JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2022;21:4241–4252

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

Flexural, impact and dynamic mechanical analysis of hybrid composites: Olive tree leaves powder/pineapple leaf fibre/epoxy matrix

K. Senthilkumar [a], M. Chandrasekar [b], Othman Y. Alothman [c], Hassan Fouad [d], M. Jawaid [e,*], M.A. Azeem [f]

[a] Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641 062, Tamilnadu, India
[b] School of Aeronautical Sciences, Hindustan Institute of Technology & Science, Padur, Kelambakkam, Chennai 603103, Tamil Nadu, India
[c] Department of Chemical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
[d] Biomedical Engineering Department, Faculty of Engineering, Helwan University, P.O. Box 11792, Helwan, Egypt
[e] Department of Biocomposite Laboratory, Institute of Tropical Forestry and Forest Products, University Putra Malaysia, UPM 43400 Serdang, Selangor, Malaysia
[f] School of Engineering, University of Leicester, Leicester LE1 7RH, UK

ARTICLE INFO

Article history:
Received 30 June 2022
Accepted 4 November 2022
Available online 9 November 2022

Keywords:
Olive tree leaves powder
Pineapple leaf fibre
Epoxy
Hybrid composites
Mechanical properties
Dynamic mechanical properties

ABSTRACT

The objective of this work is to determine the suitability of olive tree leaves powder (OTL) as reinforcement along with pineapple leaf fibre (PALF) in the epoxy composites. The parent and hybrid composites were fabricated using the hot press technique with the overall fibre loading at 40 wt% and OTL: PALF in the ratio of 50:50, 30:70 and 70:30, respectively. The fabricated composites were characterized using dynamic mechanical analysis (DMA), flexural and impact tests. As the proportion of PALF was increased in the hybrid composites, impact strength improved significantly. However, hybrid composites were not effective in withstanding the bending load where their bending strength and flexural modulus were lower than the parent composites. Hybrid composites outperformed parent composites with superior storage modulus, lower loss modulus and lower damping factor as per the DMA results.

1. Introduction

Developing biobased materials has become significant in many industries owing to the need to preserve our environment. The biobased materials can be developed using biopolymers or synthetic resin reinforced with lignocellulosic fibres or synthetic fibres. Recently, the interest in using the lignocellulosic fibres is increasing rapidly due to their advantages, especially their higher specific strength and stiffness

* Corresponding author.
E-mail address: jawaid@upm.edu.my (M. Jawaid).
https://doi.org/10.1016/j.jmrt.2022.11.036

than glass fibre reinforced composites [1]. These fibres are found in a wide range of applications such as aerospace, automotive, marine, construction and building, biomedical, sports, and electronics [2–5].

Though the lignocellulosic fibres possess favourable properties, they have some demerits, such as water absorption, lesser thermal stability, degradation in strength, and lesser impact properties [6,7]. One way to improve the performance of composites using hybrid composites, whereby the single fibres are incorporated with several fibres into a single matrix. As a consequence, synergistic improvement can be obtained in composite properties [8–10]. Furthermore, the usage of agricultural waste residues is currently a matter of attention. Because the environmental problems can be minimized by reducing the huge waste of agricultural residues. Besides, agricultural waste residues can be an excellent alternative to plastic materials due to their various advantages such as (i) biodegradability, (ii) ease of availability, (iii) help to improve the economy of a country, and (iv) low CO_2 emission [11]. The olive tree trunk that grows laterally is often pruned to allow it to grow to a larger height for its use as timber. The pruned trunk has hardly any purpose other than being used as firewood. Thus, this study attempted to use the olive trunk leaves (OTL) extracted from the trunk as reinforcement. When pulverized, OTL turns into powder form than as a fibre. Thus, it was used in the powder form as reinforcement, and their usefulness as reinforcement in the polymer composites were investigated.

Research works on using agricultural wastes as reinforcement have been well documented [12,13]. Further, agricultural wastes can be incorporated with several natural fibres and is said to improve the performance of the hybrid composites. For instance, Siti et al. [14] effectively hybridized bio-composite using bamboo-olive tree residues-epoxy matrix. Researchers reported an improvement in mechanical properties of hybridized composites than unhybridized olive tree residues/epoxy composites [14]. It is well known that in the poultry industry, chicken feathers generate massive waste. Thus, Araya-Letelier et al. [15], used waste-based chicken weather fibres as reinforcement in adobe mixtures. It was reported that the chicken weather fibres could be used to reduce environmental challenges. Also, the chicken weather fibres effectively facilitated the improvement of the physical, damage, and durability performances of adobe mixtures. In another work, Prithivirajan et al. [16] developed bio-based composites using agricultural wastes such as rice husk and coir pitch. The researchers varied the particulate sizes from 10% to 50% and examined their mechanical performances. As expected, the mechanical results were improved by increasing the particulate sizes. Further, the researchers suggested the developed bio-based composites for low-load bearing applications. In another research work, Khristova et al. [17] utilized sunflower stalks to fabricate particle boards using tannin/urea-formaldehyde resins. The sunflower stalks are considered agro-lignocellulosic wastes. The researchers optimized the particle board by varying the board density and resin content. Results obtained that the bending strength was higher than 16 MPa, thickness swelling, and water absorptions were less than 20% and 70%, respectively. Utilizing such raw materials would help to improve the country's economy.

In addition to the mechanical properties, determining the thermal behaviour of natural fibre reinforced composites is significant to knowing the suitability for a certain application. Sampathrajan et al. [18] developed low-density particle boards using a variety of five farm residues such as maize-cob, paddy-straw, coconut-pitch. Further, all these boards were subjected to mechanical and thermal properties. According to the results, the maize-cob board was suitable for interior applications. While the paddy-straw and coconut-pith boards were suggested for insulation purposes. Raju and Kumarappa [19] extensively studied the mechanical and thermal behaviour of groundnut shell/epoxy composites, whereby the groundnut shell can be considered agricultural waste. It was reported that the groundnut shell/epoxy composites could be promising materials for general applications.

The olive tree is botanically known as Olea europaea L [14,20]. In this work OTL was used as reinforcement. Along with this, pineapple leaf fibre (PALF) was incorporated for developing hybrid composites. Among the various natural fibres, the PALF possesses higher cellulose content (85%) [21] while the olive leaves have 11.28% [14]. Because the mechanical properties of fibres increase with increasing cellulose content [22]. Thus, hybridizing these two fibres was expected to synergistically improve the properties of developed composite materials.

Till date, the performance characteristics of OTL/PALF/epoxy composites have never been explored as per the authors' knowledge. Thus, an attempt has been made to develop the hybrid composites using OTL and PALF as reinforcement

Fig. 1 – (a) PALF fibre and (b) OTL powder.

Table 1 – Fibre specifications.

Description	OTL [14]	PALF [21]
Density (g/cm^3)	–	1.53
Fibre diameter (μm)	250–500	800–1000
Cellulose (%)	11.28	70.51
Hemicellulose (%)	14.73	14.21
Lignin (%)	16.33	2.93
Others (%)	57.66	–

in the epoxy matrix at different fibre weight ratios. Further, the developed composites were subjected to flexural, impact, and dynamic mechanical analysis properties.

2. Materials and method

2.1. Materials

OTL were taken from the Al-Jouf region in Saudi Arabia, and PALF was taken from a farmhouse in Malaysia. The OTL used here was obtained in the powder form in the size of 250–500 μm while raw PALF was pulverized using the ring flaker machine, and fibres of size 1–2 mm were separated with the help of a mechanical sieve (Fig. 1(a and b)). D.E.R.™ liquid epoxy resin and Jointmine hardener 905-3S were supplied by Tazdiq Engineering Sdn. Bhd., Selangor, Malaysia. The fibre specifications are presented in Table 1.

2.2. Fabrication

In this work, composites were fabricated by the hot press molding technique. Initially, OTL and PALF were mixed in the epoxy resin at different weight ratios (50:50, 30:70, and 70:30 represented as 1OTL/1PALF, 3OTL/7PALF, and 7OTL/3PALF) while the overall fibre loading was maintained to 40 wt%. The fibre and resin mixture is further mixed with hardener and placed in the 150 × 150 × 3 mm^3 mold and cured at a temperature of 110 °C for 10 min under a pressure of 20 bar. The parent composites were also fabricated and characterized for comparison.

3. Characterization

3.1. Flexural test

Flexural test was done as per the ASTM D790 [23]with 30 kN Bluehill INSTRON 5567 and the average results of 5 specimens were reported. The crosshead displacement rate was 2 mm min^{-1} and the span: depth was maintained to 16:1 respectively.

3.2. Impact test

Izod impact test was done using the INSTRON CEAST 9050 as per the ASTM D256-10 standard [24]. Average value of 5 specimens was reported.

3.3. DMA

DMA was carried out on the composite specimen with TA Instruments Q800 model in 3-point bending mode at a frequency of 1 Hz and a ramp rate of 5 °C min^{-1} in the temperature range between 30 and 150 °C.

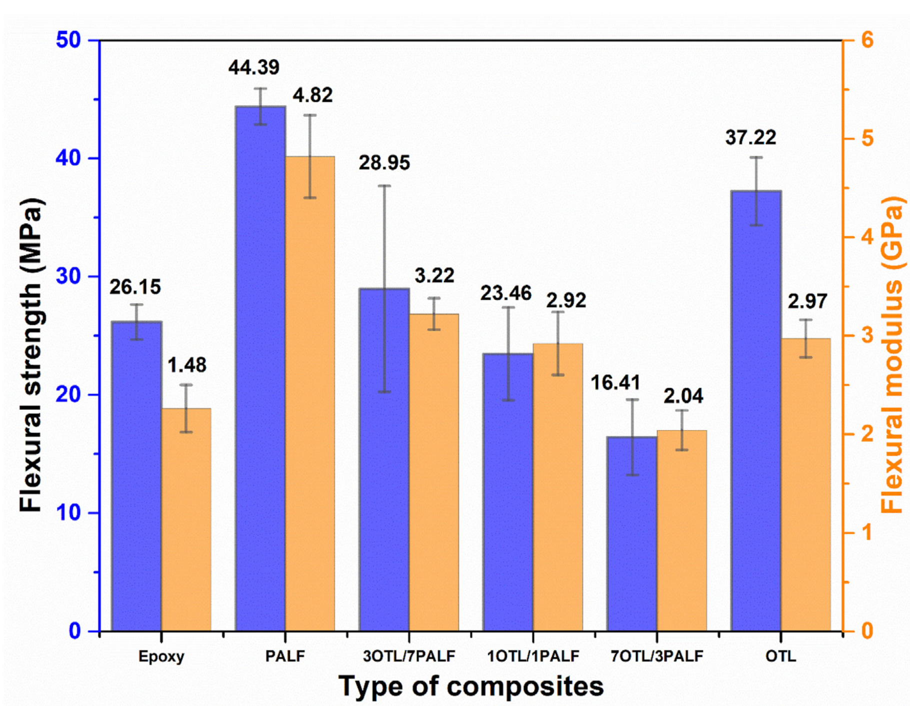

Fig. 2 – Flexural strength and modulus of PALF/OTL composites.

Table 2 – Flexural properties of OTL/PALF hybrid composites in comparison with the related hybrid composite works.

Type of composite	Details of fabrication	Type of fabrication technique	Flexural properties	Observation	References
PALF/OTL/epoxy matrix hybrid composites	The PALF/OTL hybrid composites were fabricated by varying the fibre loadings in the ratio of 50:50, 30:70 and 70:30, respectively	Hot press technique	Pure pineapple leaf fibre reinforced composites exhibited higher flexural properties. In hybrid composites, the flexural properties were reduced by decreasing the fibre loading of pineapple leaf fibre.	Range of flexural strength of PALF/OTL/epoxy matrix composites were measured between 16.41 MPa and 44.39 MPa Flexural modulus of composites observed between 2.04 GPa and 4.82 GPa	Present work
Sisal/silk/unsaturated polyester matrix hybrid composites	The composites were fabricated by varying the fibre lengths such as 1 cm, 2 cm and 3 cm. The fibre loading of hybrid composites was maintained as 1:1 (sisal:silk)	Hand lay-up	The flexural strengths were measured as 33.498 MPa, 46.181 MPa and 34.024 MPa for 1 cm, 2 cm and 3 cm fibre length hybrid composites, respectively	Higher flexural strength of hybrid composites was observed at 2 cm fibre-loaded composites	[31]
Banana/sisal/epoxy matrix hybrid composites	• Fibre length was varied from 5 mm to 20 mm (increasing order of 5 mm) • Fibre weight percentage was varied from 8 to 20	Compression moudling technique	Minimum and maximum flexural strengths were measured as 21.58 MPa and 57.53 MP at 8% and 16% of fibre-loaded composites, respectively.	The flexural strength of hybrid composites was observed to increase by 4% due to the addition of sisal fibre	[32]
Coir/silk/unsaturated polyester matrix hybrid composites	The composites were fabricated by varying the fibre lengths such as 1 cm, 2 cm and 3 cm. The fibre loading of hybrid composites was maintained as 1:1 (coir:silk)	Hand lay-up	Flexural strength of hybrid composites was measured as 37.419 MPa, 43.744 MPa and 39.692 MPa	The flexural strength of hybrid composites was increased by using 2 cm fibre-loaded composites	[33]
Sugar palm/glass fibre/thermoplastic polyurethane	The sugar palm/glass hybrid composites were fabricated by varying the fibre loading of 30:10, 20:20 and 10:30	Melt compounding followed by hot press	Flexural strength was measured as ~ 17 MPa–31 MPa Flexural modulus was measured as ~280 MPa–~500 MPa	The flexural properties were dominated by glass fibre rather than sugar palm fibre	[34]

Kenaf/pineapple leaf fibre/high-density polyethylene hybrid composites	The hybrid composites were fabricated by varying the fibre loadings of kenaf and pineapple leaf fibre were 30:70, 40:60, 60:40, 70:30. The total fibre loading of fibres was maintained at 40 wt%	Compression moulding technique	• The range of flexural strength of hybrid composites was observed between ~22 MPa and ~28 MPa. • The range of flexural modulus was observed between 1900 MPa and 2200 MPa	Optimum flexural properties were measured at a fibre loading of 1:1	[35]
Jute/hemp/flax/epoxy matrix hybrid composites	• Hybrid composites were fabricated by varying fibre layering sequences using three different fibres: jute, hemp and flax. • The total fibre loading of hybrid composites was maintained as 25% by weight.	Hand lay-up	The range of flexural modulus of hybrid composites was measured between ~0.95 GPa and ~1.25 GPa	The flexural modulus of hybrid composites was observed to reduce by hybridizing the fibres with the epoxy matrix	[36]

4. Results and discussion

4.1. *Flexural properties*

Flexural strength of PALF/epoxy, OTL/epoxy, and PALF/OTL/epoxy hybrid composites is presented in Fig. 2. The bending strength of epoxy matrix reinforced with PALF and OTL composites was increased by 69.75% and 42%, respectively, as compared to epoxy matrix. The flexural strength enhancement could be due to a reinforcing effect of PALF and OTL fillers. On the other hand, higher flexural strength was observed for PALF/epoxy composites as compared to OTL/epoxy. Thus, the PALF/epoxy composites could withstand higher stresses during flexural testing (or bending), and the strength of the composites was higher. A similar type of behaviour was observed by Maries et al. [25].

Besides that, the hybrid composites exhibited lower flexural strength than unhybridized composites. The flexural strength of hybrid composites decreased with increasing OTL content. Because the OTL fillers have an irregular shape, it could not contribute to the stress transferred to the epoxy matrix [26]. In this way, the OTL just acted as a filler rather than a better reinforcement. Furthermore, many researchers correlated the mechanical properties of natural fibres with their main constituent named, cellulose [27]. The percentage of cellulose content can influence the mechanical properties among the constituents. For instance, higher cellulose in natural fibres can give better mechanical strength [28,29]. Since OTL has a cellulose content of 11.28% over PALF, which has 70–85%, hybrid composites with a higher proportion of OTL were not effective in resisting the bending load. A similar pattern was noticed in the case of the flexural modulus of the hybrid composites shown in Fig. 2. Though the hybrid composites possessed superior flexural modulus than the epoxy, their flexural strength was comparatively lower than the epoxy. Further, the flexural strength declined with the increase in OTL proportion in the hybrid composite. This trend indicates that OTL acts as a filler improving the rigidity while it remains ineffective in handling the applied bending load. Thus, the PALF acts as a load carrier and the decrease in their fibre loading leads to inferior strength.

Table 2 shows the flexural properties of different hybrid composites compared to the present work. PALF/OTL-based hybrid composites exhibited competitive results than other reported hybrid composite works. For instance, comparing the flexural modulus of 3OTL/7PALF reinforced hybrid composites with sisal/hemp/bioepoxy hybrid composites, the values were 3.22 GPa (present study) and ~2.69 GPa [30], respectively.

4.2. *Impact strength*

Impact strength of PALF/epoxy, OTL/epoxy, and PALF/OTL/epoxy hybrid composites is presented in Fig. 3. The impact strength of PALF/epoxy and hybridized composites was found to be higher than the pure epoxy matrix. Further, it was clear from Fig. 3 that increasing the content of OTL within the epoxy and PALF resulted in lower impact strength.

Besides that, the impact strength of hybridized composites was higher than OTL/epoxy composites. It happened due to the addition of PALF. When the PALF loading in hybrid

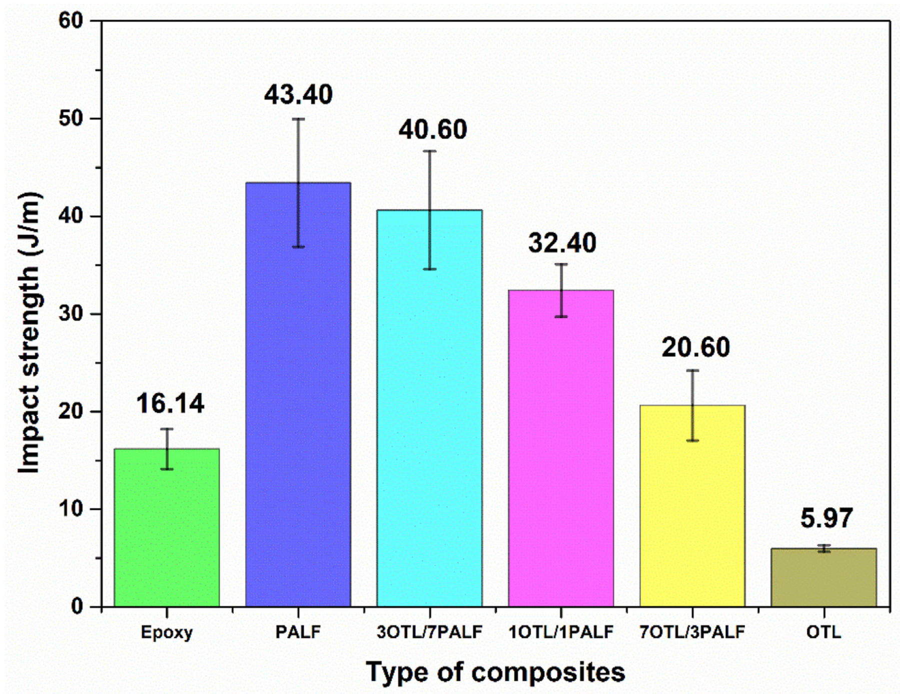

Fig. 3 – Impact strength of PALF/OTL fibre reinforced composites.

composites increased from 10 wt% to 20 wt% and 30 wt%, the increase in impact strength was 57% and 97%, respectively. Thus, hybridizing the PALF with OTL, a synergistically-improved impact strength was obtained.

The scanning electron micrographs of impact-tested samples are shown in Fig. 4. Fig. 4(a–e) shows the SEM images of PALF/epoxy, 7OTL/3PALF, 1OTL/1PALF, 3OTL/7PALF, and OTL. The failure of impact strength was associated with many factors: fibre pull out, matrix fracture, and fibre-to-matrix debonding. Among these factors, fibre pull-out can be the significant energy dissipation mechanism in fibre-reinforced composites [25]. A strong fibre-matrix bonding and lesser fibre pull-outs are observed in Fig. 4(a). In contrast, a lack of interfacial bonding and matrix crack is observed in OTL/epoxy composites due to the deposition of waxy layers (Fig. 4(b)). The energy needed for fibre pull-out depends on the fibre diameter and length and the interfacial shear stress. The larger the fibre diameter and length, the higher the fibre pull-out energy; the fibre pull-out energy also increases with an increase in interfacial shear stress [37]. The interfacial shear stress contributes to the fibre-matrix debonding; the magnitude of this shear stress depends on the relative elastic modulus of the fibre to the matrix as well as fibre aspect ratio (i.e., a ratio of fibre length to diameter). High relative elastic modulus and fibre aspect ratio could enhance the composite properties by conferring high interfacial shear stresses during elastic stress transfer [38]. Fibre-matrix debonding must be avoided as this could limit the stress transfer and, henceforth, the stress uptake in fibre (as well as in the powder). This is because the interfacial shear stress regulating the stress transfer is constant of the applied load during plastic loading following fibre-matrix debonding [39]. Increasing the fibre loading of PALF within the epoxy and OTL resulted in a noticeable improvement in impact strength, as shown in Fig. 3. Because the impact strength of hybrid composites was influenced by the PALF. Thus, reductions in fibre pull-outs increased fibre-matrix bonding, and lesser fibre fractures were noticed in Fig. 4(c–e).

Table 3 shows the impact properties of existing reported hybrid composite works compared to the present work. It is observed that PALF/OTL-based hybrid composites exhibited competitive results over other hybrid-reported works.

4.3. *Dynamic mechanical analysis*

Fig. 5 illustrates the storage modulus plot for the OTL and PALF-based hybrid composites. All the composites displayed a typical trend of higher storage modulus at room temperature, whereas it was the least value at elevated temperatures. This decrease in storage modulus over the increasing temperature represents the phase transition from a glassy state to a rubbery state in the polymer composites, which usually occurs beyond the glass transition temperature (T_g) [45]. The peak storage modulus for the composites was found to be in the following order: 1OTL/1PALF > 3OTL/7PALF > 7OTL/3PALF > PALF > OTL. It can be noticed from the trend that all hybrid configurations had superior peak storage modulus values than the parent composites with the individual fibre. Since the storage modulus is equivalent to the stiffness or elastic modulus of the composite, higher values for the hybrid configurations are an advantage. The highest value of peak storage modulus was observed for the 1OTL/1PALF with 50:50 fibre loading, whereas as the filler weight was varied at 30:70, the peak storage modulus was significantly lower. The

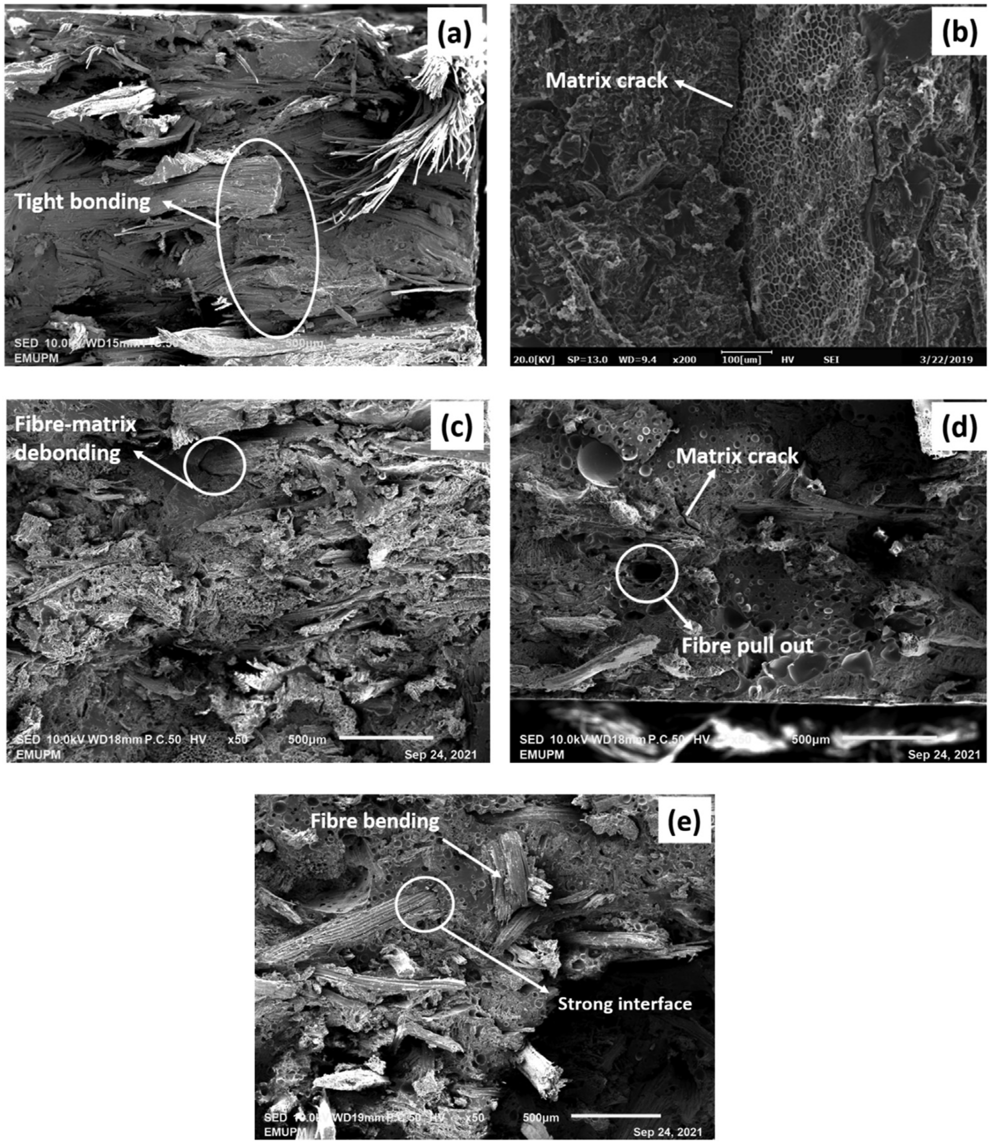

Fig. 4 – Scanning electron micrographs of impact tested samples (a) PALF/epoxy, (b) OTL/epoxy, (c) 7OTL/3PALF, (d)1OTL/1PALF and (e) 3OTL/7PALF

superior storage modulus for the hybrid composites can also be equated to the uniform filler dispersion according to the recently published works [46–49].

Fig. 6 presents the loss modulus plot as a function of the temperature. Above T_g, the segmental motion of the polymeric chains at a molecular level is initiated. However, the segmental motion is restricted in the transition region, leading to increased loss modulus as more energy dissipates. On the other hand, a much lower force is required to dissipate energy well beyond T_g; hence loss modulus decreases. The initial increase and the decreasing trend were prominent for the OTL composite, whereas PALF and hybrid configurations displayed a flattened curve, indicating lower energy dissipation characteristics. The energy dissipation characteristics of the hybrid composites imitated the parent laminates and were dependent on the proportion of the parent fibres in the hybrid composite. Among the hybrid composites, 1OTL/1PALF exhibited the peak loss modulus value of 223 MPa, slightly higher than the OTL (156 MPa), which was then followed by 3OTL/7PALF (122 MPa), and 7OTL/3PALF (103 MPa) with values equivalent to the PALF (112 MPa).

Peak tan delta or damping factor obtained from Fig. 7 is said to be in the following order: OTL > 1OTL/1PALF > 7OTL/3PALF > 3OTL/7PALF > PALF. It can be noticed from the trend that hybrid composites displayed a lower damping factor than OTL composites. Lower damping factor for the hybrid composites reinforced with the bamboo fibre and olive fibres from different parts of the tree, such as from leaf, big and small branches, respectively [48]. According to Saba et al. [50], a lower value indicates better interfacial bonding and uniform filler dispersion characteristics. Thus, it can be concluded that both OTL and PALF had better fibre–fibre interaction and fibre-matrix compatibility, which led to lower damping for the hybrid composites. In particular, the stress uptake in fibre during

Table 3 – Impact strength of OTL/PALF hybrid composites in comparison with the related hybrid composite works.

Type of composite	Details of fabrication	Type of fabrication technique	Impact strength	Observation	References
PALF/OTL/epoxy matrix hybrid composites	The PALF/OTL hybrid composites were fabricated by varying the fibre loadings in the ratio of 50:50, 30:70 and 70:30, respectively	Hot press technique	Pure pineapple leaf fibre-reinforced composites exhibited higher impact strength. In hybrid composites, the impact strength was observed to decrease by reducing the pineapple leaf fibre content	The range of impact strength of PALF/OTL composites ranged between 5.97 J/m to 43.40 J/m	Present work
Calotropis Gigantea Fibre/Areca Fine Fibres/phenol formaldehyde	Fibre loading was varied for 25 wt%, 35 wt% and 45 wt%	Hand lay-up	~1.3 kJ/m^2 to 1.4 kJ/m^2	At 35 wt% of fibre loading, the composites exhibited improved performance	[40]
Bamboo/jute/epoxy	Composites were fabricated by varying the fibre layering sequences	Hand lay-up	~0.10 J–0.34 J	When the bamboo fibres were used as outer skinned layers, the respective hybrid composites exhibited higher impact strength	[41]
Sisal, sorghum and jute fibres/unsaturated terephthalic polyester resin	• Fibre loading varied from 70 wt% to 95 wt% for sisal and jute fibre. • Sorghum varied from 5 wt% to 30 wt%.	Hand lay-up	20.3 J–26.3 J	The higher impact strength was observed for 40:30:30 (sisal: jute: Sorghum bicolor	[42]
Roselle fibre/sisal fibre/polyester	Fibre loading varied from 10 wt% to 30 wt%	Compression molding technique	~1.25 kJ/m^2 to ~ 1.5 kJ/m^2	No significant changes were observed by varying the fibre loading	[43]
Banana/sisal/epoxy matrix hybrid composites	• Fibre length was varied from 5 mm to 20 mm (increasing order of 5 mm) • Fibre weight percentage varied from 8 to 20	Compression molding technique	2.15 kJ/m^2 to 13.25 kJ/m^2	The impact strength was increased by 35% by increasing the addition of sisal fibre	[32]
Jute/banana/epoxy matrix hybrid composites	Hybrid composites were fabricated by varying the fibre layering sequences	Hand lay-up	~50 kJ/m^2 to ~ 110 kJ/m^2	When the jute fibres were used as outer skinned layers, the respective hybrid composites exhibited higher impact strength	[44]

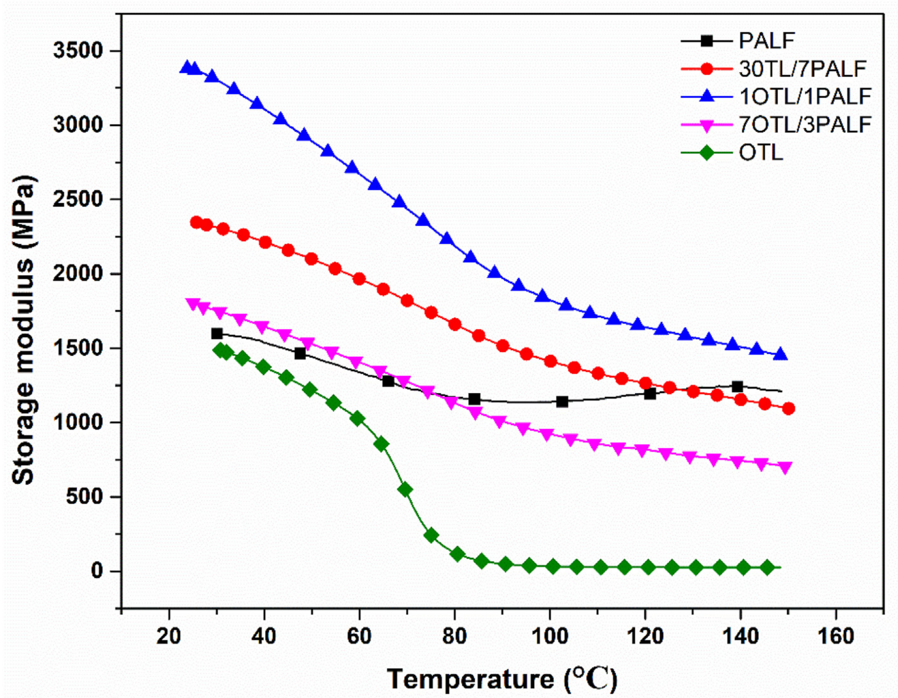

Fig. 5 – Storage modulus-temperature plot for OTL and PALF-based hybrid composites.

fibre–fibre interaction depends on the fibre-matrix properties, namely the relative elastic modulus of the fibre to the matrix. High relative elastic modulus confers enhanced stress transfer from the matrix to the fibre, leading to high-stress uptake in fibre [51]. Also, T_g obtained from the peak tan delta is the least for the parent composites (96 °C for 80 °C for OTL and PALF, respectively), whereas it was approximately 150 °C for the hybrid composites. Higher T_g indicates a delay in the phase transition from glassy to rubbery state, which can be interpreted as superior thermal stability for the hybrid composites.

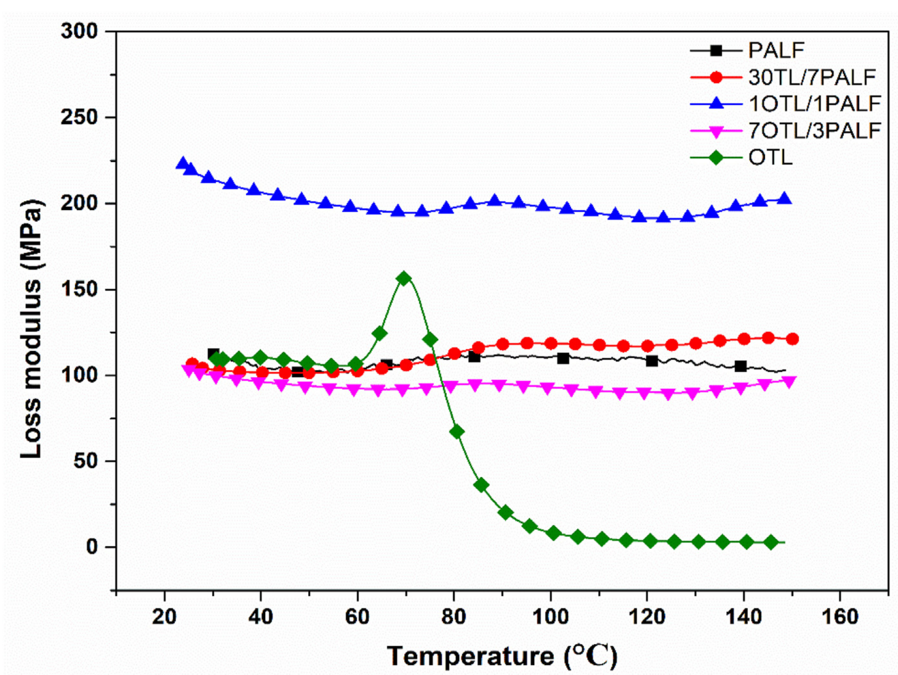

Fig. 6 – Loss modulus-temperature plot for OTL and PALF-based hybrid composites.

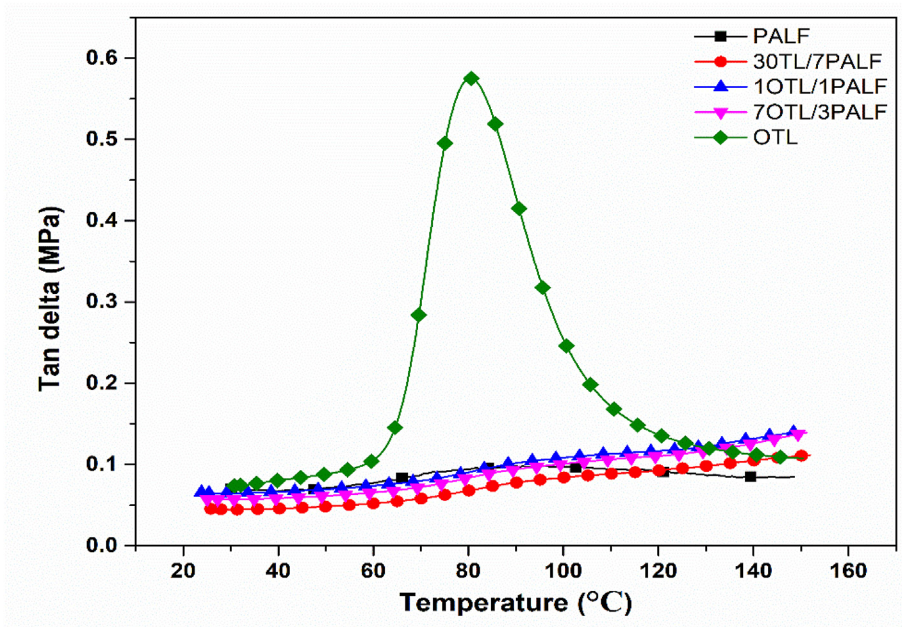

Fig. 7 – Tan delta-temperature plot for OTL and PALF-based hybrid composites.

5. Conclusion

In this work, hybrid composites reinforced with OTL and PALF at different weight ratios, such as 50:50, 30:70 and 70:30 were fabricated. Following were the conclusions from the flexural, impact, and dynamic mechanical analysis:

- The pure pineapple leaf fibre-reinforced epoxy matrix composites exhibited higher flexural strength of 44.39 MPa than other counterparts. Hybridizing the pineapple leaf fibres with olive tree leaves powder showed reductions in flexural properties. The range of flexural strength of hybrid composites was between 16.41 MPa and 28.95 MPa.
- Regarding the flexural modulus, the pure pineapple leaf fibre-reinforced epoxy matrix composites exhibited higher values, such as 4.82 GPa. The flexural modulus of hybrid composites was reduced by decreasing the fibre content of pineapple leaf fibres. The range of flexural modulus of hybrid composites was between 2.04 GPa and 3.22 GPa.
- Though the flexural strength was observed lower in hybrid composites, the flexural modulus of 3OTL/7PALF hybrid composites was 8.4% higher than olive tree leaves powder-reinforced epoxy matrix composites.
- Similarly, the impact strength of hybrid composites exhibited 3 to 8 times higher than the olive tree leaves powder-reinforced epoxy matrix composites. Thus, adding pineapple leaf fibre was beneficial, resulting in hybrid composites with better impact resistance.
- DMA results reported that hybrid composites presented higher storage modulus. The order of storage modulus of composites was 1OTL/1PALF > 3OTL/7PALF > 7OTL/3PALF > PALF > OTL.
- In loss modulus, 1OTL/1PALF exhibited the value of 223 MPa, followed by 3OTL/7PALF (122 MPa) and 7OTL/3PALF (103 MPa) with values equivalent to the PALF (112 MPa).
- Regarding the tan delta, hybrid composites presented lower damping than the parent composites, indicating better fibre dispersion characteristics and good interfacial bonding.

The developed hybrid composites can be used in the building and construction as door panels, window frames and handrails.

Author contributions

K. Senthilkumar: Investigation, Methodology, Writing - review & editing, Formal analysis; M. Chandrasekar: Investigation, Writing - review & editing; Othman Y Alothman: Investigation, Methodology, Conceptualization, Writing - review & editing, Funding; Hassan Foud: Investigation, Writing - review & editing; Mohammad Jawaid: Conceptualization, Investigation, Methodology, Supervision, Writing - review & editing; M.A. Azeem: Investigation, Writing - review & editing.

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.

Acknowledgement

Authors would like to extend their gratitude to King Saud University (Riyadh, Saudi Arabia) for the funding of this research through Researchers supporting Project number (RSP-2022R435).

REFERENCES

[1] Faruk O, Bledzki AK, Fink HP, Sain M. Progress report on natural fiber reinforced composites. Macromol Mater Eng 2014;299:9–26. https://doi.org/10.1002/mame.201300008.

[2] Allafi F, Hossain MS, Lalung J, Shaah M, Salehabadi A, Ahmad MI, et al. Advancements in applications of natural wool fiber. J Nat Fibers 2022;19:497–512. https://doi.org/10.1080/15440478.2020.1745128.

[3] Muthalagu R, Srinivasan V, Kumar SS, Krishna VM. Study of fabrication methods, mechanical features and applications of natural fiber composites. In: Advances in mechanical and materials Technology. Springer; 2022. p. 785–98. https://doi.org/10.1007/978-981-16-2794-1_70.

[4] Davim JP. Modern mechanical engineering. Springer; 2014. https://doi.org/10.1515/9783110435788.

[5] Xu J, Davim JP. Machining of fibrous composites: recent advances and future perspectives. Mech Ind Eng 2022:161–77. https://doi.org/10.1007/978-3-030-90487-6_6.

[6] Dittenber DB, GangaRao HVS. Critical review of recent publications on use of natural composites in infrastructure. Compos Part A Appl Sci Manuf 2012;43:1419–29. https://doi.org/10.1016/j.compositesa.2011.11.019.

[7] Nurazzi NM, Asyraf MRM, Rayung M, Norrrahim MNF, Shazleen SS, Rani MSA, et al. Thermogravimetric analysis properties of cellulosic natural fiber polymer composites: a review on influence of chemical treatments. Polymers 2021;13. https://doi.org/10.3390/polym13162710.

[8] Krishnasamy S, Thiagamani SMK, Muthu Kumar C, Nagarajan R, S RM, Siengchin S, et al. Recent advances in thermal properties of hybrid cellulosic fiber reinforced polymer composites. Int J Biol Macromol 2019;141:1–13. https://doi.org/10.1016/j.ijbiomac.2019.08.231.

[9] Vinod A, Gowda Y, Krishnasamy S, Sanjay MR, Siengchin S. Thermal properties of hybrid natural fiber-reinforced thermoplastic composites. Nat Fibre Reinf Compos Therm Prop Appl 2022:17–30. https://doi.org/10.1002/9783527831562.ch2.

[10] Parameswaranpillai J, Krishnasamy S, Siengchin S, Radoor S, Joy R, George JJ, et al. Thermal properties of the natural fiber-reinforced hybrid polymer composites: an overview. Nat Fibre Reinf Compos Therm Prop Appl 2022:31–51. https://doi.org/10.1002/9783527831562.ch3.

[11] Nguyen H, Zatar W, Mutsuyoshi H. Mechanical properties of hybrid polymer composite. Hybrid Polym Compos Mater 2017:83–113. https://doi.org/10.1016/B978-0-08-100787-7.00004-4.

[12] Capanoglu E, Nemli E, Tomas-Barberan F. Novel approaches in the valorization of agricultural wastes and their applications. J Agric Food Chem 2022. https://doi.org/10.1021/acs.jafc.1c07104.

[13] de Azevedo ARG, Amin M, Hadzima-Nyarko M, Agwa IS, Zeyad AM, Tayeh BA, et al. Possibilities for the application of agro-industrial wastes in cementitious materials: a brief review of the Brazilian perspective. Clean Mater 2022;3:100040. https://doi.org/10.1016/j.clema.2021.100040.

[14] Sarmin SN, Jawaid M, Mahmoud MH, Saba N, Fouad H, Alothman OY, et al. Mechanical and physical properties analysis of olive biomass and bamboo reinforced epoxy-based hybrid composites. Biomass Convers Biorefin 2022:1–11. https://doi.org/10.1007/s13399-022-02872-9.

[15] Araya-Letelier G, Gonzalez-Calderon H, Kunze S, Burbano-Garcia C, Reidel U, Sandoval C, et al. Waste-based natural fiber reinforcement of adobe mixtures: physical, mechanical, damage and durability performance assessment. J Clean Prod 2020;273:122806. https://doi.org/10.1016/j.jclepro.2020.122806.

[16] Prithivirajan R, Jayabal S, Bharathiraja G. Bio-based composites from waste agricultural residues: mechanical and morphological properties. Cellul Chem Technol 2015;49:65–8.

[17] Khristova P, Yossifov N, Gabir S, Glavchev I, Osman Z. Particle boards from sunflower stalks and tannin-modified UF resin. Cellul Chem Technol 1998;32:327–37.

[18] Sampathrajan A, Vijayaraghavan NC, Swaminathan KR. Mechanical and thermal properties of particle boards made from farm residues. Bioresour Technol 1992;40:249–51. https://doi.org/10.1016/0960-8524(92)90151-M.

[19] Raju GU, Kumarappa S. Experimental study on mechanical and thermal properties of epoxy composites filled with agricultural residue. Polym Renew Resour 2012;3:117–38. https://doi.org/10.1177/204124791200300303.

[20] Rong S, Wu Z, Cheng Z, Zhang S, Liu H, Huang Q. Genome-wide identification, evolutionary patterns, and expression analysis of bZIP gene family in olive (*Olea europaea* L.). Genes 2020;11:510. https://doi.org/10.3390/genes11050510.

[21] Asim M, Abdan K, Jawaid M, Nasir M, Dashtizadeh Z, Ishak MR, et al. A review on pineapple leaves fibre and its composites. Int J Polym Sci 2015;2015:1–16. https://doi.org/10.1155/2015/950567.

[22] John MJ, Thomas S. Biofibres and biocomposites. Carbohydr Polym 2008;71:343–64. https://doi.org/10.1016/j.carbpol.2007.05.040.

[23] ASTM 790-10 Standard Test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. West Conshohocken, PA, 19428-2959 USA: ASTM 790-17 Standard; 2017. https://www.astm.org/d0790-17.html.

[24] ASTM D256 determining the Izod Pendulum impact resistance of plastics.

[25] Idicula M, Neelakantan NR, Oommen Z, Joseph K, Thomas S. A study of the mechanical properties of randomly oriented short banana and sisal hybrid fiber reinforced polyester composites. J Appl Polym Sci 2005;96:1699–709. https://doi.org/10.1002/app.21636.

[26] Sarmin SN, Jawaid M, Awad SA, Saba N, Fouad H, Alothman OY, et al. Olive fiber reinforced epoxy composites: dimensional Stability, and mechanical properties. Polym Compos 2022;43:358–65. https://doi.org/10.1002/pc.26380.

[27] Shyam Kumar, Prasad Durga. Chemical composition of natural fibers and its influence on their mechanical properties. Mech Compos Mater 2014;50:359–76. https://doi.org/10.1007/s11029-014-9422-2.

[28] Komuraiah A, Kumar NS, Prasad BD. Chemical composition of natural fibers and its influence on their mechanical properties. Mech Compos Mater 2014;50:359–76. https://doi.org/10.1007/s11029-014-9422-2.

[29] Petroudy SRD. Physical and mechanical properties of natural fibers. In: Advanced high strength natural fibre composites in construction. Elsevier; 2017. p. 59–83. https://doi.org/10.1016/B978-0-08-100411-1.00003-0.

[30] Krishnasamy S, Thiagamani SMK, Muthukumar C, Tengsuthiwat J, Nagarajan R, Siengchin S, et al. Effects of stacking sequences on static, dynamic mechanical and thermal properties of completely biodegradable green epoxy hybrid composites. Mater Res Express 2019;6:105351. https://doi.org/10.1088/2053-1591/ab3ec7.

[31] Noorunnisa Khanam P, Mohan Reddy M, Raghu K, John K, Venkata Naidu S. Tensile, flexural and compressive properties of sisal/silk hybrid composites. J Reinforc Plast Compos 2007;26:1065–70. https://doi.org/10.1177/0731684407079347.

[32] Venkateshwaran N, ElayaPerumal a, Alavudeen a, Thiruchitrambalam M. Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites.

Mater Des 2011;32:4017–21. https://doi.org/10.1016/j.matdes.2011.03.002.

[33] Noorunnisa Khanam P, Ramachandra Reddy G, Raghu K, Venkata Naidu S. Tensile, flexural, and compressive properties of coir/silk fiber-reinforced hybrid composites. J Reinforc Plast Compos 2010;29:2124–7. https://doi.org/10.1177/0731684409345413.

[34] Afzaluddin A, Jawaid M, Salit MS, Ishak MR. Physical and mechanical properties of sugar palm/glass fiber reinforced thermoplastic polyurethane hybrid composites. J Mater Res Technol 2019;8:950–9. https://doi.org/10.1016/j.jmrt.2018.04.024.

[35] Aji IS, Zainudin ES, Abdan K, Sapuan SM, Khairul MD. Mechanical properties and water absorption behavior of hybridized kenaf/pineapple leaf fibre-reinforced high-density polyethylene composite. J Compos Mater 2013;47:979–90. https://doi.org/10.1177/0021998312444147.

[36] Chaudhary V, Bajpai PK, Maheshwari S. Studies on mechanical and morphological characterization of developed jute/hemp/flax reinforced hybrid composites for structural applications. J Nat Fibers 2018;15:80–97. https://doi.org/10.1080/15440478.2017.1320260.

[37] Ng XW, Hukins DWL, Goh K-L. Influence of fibre taper on the work of fibre pull-out in short fibre composite fracture. J Mater Sci 2010;45:1086–90. https://doi.org/10.1007/s10853-009-4050-2.

[38] Goh KL, Meakin JR, Hukins DWL. Influence of fibre taper on the interfacial shear stress in fibre-reinforced composite materials during elastic stress transfer. Compos Interfaces 2010;17:74–80. https://doi.org/10.1163/092764409X12580201111665.

[39] De Silva R, Pasbakhsh P, Qureshi AJ, Gibson AG, Goh K-L. Stress transfer and fracture in nanostructured particulate-reinforced chitosan biopolymer composites: influence of interfacial shear stress and particle slenderness. Compos Interfaces 2014;21:807–18. https://doi.org/10.1080/15685543.2014.960334.

[40] Sanjeevi S, Shanmugam V, Kumar S, Ganesan V, Sas G, Johnson DJ, et al. Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. Sci Rep 2021;11:1–11. https://doi.org/10.1038/s41598-021-92457-9.

[41] Krishnan GS, Velmurugan P. Investigation on the characteristics of bamboo/jute reinforced hybrid epoxy polymer composites. Mater Res Express 2019;6:105346. https://doi.org/10.1088/2053-1591/ab3ae7.

[42] Sathees Kumar S. Effect of natural fiber loading on mechanical properties and thermal characteristics of hybrid polyester composites for industrial and construction fields. Fibers Polym 2020;21:1508–14. https://doi.org/10.1007/s12221-020-9853-4.

[43] Athijayamani A, Thiruchitrambalam M, Natarajan U, Pazhanivel B. Effect of moisture absorption on the mechanical properties of randomly oriented natural fibers/polyester hybrid composite. Mater Sci Eng, A 2009;517:344–53. https://doi.org/10.1016/j.msea.2009.04.027.

[44] Venkateshwaran N, ElayaPerumal A. Mechanical and water absorption properties of woven jute/banana hybrid composites. Fibers Polym 2012;13:907–14.

[45] Naveen J, Jawaid M, Zainudin ES, Sultan MTH, Yahaya R, Abdul Majid MS. Thermal degradation and viscoelastic properties of Kevlar/Cocos nucifera sheath reinforced epoxy hybrid composites. Compos Struct 2019;219:194–202. https://doi.org/10.1007/s12221-012-0907-0.

[46] Krishnasamy S, Thiagamani SMK, Muthukumar C, Tengsuthiwat J, Nagarajan R, Siengchin S, et al. Effects of stacking sequences on static, dynamic mechanical and thermal properties of completely biodegradable green epoxy hybrid composites. Mater Res Express 2019;6:105351. https://doi.org/10.1088/2053-1591/ab3ec7.

[47] Böhning M, Frasca D, Schulze D, Schartel B. Multilayer graphene/elastomer nanocomposites. In: Carbon-based nanofillers and their rubber nanocomposites. Elsevier; 2019. p. 139–200. https://doi.org/10.1016/B978-0-12-817342-8.00006-8.

[48] Rashid B, Jawaid M, Fouad H, Saba N, Awad S, Khalaf E, et al. Improving the thermal properties of olive/bamboo fiber-based epoxy hybrid composites. Polym Compos 2022. https://doi.org/10.1002/pc.26608.

[49] Chandrasekar M, Senthilkumar K, Jawaid M, Mahmoud MH, Fouad H, Sain M. Mechanical, morphological and dynamic mechanical analysis of pineapple leaf/Washingtonia trunk fibres based biophenolic hybrid composites. J Polym Environ 2022:1–9. https://doi.org/10.1007/s10924-022-02482-6.

[50] Saba N, Jawaid M, Alothman OY, Paridah MT. A review on dynamic mechanical properties of natural fibre reinforced polymer composites. Constr Build Mater 2016;106:149–59. https://doi.org/10.1016/j.conbuildmat.2015.12.075.

[51] Mohonee VK, Goh KL. Effects of fibre–fibre interaction on stress uptake in discontinuous fibre reinforced composites. Compos B Eng 2016;86:221–8. https://doi.org/10.1016/j.compositesb.2015.10.015.