiber, which highlights that the global behavior is not controlled only by fiber strength but also by the efficiency of stress transfer at the fiber–matrix interface. In this context, interfacial adhesion plays a critical role in determining reinforcement effectiveness, as it governs load transfer, stiffness improvement, and damage resistance.

The failure process in the composites involves a progressive sequence of mechanisms, starting from matrix microcracking, followed by fiber–matrix debonding, fiber pull-out, and finally fiber fracture. At the macro-morphological level, EP exhibited a more abrupt and brittle fracture appearance, whereas the reinforced configurations showed more irregular failure paths associated with fiber bridging and localized pull-out. This difference supports the transition from catastrophic matrix cracking in neat epoxy toward a more progressive damage process in the palm fiber-reinforced composites. These mechanisms contribute to a non-brittle failure response, where energy is gradually dissipated during damage evolution. As a result, fiber-reinforced composites show improved toughness and delayed catastrophic failure compared with neat epoxy.

Overall, while raw palm fiber provides the highest intrinsic strength, the composite performance is mainly governed by interfacial quality and damage mechanisms that control load transfer and failure evolution [44, 45,47].

4.1.5. Comparative analysis of Young's modulus

Fig. 7 presents the Young's modulus values extracted from the initial elastic region of the stress–strain curves shown in Fig. 6. Young's modulus represents the resistance of the material to elastic deformation and provides important information regarding composite stiffness.

The neat epoxy resin exhibits a modulus of approximately 3.15 GPa, which is consistent with conventional brittle thermosetting polymers reported in the literature [48].

After the incorporation of one palm fiber, the modulus increases to 3.28 GPa, corresponding to an improvement of approximately 4.1%. The addition of two palm fibers further increases the modulus to 3.41 GPa, representing an overall enhancement of nearly 8.3%.

The progressive increase in stiffness confirms that palm fibers contribute effectively to restricting elastic deformation of the matrix. However, the improvement remains moderate compared with the intrinsic modulus of the raw palm fiber (4.48 GPa).

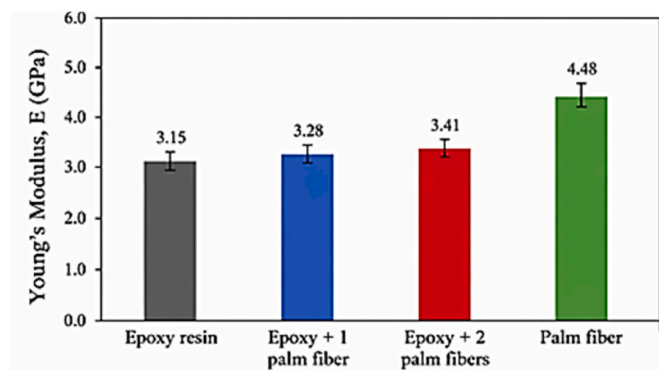


Fig. 7. Young's modulus values of neat epoxy resin, palm-fiber-reinforced epoxy composites, and raw palm fiber.

4.1.6. Elastic behavior, reinforcement efficiency and engineering significance

The elastic response of the studied epoxy/palm fiber composites shows a progressive increase in stiffness with fiber addition, confirming the reinforcement effect of natural fibers. However, the experimental Young's modulus remains lower than ideal micromechanical predictions, indicating that the reinforcement efficiency is not fully achieved due to non-ideal interfacial and morphological conditions.

Numerically, the Young's modulus increases from 3.15 GPa (neat epoxy) to 3.28 GPa with one palm fiber, and reaches 3.41 GPa with two palm fibers, corresponding to improvements of only +4.1% and +8.3%, respectively. In contrast, the raw palm fiber exhibits a much higher modulus of 4.48 GPa (+42.2%), which confirms that the composite does not fully exploit the intrinsic stiffness of the reinforcement phase.

This limited efficiency may be related to incomplete stress transfer at the fiber–matrix interface, together with possible non-uniform fiber dispersion, limited fiber aspect ratio, and micro-void formation during processing. These factors reduce the effective contribution of fibers to the global elastic response, particularly in the low-strain linear region where the matrix still dominates the mechanical behavior. This result indicates that improving interfacial compatibility is expected to be more critical than simply increasing the number of fibers, since reinforcement efficiency depends strongly on the quality of stress transfer across the fiber matrix interface.

From an engineering point of view, the results clearly demonstrate that palm fibers are effective in improving stiffness, but the reinforcement efficiency remains moderate at low fiber content. This means that mechanical performance is governed not only by fiber properties but also by the quality of the interface and the microstructural organization of the composite system.

The comparison between raw fiber modulus (4.48 GPa) and composite modulus (3.41 GPa) further highlights the interfacial limitation. The loss of nearly 1.07 GPa from fiber to composite level reflects the incomplete transfer of mechanical load from matrix to reinforcement, which is a typical behavior in untreated natural fiber composites.

To improve this efficiency, interfacial engineering becomes essential. Techniques such as alkali treatment, silane coupling, acetylation, plasma activation, and optimized curing cycles are necessary to enhance fiber wettability and chemical compatibility with the epoxy matrix, thereby improving stress transfer and reducing interfacial debonding phenomena.

Overall, despite the moderate increase in stiffness, the composite system demonstrates a clear reinforcement trend: +4.1% (1 fiber) and +8.3% (2 fibers), confirming that increasing fiber content remains beneficial. However, the results also indicate that the mechanical potential of palm fibers is not fully exploited, and that interface optimization is the key factor for achieving higher-performance bio-composites suitable for structural and semi-structural engineering applications.

4.2. Creep behavior of palm fiber-reinforced epoxy composites

Creep behavior is one of the most important long-term mechanical characteristics of polymeric materials and fiber-reinforced composites subjected to constant loading over time. In epoxy-based composites, creep deformation is mainly governed by the viscoelastic nature of the polymer matrix, which progressively undergoes molecular rearrangement under sustained stress. The incorporation of natural fibers can significantly modify this behavior by improving stiffness, restricting polymer chain mobility, and enhancing stress transfer within the composite structure. Thus, the creep stages discussed below are interpreted in direct relation to the viscoelastic deformation mechanisms introduced in Section 2, including instantaneous elastic deformation, delayed molecular rearrangement, and progressive strain accumulation under sustained loading. This approach allows the experimental curves to be discussed in terms of the deformation components represented by the Burgers-type formulation, without assigning material constants that

would require independent nonlinear fitting of the complete time–strain datasets.

In the present study, the creep performance of EP, EP + 1 PF, and EP + 2 PF was investigated under different applied loads. The objective is to evaluate the influence of palm fiber reinforcement on the time-dependent deformation behavior and long-term mechanical stability of the composites. The experimental results provide a comparative analysis of the three classical creep stages primary, secondary, and tertiary creep and highlight the role of fiber content in improving creep resistance and delaying damage evolution.

4.2.1. Creep response of neat epoxy resin

Fig. 8 illustrates the evolution of creep strain for neat epoxy composites subjected to applied loads of 400 g, 600 g, and 1000 g. The results clearly demonstrate the influence of both fiber reinforcement and stress level on the viscoelastic response of the materials.

All investigated materials exhibit the typical three-stage creep behavior observed in polymer composites, namely primary, secondary, and tertiary creep stages. This response is characteristic of viscoelastic polymeric systems and reflects the combined influence of matrix deformation [49].

The neat epoxy resin shows the highest creep deformation among all tested materials. Under an applied load of 1000 g, the creep strain increases rapidly during the first loading period, reaching approximately 0.13 within a few seconds. This initial deformation corresponds to the primary creep stage and is mainly associated with rapid viscoelastic relaxation and molecular rearrangement within the epoxy network.

As the loading time increases, the creep rate progressively decreases and the material enters the secondary creep stage, characterized by a relatively stable and slower strain accumulation. At longer exposure times, the strain begins to increase more rapidly, indicating the onset of tertiary creep. This stage is generally associated with progressive material degradation mechanisms such as matrix microcracking, local stress concentration, increased molecular mobility, and structural deterioration of the epoxy network.

The maximum creep strain reaches approximately 0.24 under the constant load of 1000 g, indicating the limited long-term dimensional stability of neat epoxy under sustained loading conditions. Similar creep behavior is also observed for lower loads (600 g and 400 g), although the total accumulated strain remains significantly lower than that measured under 1000 g. These observations confirm the strong dependence of epoxy creep behavior on the applied stress level, in agreement with previous studies on thermosetting polymers and viscoelastic composite materials [26].

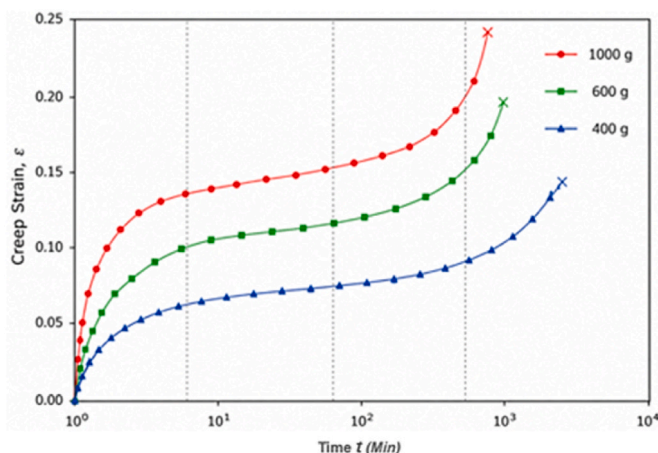


Fig. 8. Evolution of creep strain in neat epoxy composites under applied loads.

4.2.2. Effect of one palm fiber on creep resistance

The incorporation of one palm fiber layer significantly improves the creep resistance of the epoxy matrix. Compared with neat epoxy, the reinforced composite exhibits lower creep deformation at all loading levels and throughout the entire testing duration (see Fig. 9).

Under an applied load of 1000 g, the maximum creep strain decreases from approximately 0.24 for neat epoxy to nearly 0.205 for the composite reinforced with one palm fiber layer, corresponding to a reduction of about 14–15%. This decrease clearly demonstrates the beneficial effect of natural fiber reinforcement on the time-dependent deformation resistance of the composite.

Several reinforcing mechanisms contribute to this improvement. First, the palm fiber limits the mobility of the epoxy polymer chains, thereby reducing molecular rearrangement under sustained loading. Second, part of the applied load is transferred from the viscoelastic matrix to the stiffer reinforcing fiber, resulting in more efficient stress distribution throughout the composite. Moreover, the presence of the fiber reduces localized deformation zones that typically accelerate creep development in neat polymers. The reinforcement also contributes to delaying microcrack initiation and propagation, leading to improved structural stability during long-term loading.

Consequently, the palm fiber acts as a rigid load-bearing phase that partially constrains the deformation of the surrounding epoxy matrix. This effect stabilizes the secondary creep stage and delays the onset of tertiary creep, which is associated with irreversible deformation and progressive damage accumulation.

Overall, the reduction in creep strain confirms that palm fibers not only enhance the instantaneous mechanical properties of epoxy systems, but also significantly improve their long-term viscoelastic stability. These findings are consistent with previous investigations on lignocellulosic fiber-reinforced epoxy composites [50,51].

4.2.3. Effect of two palm fibers on creep resistance

The epoxy composite reinforced with two palm fiber layers exhibits the best creep performance among all investigated materials. The creep strain is considerably reduced at all loading levels, while the tertiary creep stage is significantly delayed.

Under the highest applied load of 1000 g, the maximum creep strain decreases to approximately 0.165. This corresponds to a reduction of nearly 31% compared with neat epoxy and about 20% compared with the composite reinforced with one palm fiber layer.

The progressive reduction in creep deformation with increasing fiber content demonstrates the important role of reinforcement in improving the resistance of the composite to long-term viscoelastic deformation. The additional fibers strengthen the structural response of the material and effectively limit strain accumulation under constant loading

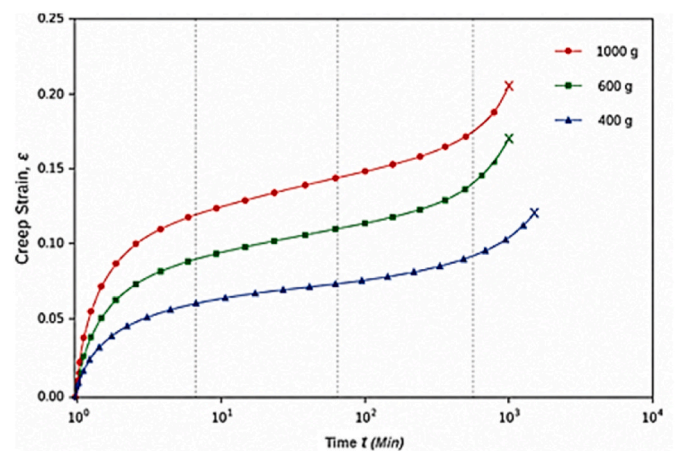


Fig. 9. Influence of one palm-fiber layer on the creep performance of epoxy composites.

conditions.

This enhanced creep resistance can be attributed to several coupled mechanisms. Increasing fiber content improves the overall stiffness of the composite, producing a more rigid load-bearing structure. At the same time, stress distribution becomes more efficient because a larger fraction of the applied load is transferred to the reinforcing fibers. In addition, the deformation of the polymer matrix is significantly constrained by the presence of multiple stiff reinforcements, reducing matrix-dominated viscoelastic strain. Improved interfacial load transfer between the epoxy matrix and the palm fibers also contributes to delaying localized deformation and damage initiation.

Furthermore, the tertiary creep stage becomes less pronounced as fiber content increases. This behavior indicates enhanced structural integrity and improved resistance to damage accumulation mechanisms such as microcracking and interfacial debonding.

Overall, these results are consistent with the classical viscoelastic behavior of fiber-reinforced polymer composites, where rigid reinforcements reduce creep susceptibility by restricting molecular mobility and limiting long-term relaxation processes within the polymer matrix [49,52].

4.2.4. Long-term creep performance of palm fiber-reinforced epoxy composites

The experimental results demonstrate that palm fiber reinforcement significantly enhances the long-term viscoelastic performance of epoxy composites. All tested materials exhibit the three characteristic creep stages: primary, secondary, and tertiary creep.

The primary creep stage is characterized by a rapid increase in strain immediately after loading due to instantaneous elastic deformation and molecular relaxation within the epoxy matrix. The neat epoxy resin exhibits the highest initial creep rate, whereas the reinforced composites show lower deformation because the palm fibers restrict polymer chain mobility and improve stress transfer within the composite structure [49].

During the secondary creep stage, the strain rate becomes relatively stable. The composite reinforced with two palm fiber layers exhibits the lowest steady-state creep deformation, indicating superior dimensional stability and greater resistance to long-term loading. The addition of palm fibers reduces matrix-dominated deformation and delays viscoelastic strain accumulation by increasing the stiffness and load-bearing capacity of the composite [51].

In the tertiary creep stage, the creep strain increases rapidly as a result of progressive damage accumulation and crack propagation. The neat epoxy reaches this stage earlier than the reinforced composites, reflecting its lower resistance to creep-induced degradation. In contrast, the palm fiber-reinforced systems exhibit delayed tertiary creep behavior, particularly for the composite containing two palm fiber layers. This improvement is mainly attributed to crack-bridging mechanisms, stress redistribution, and enhanced resistance to crack propagation provided by the reinforcing fibers [52].

4.2.5. Statistical analysis of maximum creep strain

The statistical analysis of the maximum creep strain confirms the beneficial influence of palm-fiber reinforcement on the viscoelastic behavior of the epoxy composites. Compared with neat epoxy, the composite reinforced with two palm-fiber layers exhibits a significant reduction in creep deformation under all applied loading conditions. The measured reductions in maximum creep strain reach approximately 37%, 34%, and 31% under applied loads of 400 g, 600 g, and 1000 g, respectively. The slight decrease in reduction efficiency at higher load levels suggests that the reinforcing effect of palm fibers becomes progressively challenged as the applied stress increases. Nevertheless, the two-layer composite maintained the lowest creep strain under all loading conditions, confirming its superior resistance to time-dependent deformation (see Fig. 11).

These results demonstrate that increasing the palm-fiber content

substantially improves the creep resistance and long-term dimensional stability of the composite material. The enhanced performance can be attributed to the effective load-transfer capability of the fibers and their ability to restrict the mobility of the polymer chains within the epoxy matrix, thereby delaying time-dependent deformation and damage evolution.

Overall, the experimental results confirm that increasing the palm-fiber content significantly enhances the creep resistance and long-term structural stability of epoxy composites. Palm fibers act as effective reinforcement agents by reducing time-dependent deformation and improving the durability of the material under sustained mechanical loading. Among the investigated composites, the epoxy reinforced with two palm-fiber layers exhibits the best creep performance, highlighting its potential as an eco-friendly and lightweight material for structural and semi-structural engineering applications.

4.3. Temperature-dependent creep behavior of EP, EP + 1 PF, and EP + 2 PF

Temperature-dependent creep tests were evaluated at four temperature levels, namely 20°C, 40°C, 60°C, and 80°C, for neat epoxy, EP + 1 PF, and EP + 2 PF composites. The experimental creep curves of neat epoxy (EP), epoxy reinforced with one palm-fiber layer (EP + 1 PF), and epoxy reinforced with two palm-fiber layers (EP + 2 PF) exhibit the classical viscoelastic response of polymeric composites, typically divided into three stages: primary, secondary, and tertiary creep.

In the primary creep stage, a rapid increase in strain is observed due to instantaneous elastic deformation combined with molecular chain rearrangement. This stage is governed by transient viscoelastic effects immediately after load application.

The secondary creep stage is characterized by an approximately constant creep rate, resulting from a dynamic equilibrium between molecular relaxation and viscous flow. This region represents the dominant portion of long-term deformation under constant stress.

At elevated temperature (notably 80°C), the tertiary creep stage becomes more pronounced. This stage is associated with accelerated strain accumulation due to matrix softening, progressive damage, and microcrack propagation, ultimately leading to material instability and potential failure.

4.3.1. Epoxy (neat resin): temperature-dependent creep response

The creep curves of neat epoxy (Fig. 12) clearly show a strong dependence on temperature. At 20°C, the material exhibits limited creep deformation, indicating a relatively stable viscoelastic response in the glassy region. However, as temperature increases to 40°C, 60°C, and 80°C, the creep strain increases significantly, particularly at long

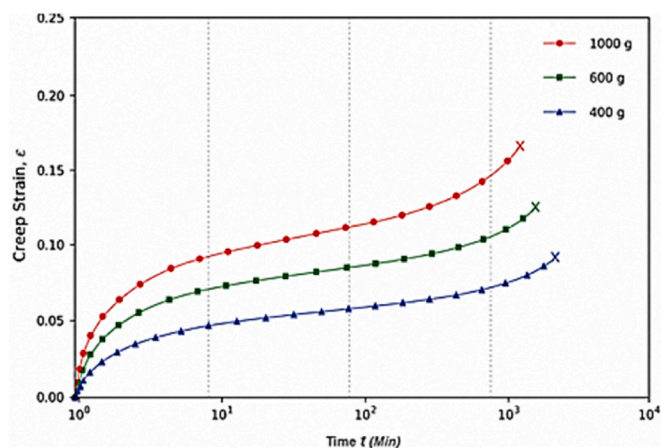


Fig. 10. Influence of two palm-fiber layers on the creep performance of epoxy composites.

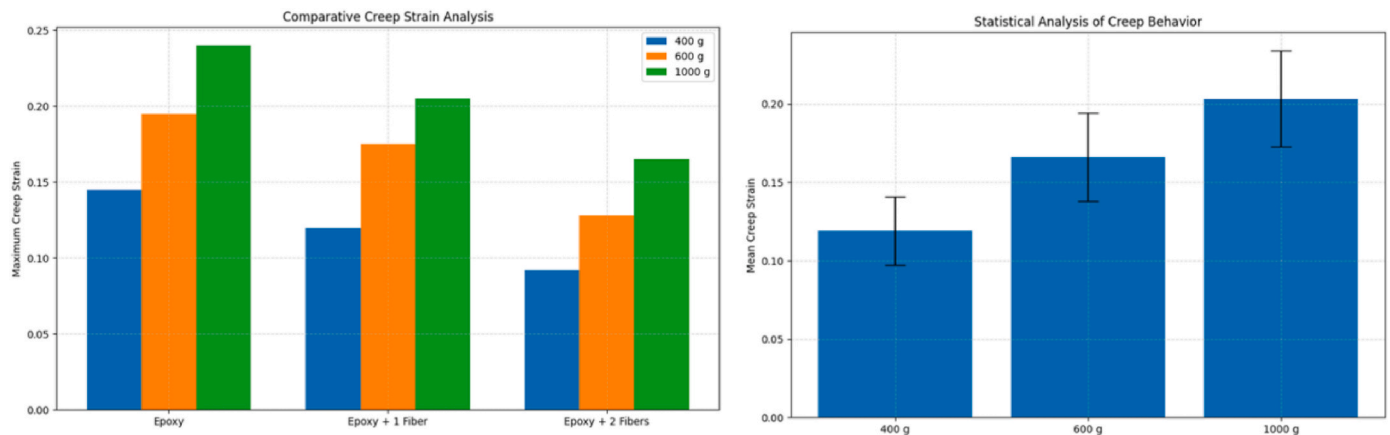


Fig. 11. Maximum creep strain reduction with palm fiber reinforcement.

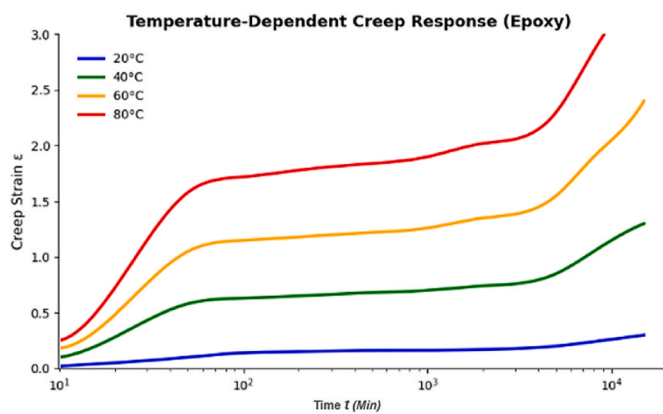


Fig. 12. Creep response of epoxy illustrating deformation curves at different temperatures for comparison.

loading times (see Fig. 11).

This behavior is attributed to increased molecular mobility of the epoxy network as it approaches and exceeds its glass transition region, which reduces stiffness and accelerates time-dependent deformation. The sharp rise in creep strain at higher temperatures confirms the thermally activated nature of polymer chain relaxation mechanisms.

Such temperature sensitivity is consistent with previous studies on epoxy systems, where elevated temperatures were shown to dramatically reduce creep resistance due to matrix softening and enhanced segmental motion [53].

4.3.2. Epoxy + one palm fiber layer

The introduction of one palm fiber layer (Fig. 13) significantly reduces creep deformation compared to neat epoxy across all temperatures. Although the general temperature-dependent trend is preserved, the magnitude of creep strain is noticeably lower. This improvement is mainly associated with more effective stress transfer from the epoxy matrix to the fibers, restriction of polymer-chain mobility near the fiber-matrix interface, and increased internal friction and load-sharing mechanisms.

At higher temperatures (60–80°C), the composite still shows increased creep, but the rate of deformation is slower than in neat epoxy, indicating partial stabilization provided by the fiber reinforcement.

These observations are consistent with natural fiber-reinforced epoxy systems reported in literature, where moderate fiber content improves viscoelastic stability but does not fully suppress thermal softening effects [54].

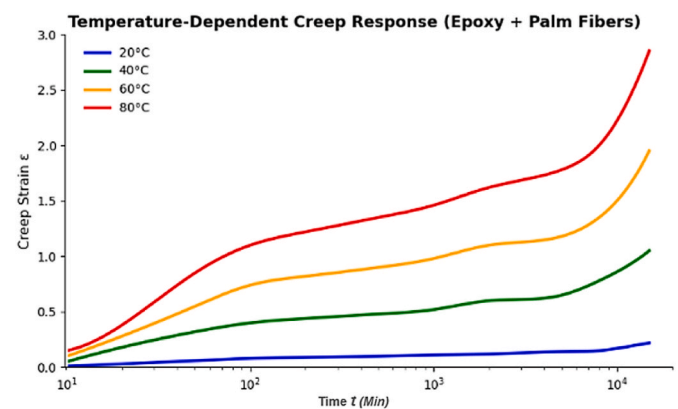


Fig. 13. Creep response of epoxy with one palm fiber layer showing deformation curves at different temperatures for comparison.

4.3.3. Epoxy + two palm fiber layers

The composite reinforced with two palm fiber layers (Fig. 14) exhibits the best creep resistance among all tested materials. Across all temperature levels, the creep strain is significantly reduced, and the deformation curves show a more stable long-term response. This improved behavior is attributed to the higher reinforcement content, enhanced load-bearing contribution of the fibers, stronger restriction of matrix deformation, and improved stress redistribution within the composite structure.

Even at elevated temperatures (80°C), the creep response remains

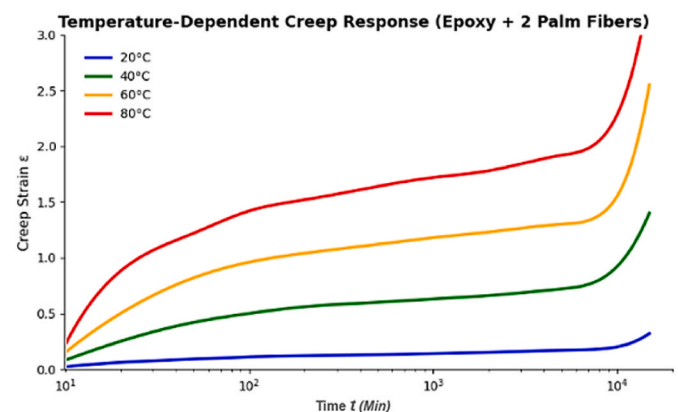


Fig. 14. Creep response of epoxy with two palm-fiber layers at different temperatures.

considerably lower than both neat epoxy and single-fiber composites. This indicates that increasing fiber content effectively delays viscoelastic deformation and improves dimensional stability under thermal and mechanical loading.

Similar improvements have been reported in natural fiber/epoxy composites, where increasing reinforcement content leads to reduced creep compliance and improved long-term structural integrity [53].

A global comparison of Figs. 12–14 reveals three main trends governing the creep response of epoxy and palm fiber/epoxy composites.

First, a strong thermal sensitivity of the epoxy matrix is observed. Neat epoxy exhibits a pronounced increase in creep deformation with rising temperature, which is attributed to polymer chain mobility enhancement and thermal softening effects.

Second, a progressive improvement in creep resistance with fiber reinforcement is clearly identified. The incorporation of one palm fiber layer reduces the overall creep strain, while the addition of two layers leads to a more significant reduction, confirming the beneficial role of fiber-layer configuration in restricting matrix deformation and improving load transfer efficiency.

Third, a synergistic effect between temperature and reinforcement is evident. Although increasing temperature accelerates creep in all materials, fiber-reinforced composites consistently exhibit lower deformation levels compared to neat epoxy, indicating that reinforcement mitigates but does not completely eliminate thermal activation effects.

Overall, palm fibers act as effective natural reinforcements by enhancing creep resistance, reducing viscoelastic deformation, and improving long-term dimensional stability under sustained loading. These findings are consistent with reported behavior in fiber-reinforced polymer composites, where viscoelastic creep is strongly governed by matrix–fiber interactions and environmental conditions [54].

In general, the experimental results confirm that creep behavior in epoxy-based composites is controlled by a strong coupling between temperature and reinforcement architecture. While neat epoxy shows high sensitivity to thermal activation, the introduction of palm fibers significantly enhances structural stability. The best performance is obtained for the composite reinforced with two fiber layers, making it more suitable for lightweight structural applications requiring long-term mechanical reliability under variable thermal conditions.

4.4. Temperature-dependent creep behavior and reinforcement efficiency of epoxy/palm fiber composites

The bar chart presents the evolution of maximum creep strain (%) of neat epoxy and palm-fiber-reinforced epoxy composites (one and two fiber layers) as a function of temperature (20°C, 40°C, 60°C, and 80°C). A consistent and strongly temperature-dependent trend is observed for all materials, where creep strain increases significantly with increasing temperature, confirming the pronounced thermo-viscoelastic nature of

epoxy-based polymers [55] (see Fig. 15).

At 20°C, all materials exhibit relatively limited deformation, with neat epoxy showing the highest creep strain compared to the reinforced configurations. As temperature rises, the creep response intensifies progressively, particularly beyond 60°C, where the increased mobility of polymer chains becomes dominant and leads to accelerated time-dependent deformation. This behavior is characteristic of thermoset polymers approaching their glass transition region, where stiffness decreases and viscoelastic effects become more pronounced [55].

The incorporation of palm fibers systematically reduces the maximum creep strain at all investigated temperatures. The composite with one fiber layer shows a moderate improvement, while the two-layer configuration demonstrates the most significant reduction, indicating enhanced reinforcement efficiency and improved load transfer mechanisms. This confirms the progressive stiffening effect induced by increasing fiber content and the role of fibers in restricting matrix deformation [56].

From a micromechanical standpoint, this behavior is attributed to the intrinsic viscoelastic nature of the epoxy matrix combined with the mechanical constraint provided by natural fibers. At elevated temperatures, epoxy chains gain mobility, leading to higher creep deformation; however, palm fibers act as rigid inclusions that limit molecular movement and improve stress transfer efficiency at the fiber–matrix interface [56]. The improvement becomes more evident at higher fiber content, where the two-layer configuration provides stronger structural restraint and better dimensional stability.

The reduction in creep strain is particularly significant at 60°C and 80°C, where neat epoxy exhibits a sharp increase in deformation, while the reinforced composites maintain a more stable response. This demonstrates the ability of palm fibers to delay viscoelastic degradation and enhance long-term mechanical stability under thermal loading conditions.

These experimental trends are fully consistent with classical viscoelastic theory and composite mechanics. Thermoset polymers such as epoxy are well known for their strong temperature-dependent creep behavior due to their time-dependent molecular structure and thermally activated deformation mechanisms. Moreover, the reduction of creep deformation through natural fiber reinforcement has been widely reported, and is generally attributed to load sharing, increased stiffness contribution, and restricted polymer chain mobility [56].

Similar observations have been documented in natural fiber composites, where increasing fiber content leads to improved creep resistance and reduced viscoelastic deformation under elevated temperatures [32]. Therefore, the results obtained in this study are in strong agreement with established theoretical models and experimental findings in polymer composite mechanics. These findings also indicate that palm fibers are more effective in delaying creep deformation than in completely eliminating thermal softening of the epoxy matrix. Thus, the reinforcement mainly improves creep resistance by stabilizing the matrix-dominated deformation process under combined thermal and mechanical effects.

From an engineering application perspective, the reduction in creep strain is critical for components subjected to long-term mechanical loading and elevated service temperatures. The two-layer palm fiber composite exhibits the best overall performance, indicating its potential suitability for lightweight structural applications, automotive components, and thermally exposed mechanical systems. These results confirm that natural fibers can serve not only as sustainable reinforcements for improving static strength but also as effective modifiers for controlling long-term deformation under thermo-mechanical conditions.

5. Conclusion

This study examined the tensile and long-term creep behavior of epoxy composites reinforced with natural palm fibers. The experimental results demonstrate that adding palm fibers significantly improves the

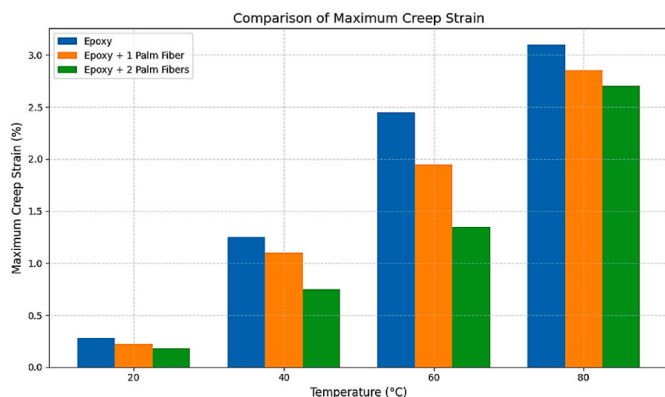


Fig. 15. Comparison of maximum creep strain of epoxy and palm-fiber reinforced epoxy composites under different temperatures.

mechanical properties of the epoxy matrix. Fiber reinforcement increased tensile strength and stiffness while reducing permanent deformation and delaying failure, indicating efficient load transfer and effective fiber participation in load bearing.

Creep tests confirmed the viscoelastic nature of the polymer matrix. Deformation was strongly dependent on applied stress and temperature: higher stress or temperature accelerated creep and shortened time to failure. Nonetheless, palm fiber-reinforced composites exhibited markedly improved creep resistance compared to neat epoxy, with lower steady-state creep rates, extended secondary creep stages, and delayed onset of tertiary creep. This improvement arises because the fibers form a constraining network that limits polymer-chain mobility, enhances stress transfer, and inhibits crack propagation.

Overall, the combined tensile and creep findings confirm that palm fiber reinforcement enhances both short-term strength and long-term dimensional stability. Given their improved performance and the renewable, eco-friendly nature of palm fibers, these epoxy composites are promising candidates for lightweight structural and semi-structural applications in sustainable engineering contexts. Future work should target further enhancement of fiber-matrix interfacial bonding, including detailed fractured-surface and microstructural analyses to better clarify damage mechanisms, together with evaluation of long-term durability under environmental aging and thermal cycling and development of predictive viscoelastic creep models for service-life estimation and reliable composite design.

Consent to participate

No external participants have contributed to the work discussed in this manuscript.

Ethical approval

The authors declare that the research was conducted according to ethical standards. This article does not contain any studies with human or animal subjects.

Consent for publication

The authors give their full consent to the editor to publish this article if accepted.

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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.

Data availability

The data that support the findings of this study are available on request from the authors.

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