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Fabrication and Characterisation of Kenaf Fibre Reinforced Polyamide Biocomposites for Railway Sleeper Applications

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ABSTRACT

Railway passing traffic, speed, and load have significantly increased over the years, prompting industry stakeholders and researchers to seek an alternative sleeper material that can demonstrate its ability to potentially possess higher in-service bending resistance and be environmentally friendly and durable. To address these needs and due to environmental concerns, kenaf-reinforced polyamide has become of great importance. However, they could not be applied as railway track components because of the non-availability of their performance in this regard. In bridging this gap, this paper focused on fabricating and characterising six different formulations of treated kenaf fibre (TKF, 0–50% at 10% loading interval) reinforced polyamide biocomposites for railway sleeper applications. The result showed that the incorporation of TKF influenced the behaviour of the polyamide with respect to its water absorption, load-carrying capacity, and thermal stability. The result further demonstrated that the load-bearing capacity peaked at TKF 40 wt.%, surpassing conventional wooden and concrete sleepers. However, its water absorption (64-days saturation) behaviour increased significantly between 11%–21% as TKF rose from 10–50 wt.%, as expected due to TKF hydrophilic characteristics. On the other hand, TKF thermal stability was hampered beyond approximately 220°C for

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all TKF percentages. Kenaf fibre-reinforced polyamide biocomposites have demonstrated their potential for railway sleeper applications as their load-bearing capacity exceeded the minimum recommended AREMA specifications. Despite the milestone achieved, water absorption of kenaf fibre remained high. The development of sustainable and effective materials to meet the changing needs of contemporary railway infrastructure is greatly aided by the insights gained from this study.

Keywords: Flexural strength, polyamide biocomposites, railway composite sleeper, thermogravimetric analysis, treated kenaf fibre, water absorption

INTRODUCTION

The rapid escalation in railway traffic, speed, and load over recent years has paralleled a growing demand for track components that offer enhanced durability, environmental sustainability, and improved service performance. In response to these evolving requirements and driven by increasing environmental concerns, kenaf-reinforced polyamide composites have emerged as a highly significant material. As they are meant to endure a variety of deterioration causes, distribute and reduce dynamic loads throughout the ballast layer, and maintain precise track gauges, sleepers are among the most important components of the railway track system (Askarinejad et al., 2018; Casado et al., 2016; Manalo & Aravinthan, 2012; Zeng et al., 2020; Zhang et al., 2022; Zhao et al., 2007). Wood, steel, and concrete are common traditional materials used to make railway sleepers. Their bending strengths for adequate performance are 70-110 MPa (Siahkouhi et al., 2022a), 120 MPa (Jing et al., 2022) and 110 MPa (Siahkouhi et al., 2022b) for timber, steel, and concrete, respectively. Increasing train speed, weight, and passing traffic have resulted in several mechanical and durability difficulties documented in the literature (Jokubaitis et al., 2020; Lee et al., 2016; Yu et al., 2021).

Railway industry stakeholders' and researchers' quest for composite material has increased due to the existence and rise of these problems. The quest for improved structural properties, reduced cost of maintenance, and increased lifetime of the sleeper have become a subject of concern to researchers and railway industry stakeholders (Axion, 2022; Integrated Recycling Pty Ltd, 2022; KLP Main Track Sleeper-Sustainable Plastic Railway Solutions, 2014; Sicut Enterprises Ltd., 2022; TieTek, 2022; TVEMA, 2022). Because of the environmental benefits, natural fibre composite materials should be preferred when developing and manufacturing railway composite sleepers.

Hitherto, the application of natural fibres as one of the constituents' materials in biocomposites and as a substitute for synthetic materials have been considered by global industries because of their advantages of being renewable and possession of marketing appeal in the composite manufacturing industries as well as their commensurable

physical and mechanical properties compared to synthetic fibres. Most importantly, the unique properties of kenaf fibre-reinforced polymer composites, such as low density, low cost, recyclability, biodegradability, and sustainability in terms of resources as well as being abundantly available, make kenaf fibre a choice material. Additionally, the simple preparation process requires little and simple equipment. Moreover, harmful gases that pollute the environment are not generated during preparation. Thus, the use of fibres obtained from agricultural crop residues as the main source of the composite's product can mitigate open burning that can lead to air pollution, thereby help in protecting the environment (Bujjibabu et al., 2018; Mochane et al., 2019; Nurazzi et al., 2021; Shireesha et al., 2019). Synthetic (glass) fibre-based composites are now considered for replacement by natural fibre-based composites development, especially for structural applications by some relevant major industries such as civil construction, aerospace, and automobile industries. These composite-based natural fibre materials can produce automobile body panels, interiors, storage devices, buildings, and industrial panels (Karthi et al., 2020; Syduzzaman et al., 2020).

The main hindrance in natural fibre composite applications is its deterioration tendencies in environments with high moisture and lack adhesion between the fibre-matrix interface, especially when proper fibre surface modification is lacking. Moisture intrusion into composite materials has a detrimental effect on the fibre-matrix interfacial adhesion, hydrolyses, and sporadically introduced microcracks in the matrix (Nurazzi et al., 2021). Water can be discovered in polymers in a variety of forms, including bound water, which has strong contact with the matrix molecule and free water existing in vessels and micro gaps within the polymer.

The application of composites in civil engineering has surged due to their advantageous properties, such as high strength-to-weight ratio and resistance to corrosion and wear. Historically, synthetic fibres have dominated this field (Hwang et al., 2019; Kaewunruen, 2015; Koller, 2015; Takai et al., 2006). However, shifting towards natural fibres is essential for sustainable and efficient composites. This study focuses on evaluating the feasibility of kenaf fibre-reinforced polyamide biocomposites for railway sleeper applications. It aims to experimentally determine the optimal fibre loading to achieve the required load-bearing capacity and to assess the effects of water absorption and thermal stability on the composite.

MATERIALS AND METHODS

Materials

The raw materials used in this study contain only two components: a matrix component made from Polyamide six (PA6) and a grade A plant-based fibre long reinforcement from kenaf fibre. The quality of the raw materials is highly dependent on their production source and processing. PA6 was supplied by the Shanghai King Chemicals Co. Ltd., having a

density of 1.13 g cm^{-3} as the matrix, and kenaf fibre was purchased from Lembaga Kenaf dan Tembakau Negara (LKTN), Kelantan, Malaysia. These companies follow standard procedures in material production. The grade A long kenaf fibre was processed using a mesh size of 2 mm at the Fibre and Biocomposite Centre (FIDEC), Malaysian Timber Industry Board (MTIB). The surface of the long kenaf fibre was treated and then dried in the industrial oven for 24 h at 60°C prior to processing at FIDEC. An optimum alkaline solution (6%) of sodium hydroxide (NaOH) (Abdullah et al., 2022) was used for the kenaf fibre surface modification. Hence, a treated kenaf fibre (TKF), 2 mm in length, was used throughout this study.

Composites Preparation

Mixture Design

In the production of recycled high-density polyethene (RHDPE) and filler composites, research consistently reports the use of filler proportions by weight ranging from 10% to 50% (Almeida et al., 2021; Atikler et al., 2006; Bartczak et al., 1999; Esmaeili et al., 2023; Ratanawilai & Taneerat, 2018; K. Yang et al., 2007). This weight range is widely adopted to optimise the material properties and performance of RHDPE/filler composites. A notable bonding behaviour was observed at 40 wt% in producing wood flour-reinforced hydrophilic polymer composites (Lu & Forcada, 2006). Similarly, Agnantopoulou et al. (2023) reported positive results with hydrophilic thermoplastic starch reinforced with 50 wt.% wood flour. These studies, among others, have demonstrated the effectiveness of using wood flour and fillers in composite production. However, this research focuses on using short-treated kenaf fibres (2 mm) as reinforcement in biocomposites. It aims to investigate the performance and behaviour of the composite when these fibres are introduced. This study investigated six PA6/TKF biocomposites with varying TKF loadings (10, 20, 30, 40 and 50 wt.%) alongside a control comprising neat PA6 without any fibre, as shown in Table 1.

Table 1
Formulation of TKF/Polyamide six biocomposite

Sample ref.	PA6 (wt. %)	TKF (wt. %)
PA6	100	0
90PA6/10TKF	90	10
80PA6/20TKF	80	20
70PA6/30TKF	70	30
60PA6/40TKF	60	40
50PA6/50TKF	50	50

Fabrication of Kenaf Fibre Reinforced Polyamide 6 Biocomposites

Treated kenaf fibre and PA6 particles were oven-dried for 24 h at 110°C. The TKF/PA6 biocomposites were prepared in two stages: internal mixing with a brabender machine and compression moulding based on the earlier formulation in Table 1. Prior to processing, the components were manually dry-mixed for 10 minutes before being fed into a Brabender feeder. The mixture was then processed using a counter-rotating twin screw extruder at a speed of 50 rpm, with the temperature profile in zones 1–3 set to 230°C. The constituents were mixed for 10 minutes, after which the blend was manually extracted. The mixture instantly solidified at room temperature and cooled within 3 to 5 minutes. The resulting biocomposite pellets were then compression-moulded into boards (150 mm × 150 mm × 3.2 mm) using a hydraulic hot thermosetting press set to 220°C and 400 kN pressure for 5 minutes. The fabrication and characterisation sequence are shown in Figure 1.

Test specimens of specific sizes were cut from the biocomposite boards (Table 2). Figure 1 (a) and (b) show a view of the typical specimen. Sixty test specimens were prepared based on the fibre loadings.

Table 2
Number of specimens and standards used for characterization

Test name/Type	Test standard	No. of specimen	Dimension (mm)		
			Thickness	Length	Width
Water absorption	ISO 62:2008	30	3.2	50	50
Flexural strength	ASTM D790-10	30	3.2	120	12.7
TGA	ASTM E1131-20	36 mg	6 mg x 6 nr.		

CHARACTERISATION

Water Absorption

The water absorption test was conducted according to ISO 62 (2008). Five replicates of samples with dimensions of 50 x 50 x 3.2 mm were dried in an oven maintained at 50 ± 2°C for at least 24 h, placed in a desiccator, and allowed to cool to room temperature before weighing them to the nearest 0.1 mg. The process was repeated until the specimen mass became constant (mass, m_1). The specimens were then placed in a container filled with distilled water. After immersion in the water for 24 h, the specimen was removed from the water one after another, their surface water was dried off, and the dried specimen was weighed within one minute of removing from the water (mass, m_2). The water content at saturation was measured by re-immersing the test specimens and reweighing them at time intervals 24, 48, 96, 192, 384, 768, and 1536 h. At each time interval, the sample was removed, its surface water cleaned off and reweighed within one minute of removal from the water (mass, $m_2/24_h$).

$$Percentage\ \ by\ mass\ of\ water\ absorbed,\ C = (m_2 - m_1)/m_1\ \times 100\% \quad (1)$$

Where m_1 is the mass of the test specimen in milligrams (mg), and m_2 is the mass of the test specimen in milligrams (mg) after immersion.

Thermal Gravimetric Analysis (TGA)

The samples were tested using thermogravimetric analysis (TGA) at a scanning rate of 10°C/min on a Mettler Toledo TGA/DSC 1HT Stare System (Switzerland) between 30 and 600°C in accordance with ASTM E1131-20. TGA is a technique that monitors weight changes as a sample is heated at a consistent rate to evaluate the thermal stability of materials and their fraction of volatile components.

Flexural Strength Testing of TKF Reinforced Polyamide Biocomposites

The flexural test was conducted based on ASTM D790-10 standards using a universal tensile testing machine INSTRON model with a maximum load of 50 kN in a typical laboratory environment with 50% relative humidity and 23°C. Five replicate specimens accurately sized and cut out using a band saw were examined for flexural strength at a crosshead loading speed and the span-to-depth ratio of 1.36 mm/min and 16:1, respectively (Figure 1) (ASTM D790, 2010). The findings show the average results of tests run on all the biocomposite samples.

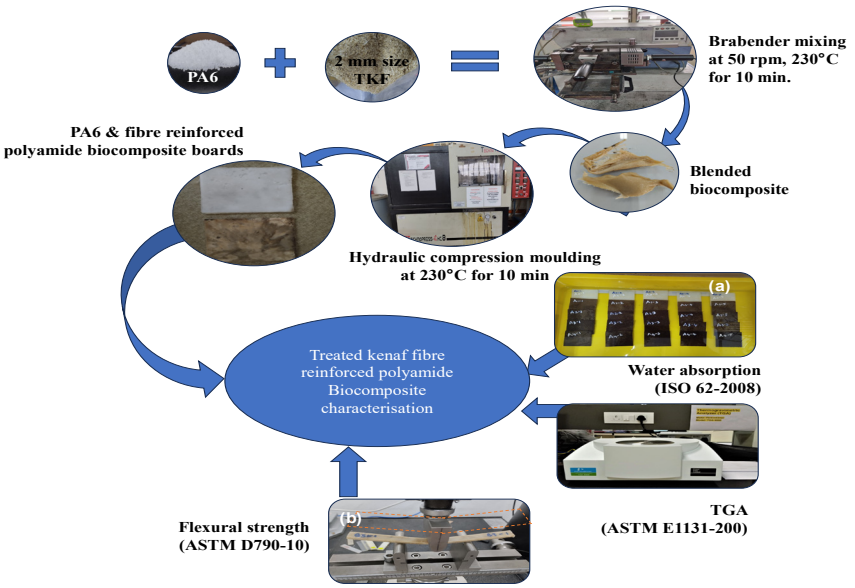

Figure 1. The sequence of treated kenaf fibre-reinforced polyamide biocomposites fabrication and characterisation: (a) water absorption and (b) flexural strength tests

RESULTS AND DISCUSSION

Water Absorption

Figure 2 illustrates the water absorption behaviour of treated kenaf fibre-reinforced polyamide biocomposites compared to neat polyamide six (PA6) as a control specimen. Over a submersion period of up to 64 days, the control specimen reached saturation at less than 10% water uptake within 32 days. Higher fibre loading (10–50%) in the composites resulted in increased water absorption, aligning with the hydrophilic nature of treated kenaf fibre (TKF) due to its hydroxyl (-OH) groups because of the presence of cellulose content, as indicated by Fourier Transform Infrared (FTIR) spectroscopy (Figure 3), (Maslinda et al., 2017; Rozali et al., 2017; Son et al., 2001; H.-S. Yang et al., 2016). The hydroxyl groups are the primary contributors to moisture ingress, enhancing the composites' susceptibility to water (Maslinda et al., 2017).

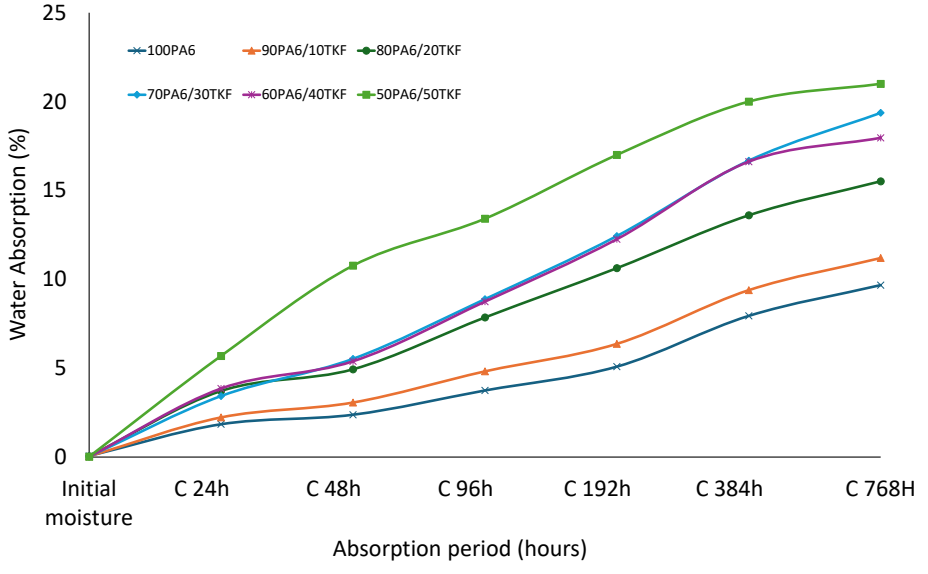

Figure 2. Rate of water absorption of PA6/TKF 0–50% (at 10% intervals) reinforced polyamide biocomposites at 64 days

Absorption levels ranged from 10% to 21%, with the highest reading observed in composites with 50 wt.% treated kenaf fibre (TKF). This elevated water uptake is likely due to the matrix's inadequate performance shielding the fibres from water exposure because of pores, as shown in Figure 4. The inability to effectively coat the fibre surfaces may result in the formation of microcracks (Figure 5), facilitating active and dominant moisture ingress in these regions. As a result, biocomposite panels with higher fibre loadings of up to 50 wt.% exhibited greater water absorption compared to those with lower fibre loadings of 10 to 40 wt.%.

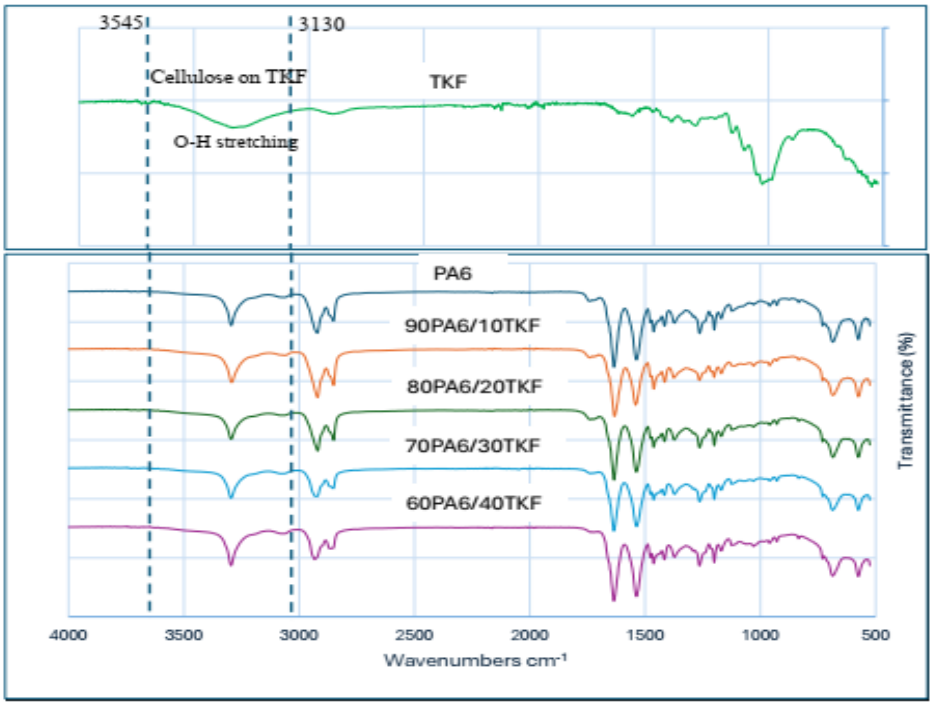

Figure 3. FTIR analysis showing the presence of cellulose on TKF

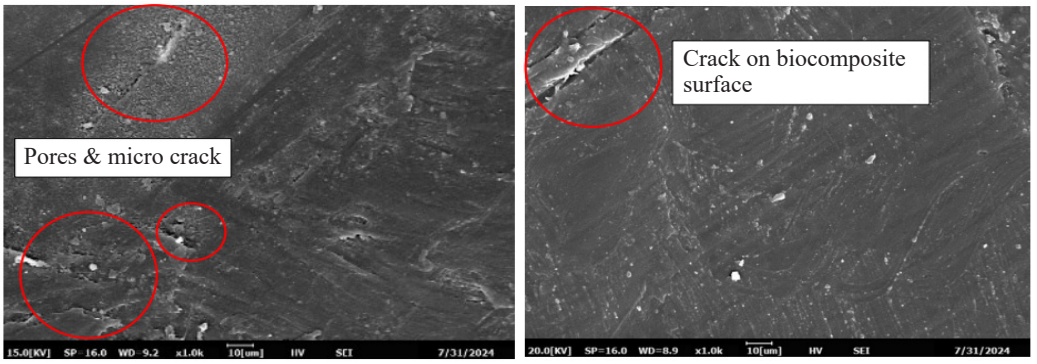

Figure 4. SEM images of PA6/TKF reinforced polyamide biocomposites

Thermogravimetric Analysis (TGA)

The thermal behaviour of the composites is an important parameter for composites determined by the thermogravimetric analysis technique. The effect of fibre loading on TGA and DTG (derivative thermogravimetric analysis) curves for thermosetting plastic/kenaf fibre biocomposites are presented in Figure 5. In contrast, the TGA data of the biocomposite samples is depicted in Table 3. Three zones were identified by the TGA curves of the PA6 biocomposites reinforced with TKF. The first zone's weight loss, less

than 250°C and not more than 3% may have been caused by small molecular components and residual moisture evaporating during sample processing and storage (Hirçin et al., 2021; Xu et al., 2019). In the second zone, weight loss ranging between 50–90 wt.% was exhibited up to 500°C, while up to 600°C in the third zone recorded loss up to 12 wt.%. It showed a varied degradation temperature between neat PA6 and TKF/PA6 biocomposites. The thermal stability of the biocomposites was reduced as the fibre loading was increased, resulting in the shifting of the main DTG peak to a lower temperature (Figure 4). The higher onset temperature associated with PA6 led to the conclusion that TKF had lower but quicker thermal degradation temperature at onset than PA6 composites. This finding is similar to Kiziltas et al. (2016) and Abdullah et al. (2022).

The different fibre loadings used revealed that it caused a decrease in the thermal performance of the matrix biocomposite. Furthermore, the increase in weight loss upon increase in fibre loading matched other researchers' findings (Bijwe et al., 2002; Harsha & Tewari, 2003). The PA6's thermal constancy was notably higher than that of TKF, as presented in Figure 5.

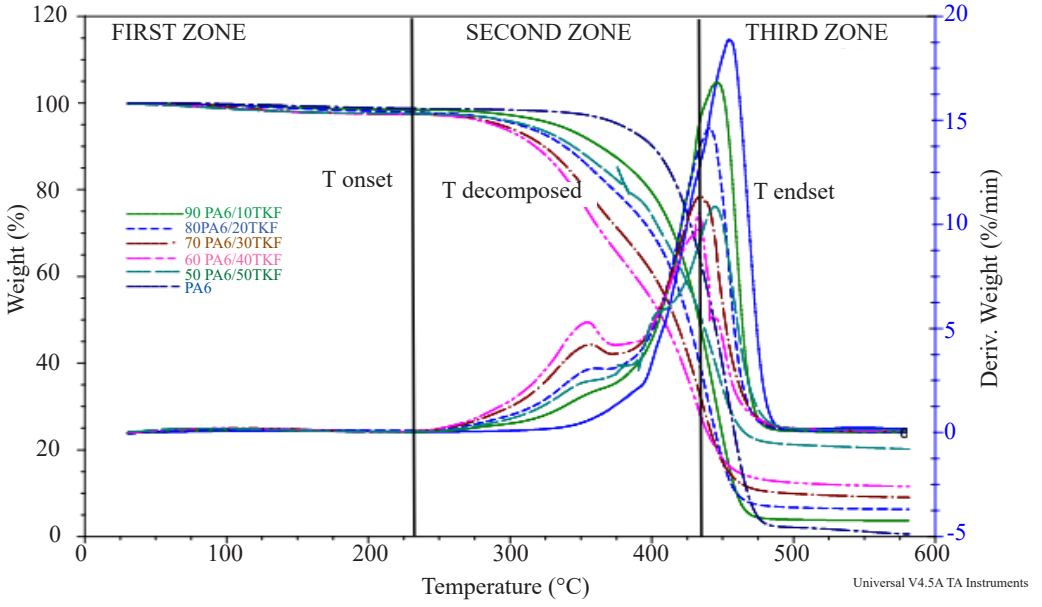

Figure 5. TGA curves and DTG peaks for PA6/TKF reinforced polyamide biocomposites

Flexural Strength

The load-bearing capacity of the kenaf fibre-reinforced polyamide biocomposite was evaluated by its ultimate flexural strength. The ultimate flexural strength was plotted against fibre loading, as presented in Figure 6. The initial decline in flexural strength with the addition of kenaf fibres (at 10, 20, and 30 wt.%) can be attributed to several factors.

Table 3
TGA data for neat PA6 and PA6/TKF biocomposite

Sample	Temperature (°C)			Weight loss (%)	Residue at 600°C (%)
	T onset	Tendset	Tdecomposed		
PA6	250	475	418.13	98.15	0.543
90PA6/10TKF	225	470	405.03	94.77	3.662
80PA6/20TKF	230	470	414.87	75.24	6.288
70PA6/30TKF	213	460	412.30	63.47	9.003
60PA6/40TKF	220	463	410.28	53.90	11.560
50PA6/50TKF	225	465	369.27	77.47	20.170

Firstly, the dispersion and interfacial bonding between the fibres and the polyamide matrix play a crucial role. Inadequate bonding can lead to stress concentration points, reducing mechanical properties. Furthermore, fibres might introduce microstructural flaws, such as voids or microcracks, which can act as stress concentrators and weaken the composite. However, at 40 wt.% fibre loading, an increase in flexural strength to 92.4 MPa is observed, suggesting that the fibre-matrix interaction and stress transfer are optimised at this particular loading. It implies a more efficient load-bearing mechanism, where the fibres contribute positively to the overall strength of the composite due to good stress transmission by the fibre through the matrix with less stress concentration in the composite. This value was greater by more than 50% of similar results reported by Arema (2013), Esmaeili et al. (2023), Khalil (2018), and Khalil et al. (2019). The minimum plastic sleeper bending requirements should be more than 28 MPa as ISO 12856-1 (2014) recommended, and this study surpassed the recommended minimum by more than 200%.

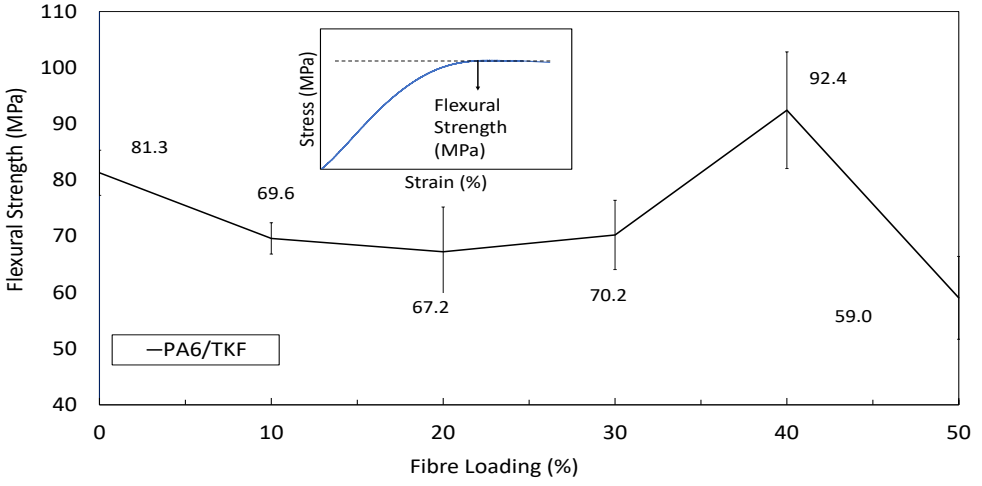

Figure 6. Flexural strength of PA6/TKF reinforced polyamide biocomposites

However, the flexural strength significantly drops to 59.0 MPa at 50 wt.% fibre loading. This substantial decline is likely due to fibre agglomeration, which can occur at higher loadings. Fibre agglomeration reduces the effective stress transfer from the matrix to the fibres, increasing the likelihood of voids and defects within the composite structure. Additionally, the high volume of fibres can disrupt the continuity of the polyamide matrix, leading to compromised structural integrity and reduced mechanical performance.

The TKF-reinforced polyamide biocomposites have demonstrated their potential for railway sleeper applications. Their modulus of elasticity exceeded some available plastic sleepers in the industry by more than 29%. The initial tangent modulus of the biocomposite specimens tended to increase when fibre loading was increased. The increase in fibre loading up to 40 wt.% resulted in a large increase in modulus, thereby indicating lesser damage of the biocomposite under loading. Consequently, it would result in a longer sleeper fatigue life (Esmaeili et al., 2023).

In summary, the variation in flexural strength with different fibre loadings results from the complex interplay between fibre dispersion, interfacial bonding, and the intrinsic properties of the fibres and the matrix. Optimal fibre loading is critical to achieving the desired mechanical properties in fibre-reinforced composites.

CONCLUSION

In conclusion, kenaf fibre-reinforced polyamide biocomposites show significant promise for railway sleeper applications, exceeding the minimum load-bearing capacity recommended by AREMA specifications. Thermogravimetric analysis (TGA) has confirmed the thermal stability of kenaf fibre below 220°C, indicating its suitability as reinforcement at moulding temperatures below this threshold. Fibre loading should be limited to 40 wt.% of TKF for optimal mechanical performance. This study provides critical insights for developing sustainable and efficient materials to meet the demands of modern railway infrastructure, achieving an optimal flexural strength of 92.4 MPa, three times higher than the AREMA standard and existing plastic sleepers. A modulus of elasticity of 4.1 GPa is 29.3% higher than current industry standards.

Overall, natural fibre polymer composites, including kenaf fibre polymeric biocomposites, have demonstrated their potential in measuring up to or even better than synthetic (glass) fibre-reinforced composites, especially in mechanical properties, which is significant in sleeper construction. Notably, the weight reduction ability of kenaf fibre as a substitute to synthetic fibre composites and its low environmental impact coupled with its competitive, stable price makes kenaf fibre a choice material in railway infrastructure material. Hence, natural fibre composites, including kenaf polymeric biocomposites, are rapidly growing, and their application in the railway transport infrastructure seems to have a brighter prospect in the near future.

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