INVESTIGATION OF MECHANICAL AND THERMAL CHARACTERISTICS OF BANANA FIBER-REINFORCED POLYESTER COMPOSITES FOR AUTOMOTIVE APPLICATIONS

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This study investigates the mechanical and thermal properties of Nendran fiber rope mat (NFRM) reinforced polyester composites. The composites were fabricated and tested for tensile, flexural, and impact properties, as well as thermal conductivity and heat deflection temperature. Results show that composites prepared with Nendran fiber rope vertical mat (NFRVM) orientation exhibited superior tensile strength (51.9 MPa), flexural strength (261 MPa), and impact strength (22.3 KJ/m^2) compared to other Nendran fiber forms and several other natural and synthetic fiber-reinforced composites. The Barcol hardness of NFRVM composites was the highest among the tested composites, indicating robust bonding and enhanced material rigidity. The thermal properties were also significantly improved. Scanning electron microscopy reveals strong fiber-matrix interactions in rope mat-oriented composites, indicating effective stress transfer and adhesion. These findings highlight the potential of NFRVM composites as a competitive and eco-friendly alternative to traditional glass fiber composites for various industrial applications, particularly in the automotive sector for components like engine guards. The enhanced mechanical and thermal properties, along with the eco-friendly nature of NFRVM composites, make them an attractive option for sustainable material development.

Keywords: Nendran fiber rope mat, polyester composites, mechanical properties, thermal properties, eco-friendly materials, automotive applications, natural fiber composites

INTRODUCTION

Extensive research has been conducted on synthetic fiber-based polymer composites for various engineering applications, including automotive, marine, aerospace, sports, civil engineering, and household products. However, many of these composites fail to meet environmental sustainability standards. Additionally, the production and market costs of synthetic fibers – especially those incorporating carbon, aramid, and glass fibers – are significantly higher than those of basic polymer matrix materials.[1-5]

To address these challenges, recent research trends have increasingly focused on developing lignocellulosic fiber-based polymer composites, attracting significant interest from scientists and engineers worldwide. Lignocellulosic fibers offer several advantages over their synthetic counterparts, including lower density, cost-effectiveness, acceptable specific properties, minimal health risks, renewability, and biodegradability.[6-9]

In the automotive sector, several major manufacturers – such as Audi, BMW, Daimler

Chrysler, Ford, Mercedes-Benz, and Volkswagen – have incorporated lignocellulosic fiber-based composites into various vehicle components. For instance, Mercedes-Benz uses coconut fiber-rubber latex composites for seat cushioning in its A-Class model, while the E-Class features flax-sisal fiber mat-reinforced epoxy composites for car door panels. Similarly, Audi employs sisal mat-reinforced polyurethane composites for door trim panels, and Ford integrates kenaf fiber-reinforced composites into the Mondeo model's door panels. The BMW Group has also extensively adopted natural fiber-reinforced composites across its automobile designs, highlighting the growing significance of sustainable materials in the automotive industry.[10]

Researchers worldwide are actively exploring natural fiber composites reinforced with various fiber types, including seed fibers (*e.g.*, cotton, coir), bast fibers (*e.g.*, hemp, flax, kenaf, jute), leaf fibers (*e.g.*, sisal), stem fibers (*e.g.*, banana, coconut, Indian mallow), and grass fibers (*e.g.*, elephant grass, bamboo, wild cane, golden cane) for automotive and industrial applications. Transforming this cellulosic biomass into fibrous reinforcing material for polymer matrices not only adds value, but also alleviates the burden on solid waste management by reducing the volume of waste requiring disposal. Furthermore, the abundant availability of lignocellulosic biomass resources can contribute to an increased production rate of reinforcing materials, helping to meet the global demand for lightweight composites suitable for structural applications.[9-15] Bio-composites derived from these fibers exhibit high strength and stiffness, excellent thermal and acoustic insulation properties, and notable resistance to fracture.

The performance of lignocellulosic fiber composites depends on multiple factors, including fiber orientation, fiber strength, physical properties, composite processing, and matrix-reinforcement interfacial adhesion. Strength enhancements can be achieved through chemical treatments and hybridization with synthetic fibers.[16-21] However, despite these advancements, natural fiber composites often exhibit lower strength than their synthetic counterparts. Weaving natural fibers has been shown to significantly improve their mechanical properties, making them comparable to synthetic fiber composites. While some research has been conducted on randomly oriented natural fiber-reinforced polyester composites, studies on naturally woven and man-made woven fiber-reinforced polyester composites remain limited.[22-26] Literature suggests that woven fiber-reinforced polymer composites generally outperform those with randomly oriented fibers.

Banana is one of the earliest and most significant fruit crops grown in tropical regions. In India, approximately 51.18 million tons of pseudostem waste are generated annually from about 830.000 hectares of banana cultivated area (Indian Horticulture Database, 2011), with the potential to yield around 3.87 million tons of fiber.[27] A study by Kiruthika and Veluraja on the physical properties of banana pseudostem fibers from various cultivars – such as Nendran, Rasthaly, Morris, and Poovan – found that Nendran fibers exhibited the highest tensile strength (456 MPa).[28] Given these properties, Nendran fiber rope mat was selected as the reinforcement material for this study.

This research aimed to evaluate the mechanical and thermal properties of polyester composites reinforced with Nendran fibers with different orientation, specifically, in random, rope-random, and rope-mat orientations. The study assessed the tensile strength, flexural strength, impact resistance, and Barcol hardness, along with thermal conductivity and heat deflection temperature, of the composites. Scanning electron microscopy (SEM) analysis was conducted to examine fiber-matrix interactions. The findings revealed that Nendran fiber rope mat-oriented composites exhibited superior mechanical and thermal properties compared to their randomly oriented counterparts, as well as other natural and synthetic fiber composites. SEM analysis confirmed strong fiber-matrix adhesion and efficient stress transfer in rope mat-oriented composites, indicating their potential as effective reinforcement materials.

Based on these results, products were developed for automotive applications, demonstrating the feasibility of using Nendran fiber rope mats in high-performance composites. Their exceptional strength and heat resistance make them particularly suitable for manufacturing engine guards for two-wheelers. This study highlights the potential of Nendran fiber rope mats in creating sustainable, cost-effective, and high-performance composite materials for diverse industrial and automotive applications.

EXPERIMENTAL

Materials

Nendran fibers extracted from bark were purchased from Vijay Industries, Sukravarpet, Coimbatore, Tamil Nadu, India. Figure 1 (a) and (b) illustrates the Nendran banana tree and its extracted fibers.

Unsaturated polyester resin was used as the matrix due to its excellent processability, cross-linking properties, and mechanical strength. Cobalt naphthenate and methyl ethyl ketone peroxide (MEKP) were employed as the accelerator and catalyst, respectively. The polyester resin matrix, catalyst, and accelerator were supplied by Vasavibala Resins (P) Ltd., Chennai, Tamil Nadu, India.

Preparation of Nendran fiber rope mat

The preparation of a Nendran fiber rope mat involves several steps. Nendran fiber is extracted from the pseudostems of the Nendran banana plant, known for its strength and durability. Harvesting involves stripping the outer layers of the pseudostems and soaking the inner parts in water to loosen the fibers, followed by scraping and washing. To convert these fibers into rope, a rope-making machine is used, which consists of rollers and twisting mechanisms. The cleaned and aligned fibers are fed into the machine, which twists five individual strands together to form a robust rope. The twisting process ensures the fibers are interlocked, enhancing the rope's durability and resistance to wear. Once the Nendran fiber rope is ready, it is converted into a mat using a weaving machine, either manually operated or automated. The rope is arranged according to the desired mat size and pattern, and the machine interlaces the rope into a mat formation by weaving additional ropes over and under the primary strands. The final steps involve trimming the mat to size and securing its edges to prevent fraying, often through additional stitching or binding.

Fabrication of composites

In this study, composites were fabricated using a combination of chopped Nendran fiber, Nendran fiber ropes of 30-mm length, and Nendran fiber rope mats. The hand lay-up technique was employed for composite preparation to ensure meticulous layering and integration of the fibers. The fabrication process began with maintaining a constant weight fraction of Nendran fiber relative to the weight of the fiber mat to ensure consistency. The Nendran fiber rope mat, measuring 300 mm x 300 mm x 3 mm, was placed into a precisely sized mould.

Figure 1: Preparation of Nendran fiber rope mat; (a) Nendran banana tree, (b) extracted fiber, (c) prepared fiber rope, and (d) woven fiber rope mat

Table 1
Denotation of prepared polyester composites with different orientation of Nendran fiber

Fiber orientation in composite	Denotation
Nendran fiber random	NFR
Nendran fiber rope random	NFRR
Nendran fiber rope horizontal mat	NFRHM
Nendran fiber rope vertical mat	NFRVM

Resin, mixed with curing agents to initiate the hardening process, was then poured into the mould cavity, ensuring complete saturation of the fiber mat. Air bubbles, which could compromise the quality of the composite, were carefully removed using a grooved roller. The mould was sealed and subjected to constant pressure to promote uniform curing. The composites were allowed to cure for 24 hours at room temperature, providing sufficient time for the resin to fully bond with the fibers.

For the preparation of randomly oriented chopped Nendran fiber and Nendran fiber rope composites, a similar procedure was followed, with extra attention given to achieving a uniform distribution of the fibers within the resin matrix. The different orientations of the Nendran fiber used in the polyester composites were denoted with symbols, as detailed in Table 1. This comprehensive approach ensured the production of high-quality composites with consistent fiber reinforcement.

Characterization of prepared composites

Mechanical characterization

The tensile and flexural strengths of Nendran fiber mat-reinforced polyester composite specimens were evaluated using a universal testing machine (Tinius Olsen H50K). The tensile tests adhered to ASTM D 638-10 guidelines (specimen dimensions: 165 mm × 10 mm × 3 mm), performed at a crosshead speed of 1 mm/min, while the flexural tests followed ASTM D790-10 standards (specimen dimensions: 127 mm × 13 mm × 3 mm), at a crosshead speed of 2 mm/min.

Impact testing was performed using a Tinius Olsen (Model: 104) machine, following ASTM D 256-10 (specimen dimensions: 65 mm × 13 mm × 3 mm).

The hardness of the composite plates was examined using a Barcol Hardness Tester (Model: VBH2), following the ASTM D2583 standard.

Each test was conducted five times, and the average values were calculated for further analysis.

Fractography analysis

A SEM instrument, operating at an acceleration voltage of 20 to 40 kV, was used to analyze the fractography of composite specimens after tensile, flexural, and impact tests. The fractured regions were first cut into 10 × 10 mm squares and then coated with a thin gold layer to improve conductivity.

Thermal characterization

Thermal conductivity tests were conducted to assess the heat transfer properties of the composite materials, specifically measuring the transverse thermal conductivity using a guarded heat flow meter (Unitherm Model No. 2022) in accordance with ASTM E1530 standards.[32] The test specimens were precisely cut from the fabricated composites into discs, with a diameter of 50 mm and a thickness of 3 mm, to fit the testing equipment. Each specimen was placed into the thermal conductivity apparatus, where it was subjected to a mean temperature of 55 °C and a compressive load of 0.28 MPa. This setup ensured that the specimen was under controlled conditions for accurate measurement. The testing procedure involved reaching thermal equilibrium, which was crucial for obtaining precise and consistent results. Once thermal equilibrium was achieved, the temperature difference across the specimen was measured, and the output from the heat flux transducer was recorded. The heat flux transducer provided data on the rate of heat flow through the specimen, which, combined with the measured temperature gradient, allowed for the calculation of the specimen's thermal conductivity. This property indicates how effectively the composite material can conduct heat, providing valuable insights into its performance in thermal management applications.

The heat deflection temperature (HDT) test was implemented using an HDT-Vicat tester (XRW300A, Chengde Jinhe Instrument Manufacturing Co., Ltd., Chengde, China) according to ASTM D648 (60 mm × 12 mm × 3 mm) standard.

RESULTS AND DISCUSSION

Table 2 presents a comparison of the physico-chemical properties of Nendran fibers with those of other banana fiber varieties. Nendran fibers contain the highest cellulose content (59.22 wt%) among the listed varieties, indicating superior tensile properties and suitability for reinforcement applications. Their composition includes 59.22 wt% cellulose, 12.09 wt% hemicelluloses, 14.39 wt% lignin, and 2.69 wt% pectin. The mechanical properties of lignocellulosic fibers are significantly influenced by their chemical composition. The high α-cellulose content (59.22 wt%) enhances the mechanical strength of Nendran fibers, while the relatively low hemicellulose content (12.09 wt%) supports strong attachment to cellulose microfibrils, likely through hydrogen bonding. Additionally, the elevated lignin content (14.39 wt%) protects against biological degradation and contributes to the structural integrity of the fibers. These properties make Nendran fibers a viable alternative to conventional natural fibers, such as sisal, coir, flax and cotton. They show great potential as reinforcement materials for lightweight applications across various engineering industries, including construction, automotive, and aerospace.

Table 2
Chemical composition of different banana cultivars

Name of variety	Cellulose (wt%)	Hemicelluloses (wt%)	Lignin (wt%)	Pectin (wt%)
Grand Naine	48.19	15.91	19.17	3.46
Poovan	57.57	12.65	16.71	2.82
Monthan	48.55	15.75	21.56	4.08
Nendran	59.22	12.09	14.39	2.68

Mechanical characterization

Tensile properties

The tensile properties of various Nendran fiber-reinforced polyester composites were systematically evaluated, and the results are detailed in Figure 2. Figure 2(a) illustrates the typical stress-strain curves for the composites reinforced with Nendran fiber in various orientations: Nendran fiber random (NFR), Nendran fiber rope random (NFRR), Nendran fiber rope horizontal mat (NFRHM), and Nendran fiber rope vertical mat (NFRVM). The curves demonstrate that stress increases linearly with strain for all composites. However, the NFRVM composites exhibit a distinctive behavior: after reaching a high stress point, the stress suddenly decreases, indicating a ductile response. This behavior is characteristic of ductile materials and suggests that the NFRVM composites experience a yield point, beyond which they can endure more strain before ultimate failure.

Figure 2(b) presents key tensile properties, including break load, maximum displacement, and percentage elongation at break. The NFRVM-reinforced polyester composites show a significantly higher break load, approximately 3.94 times that of NFR, 3.41 times that of NFRR, and 13.27 times that of NFRHM composites. This demonstrates a superior ability to withstand tensile forces before breaking. Similarly, the maximum displacement, which reflects the composite's ability to deform under stress, was about 2.23 times higher than that of NFR, 2.27 times higher than that of NFRR, and twice higher than that of NFRHM composites. The higher maximum displacement of NFRVM composites highlights their greater ductility and ability to sustain more strain before failure. The percentage elongation at break for NFR, NFRR, NFRHM, and NFRVM composites was 2.56%, 2.52%, 2.85%, and 5.71%, respectively. The NFRVM composites exhibited the highest percentage elongation, indicating that they can endure more strain compared to the other composite types before reaching failure.

Figure 2(c) shows the tensile strength and tensile modulus of the composites. The tensile strength values were 13.2 MPa for NFR, 15.2 MPa for NFRR, 19.5 MPa for NFRHM, and 51.9 MPa for NFRVM-reinforced polyester composites. The NFRVM composites demonstrated the highest tensile strength, approximately 3.93 times that of NFR, 3.4 times that of NFRR, and 2.66 times that of NFRHM composites. This increase in tensile strength is attributed to the enhanced interfacial bonds between the matrix and the fibers, which effectively resist fiber pullout and rupture. The tensile modulus, indicating the stiffness of the composite, followed a similar trend, with NFRVM composites exhibiting the highest value among the types tested. This suggests that the mat form orientation improves the composite's resistance to deformation and breaking under tensile stress.

Figure 3 provides SEM fractography images of tensile fractured specimens of Nendran fiber rope mat composites, showing detailed features such as fiber bending, fiber pullout, and complex crack propagation. The SEM images reveal that the fibers are well-bonded with the surrounding resin, which contributes to the enhanced tensile strength and durability of the composite. The presence of a well-enriched resin matrix around the fibers is crucial for improving the overall strength and performance of the composite.

Overall, the tensile properties of the NFRVM-reinforced polyester composites are superior to those of other natural fiber-reinforced polyester composites (randomly oriented,[12,13,21] unidirectionally oriented[1] and woven[4,23]) and are comparable to, or exceed, the performance of glass fiber composites (GFC) in terms of tensile strength and modulus. This highlights the effectiveness of the mat form orientation of Nendran fibers in enhancing the mechanical properties of the composites, making them a competitive alternative to traditional glass fiber composites for various applications.

Flexural properties

The flexural properties of Nendran fiber-reinforced polyester composites were thoroughly evaluated and are presented in Figure 4. The stress-strain behavior of the composites under flexural loading, as shown in Figure 4(a), illustrates that the NFRVM-reinforced polyester composites exhibit a notable plasticizing effect due to the high extensibility of the Nendran fiber ropes. This effect imparts significant stiffness and flexibility to the otherwise brittle polyester matrix, enabling the NFRVM composites to better withstand applied stresses and delay or prevent composite failure compared to the other formulations of composites.

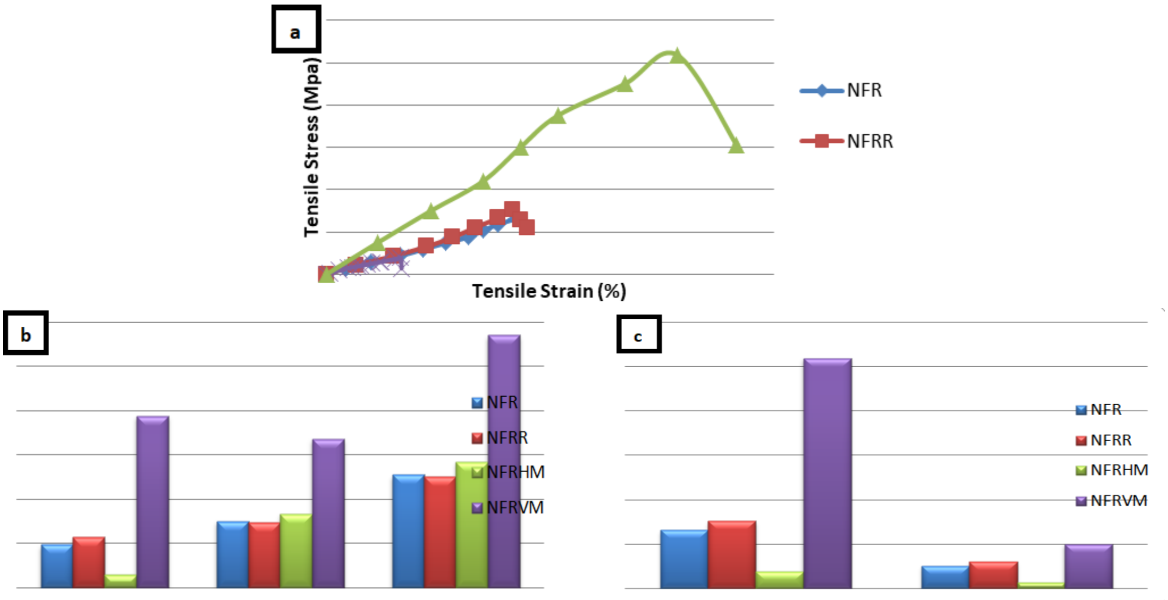

Figure 2: Tensile properties: (a) stress *vs* strain curves, (b) break load, maximum displacement and percentage elongation at break, (c) tensile strength and tensile modulus of the four different composites

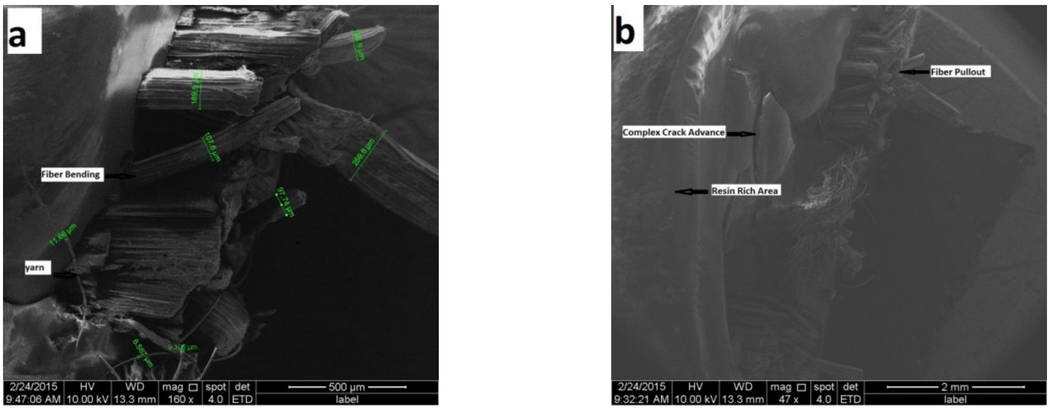

Figure 3: SEM images of tensile-tested specimens of Nendran fiber mat composites

Figure 4(b) details key flexural properties, including break load, maximum displacement, and percentage elongation at break. The NFRVM composites demonstrated the highest break load, approximately 6.5 times greater than that of the NFR composites and 2.5 times greater than those of both the NFRR and NFRHM composites. This indicates a superior ability to bear loads before failure. Similarly, the maximum displacement of NFRVM composites was about 2.41 times higher than that of the NFR and NFRR composites, and 1.33 times greater than the NFRHM composites, reflecting their enhanced capacity to deform under stress. The percentage elongation at break for the NFRVM composites was also significantly higher – 2.38 times greater than those of NFR and NFRR composites, and 1.3 times greater than that of

NFRHM composites – indicating increased ductility and strain tolerance.

Figure 4(c) presents the flexural strength and flexural modulus of the composites. The NFRVM composites exhibited the highest flexural strength at 261 MPa, which is approximately 6.69 times that of the NFR and NFRHM composites, and 2.5 times that of the NFRR composites. This superior flexural strength is attributed to the mat orientation of the Nendran fiber ropes, which enhances the adhesion between the fibers and the polyester matrix, thereby improving the composite's ability to resist bending stresses. The flexural modulus, which measures the stiffness of the composite, was also the highest for the NFRVM composites at 20.4 GPa, marginally surpassing the other composites: 6.01 GPa for NFR, 17.8 GPa for NFRR, and 10.1 GPa for NFRHM composites.

Figure 5 provides SEM images of the fractured flexural specimens for Nendran fiber rope mat composites, revealing details such as fiber fracture, interfacial gaps, and fibers detached from the matrix. The reduced occurrence of voids in the matrix suggests better consolidation and bonding, which contributes to the higher flexural strength observed. The SEM images further highlight that the improved fiber-matrix adhesion and reduced void content are key factors in the enhanced mechanical performance of the NFRVM composites.

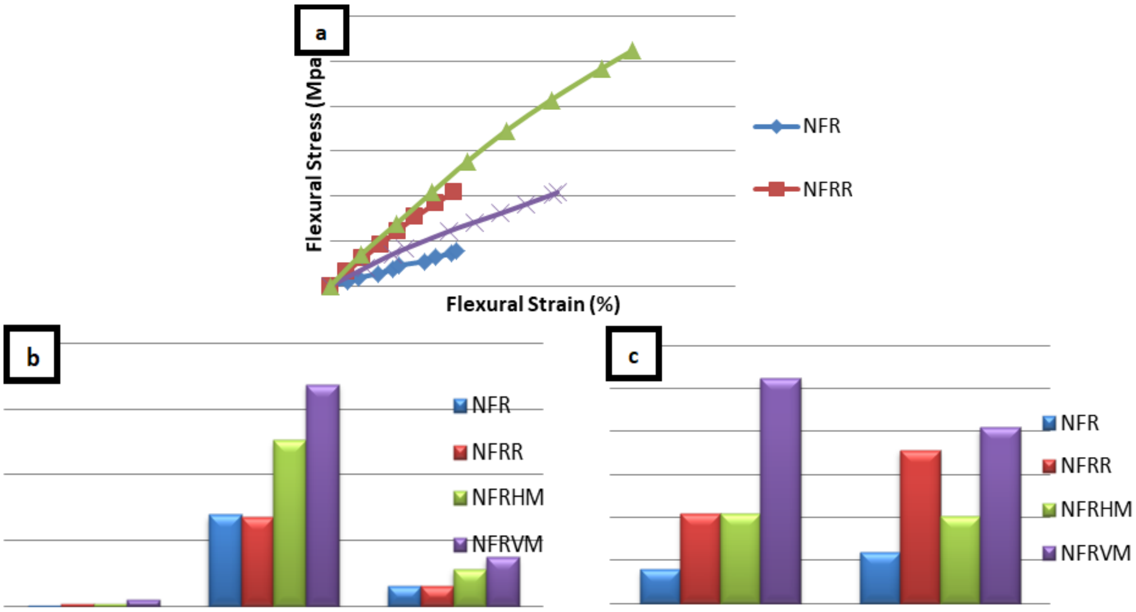

Figure 4: Flexural properties: (a) stress *vs* strain curves, (b) break load, maximum displacement and percentage elongation at break, (c) flexural strength and flexural modulus of the four different composites

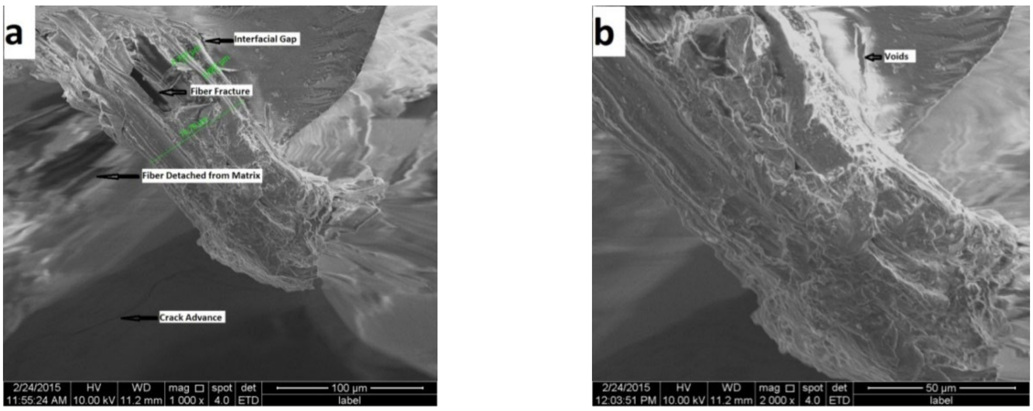

Figure 5: SEM images of flexure-tested specimens of Nendran fiber mat composites

Overall, the flexural properties of the NFRVM-reinforced polyester composites not only surpass those of other natural fiber-reinforced polyester composites, but also approach or exceed the performance of glass fiber composites (GFC), including those with random, unidirectional, and woven orientations (randomly oriented,[13,14,19,21] unidirectionally oriented[1,2,4] and woven).[4,23] This demonstrates the effectiveness of the Nendran fiber rope mat orientation in achieving high flexural strength and stiffness, making it a competitive alternative for applications requiring robust mechanical performance.

Impact strength

The impact strength test was conducted to evaluate the ability of different Nendran fiber-reinforced polyester composites to withstand sudden loads, as depicted in Figure 6. The impact strengths of the composites were measured as 3.35, 3.96, 5.8, and 22.3 kJ/m² for the NFR, NFRR, NFRHM and NFRVM composites, respectively. These results highlight a significant variation in impact resistance among the different composite types. The NFRVM-reinforced polyester composites showed the highest impact strength, showcasing an exceptional ability to absorb and disperse impact energy. Specifically, the impact strength of NFRVM composites was approximately 6.65 times greater than that of NFR composites, 5.63 times greater than NFRR composites, and 3.84 times greater than NFRHM composites.

The enhanced impact strength of the NFRVM composites can be attributed to the presence of long Nendran fiber ropes, which contribute to a more effective distribution and absorption of impact energy. The longer fibers in the mat form enhance the composite's ability to dissipate impact forces over a larger area, thereby reducing the likelihood of catastrophic failure upon impact.

Figure 7 provides SEM images of the fractured impact specimens of Nendran fiber rope mat composites, revealing detailed features of the failure surfaces. The SEM analysis shows clear signs of porous structures, fiber fractures, and fiber bending. The examination also confirms that the individual fibers within the mat were twisted together during the rope-making process, contributing to the composite's overall impact resistance. The SEM images provide visual evidence of how the fiber arrangement and bonding contribute to the material's performance under impact conditions.

The impact strength results for the NFRVM composites were notably higher compared to other randomly oriented and woven natural fiber-reinforced polyester composites, and were found to be quite close to that of glass fiber composites (randomly oriented[14,19,21] and woven[4,15]). This indicates that NFRVM composites offer competitive impact resistance, positioning them as a strong alternative to traditional glass fiber composites in applications requiring high impact durability. This superior performance underscores the effectiveness of using long fiber ropes in enhancing the mechanical properties of composite materials.

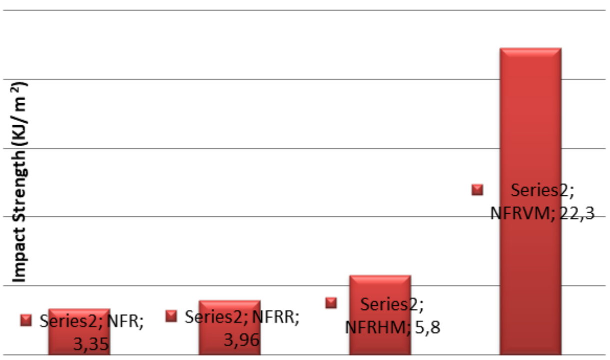

Figure 6: Impact strength for different fiber reinforced composites

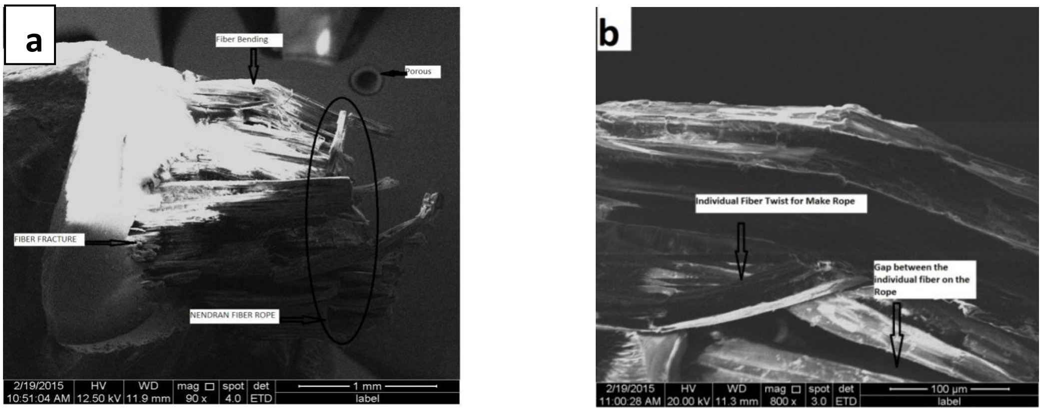

Figure 7: SEM images of impact-tested specimens of Nendran fiber mat composites

Table 3
Comparison of mechanical properties of the Nendran fiber polyester composites prepared in this study with those of glass fiber and other natural fiber-reinforced polymer composites

Fiber/matrix	Fiber orientation	Tensile strength (Mpa)	Flexural strength (Mpa)	Impact strength (KJ/m^2)	Barcol hardness	Ref.
Nendran fiber/polyester	NFR	13.2	39	3.35	22	Present work
	NFRR	15.2	104	3.96	25	
	NFRHM	19.5	40	5.8	30	
	NFRVM	51.9	261	22.3	39	
Water hyacinth/polyester	Random	23.4	41.8	---	---	[23]
Indian areca fruit husk/polyester	Random	68.20	73.9	6.82	---	[24]
Sansevieria cylindrica/polyester	Random	75	83.85	9.45	---	[29]
Palmyra palm/polyester	Random	18.7	51.1	16	---	[31]
Sisal/polyester	Random	55	84	11	---	[31]
Bagasse/polyester	Random	17-23	31-48	---	---	[31]
Wildcane grass/polyester	Unidirectional	---	111	---	---	[1]
Waste groom/polyester	Unidirectional	94.08	---	---	---	[32]
Jowar/polyester	Unidirectional	124	134	---	---	[34]
Bamboo/polyester	Unidirectional	126	128.5	---	---	[34]
Coconut sheath/polyester	Naturally woven	60	107.9	12.97	---	[25]
Banana/polyester	Woven	75	80	19	---	[4]
Kenaf/polyester	Woven	110-120	100-110	20-23	---	[4]
Rattan/polyester	Woven	20.43	57.65	---	45	[22]
GF/epoxy	Woven	83	132	52.66	---	[33]

Barcol hardness

Figure 8 illustrates the variation in Barcol hardness values for different forms of Nendran fiber-reinforced polyester composites, revealing how the orientation and form of reinforcement affect the material's hardness. The measured hardness values were 22, 25, 30, and 39 for the NFR, NFRR, NFRHM, and NFRVM composites, respectively. Among these, the NFRVM-reinforced polyester composites demonstrated the highest hardness value, significantly surpassing the other composite types. Specifically, the hardness of the NFRVM composites was approximately 1.77 times greater than that of the NFR composites, 1.56 times greater than that of the NFRR composites, and 1.3 times greater than that of the NFRHM composites.

This substantial increase in hardness observed in the NFRVM composites is indicative of a stronger bonding between the matrix and the Nendran fiber ropes used in the mat weaving. The higher hardness values suggest that the NFRVM composites have enhanced resistance to surface indentation and deformation, which can be attributed to the more effective integration and reinforcement provided by the fiber mat. This improved hardness not only reflects the quality of the bond between the matrix and reinforcement, but also indicates better overall mechanical performance of the composite. The increased hardness of the NFRVM composites makes them suitable for applications requiring greater surface durability and resistance to wear, thus highlighting the benefits of using the woven mat orientation for enhancing the properties of the composite material.

Thermal characterization

Thermal conductivity

The thermal conductivity of the four types of Nendran fiber-reinforced polyester composites NFR, NFRR, NFRHM, and NFRVM was systematically measured and presented in Figure 9. The results indicated thermal conductivities of 0.151, 0.166, 0.14, and 0.14 $Wm^{-1}K^{-1}$, respectively, for each composite type. Notably, the thermal conductivity of the NFRHM and NFRVM composites was lower compared to the NFR and NFRR composites. Specifically, the thermal conductivity decreased by 9.2% and 15.6% for NFRHM and NFRVM composites, respectively, relative to their randomly oriented counterparts (NFR and NFRR).

This reduction in thermal conductivity observed in the NFRHM and NFRVM composites can be attributed to the woven mat orientation of the Nendran fiber ropes. In these composites, the weaving of the mat likely creates a more uniform and less thermally conductive structure, compared to the random fibers found in the NFR and NFRR composites. The mat arrangement of the fibers may contribute to a more effective thermal insulation barrier, thus reducing the overall heat transfer through the material.

The lower thermal conductivity of the NFRHM and NFRVM composites is particularly advantageous for applications involving exposure to high temperatures or hot surfaces. This improved thermal insulation can enhance the material's performance in thermal management applications by minimizing heat transfer and protecting underlying structures from heat damage. Thus, the orientation of the Nendran fiber ropes plays a critical role in optimizing the thermal properties of these composites, making them suitable for specific thermal applications where heat resistance is essential.

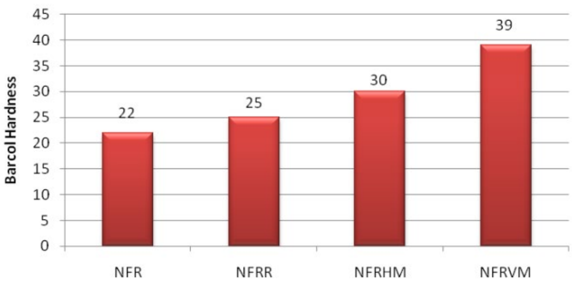

Figure 8: Barcol hardness for different forms of composites

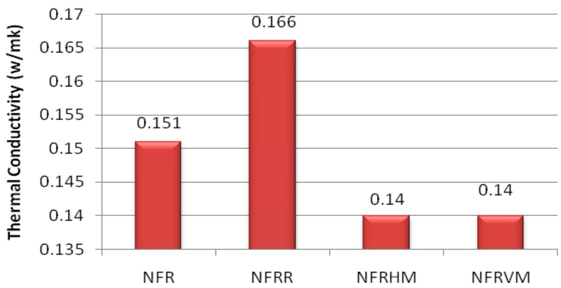

Figure 9: Thermal conductivity for different forms of composites

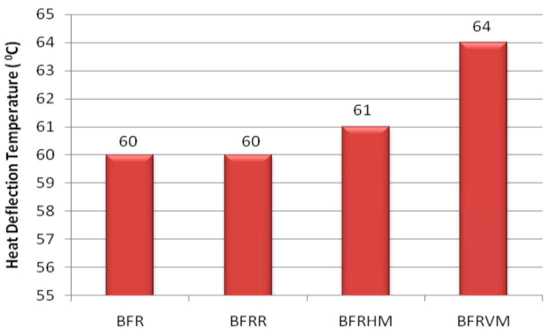

Figure 10: Heat deflection temperature test (HDT) for different forms of composites

Heat deflection temperature

The heat deflection temperature (HDT) test results for the fabricated Nendran fiber-reinforced polyester composites are illustrated in Figure 10. The HDT values measured for the NFR, NFRR, NFRHM and NFRVM composites were 60 °C, 60 °C, 61 °C, and 64 °C, respectively. These results indicate that, while there is no significant difference in the HDT values among most of the composite types, the NFRVM-reinforced polyester composites exhibit a slightly higher HDT compared to the others.

The marginally higher HDT observed in the NFRVM composites, which registered at 64 °C, is attributed to the reinforcing effect of the Nendran fiber ropes used in the woven mat orientation. This enhanced HDT reflects the ability of the NFRVM composites to better maintain their rigidity and resist deformation under elevated temperatures. The increase in HDT for the NFRVM composites is particularly noteworthy, as it suggests improved thermal stability and durability of the material when exposed to high atmospheric temperatures. This characteristic is valuable for applications where the material is subjected to significant thermal stress, as it indicates that the composite can withstand higher temperatures without experiencing substantial deflection or loss of structural integrity.

Overall, while the HDT values are relatively close among the four types of composites, the slight increase in HDT for NFRVM composites underscores the effectiveness of the mat form orientation in enhancing the thermal performance of the material. This makes NFRVM-reinforced polyester composites particularly suitable for environments where high-temperature resistance is crucial.

Applications

The application of Nendran fiber rope mat composites in automotive components, particularly in two-wheeler engine guards, presents a significant advancement in material sustainability and performance. Traditionally, engine guards are fabricated from metal, which is later replaced by glass fiber composites due to their lightweight and high-strength characteristics. However, glass fiber is not an eco-friendly material, leading to increased environmental concerns. Nendran fiber rope mat composites offer an environmentally friendly alternative, leveraging the natural and renewable properties of Nendran fibers. The engine guard made from Nendran fiber rope mat composites, depicted in Figure 11, exemplifies this transition. The Nendran fiber rope mat provides excellent protection against mud and impacts, similarly to traditional materials, but with the added benefit of reduced environmental impact. This composite material not only matches the strength and durability required for effective engine protection, but also aligns with sustainable practices by utilizing natural fibers. The adoption of Nendran fiber rope mat composites in engine guards marks a progressive step towards integrating eco-friendly materials into automotive applications, thereby contributing to more sustainable manufacturing processes and reducing the overall environmental footprint of vehicle components.

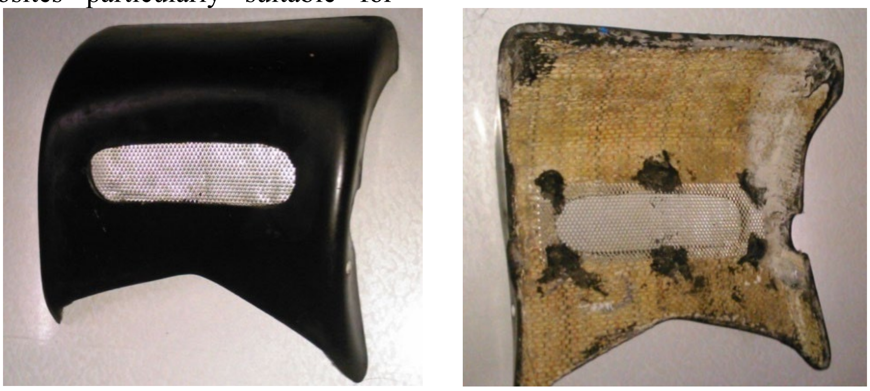

Figure 11: NFRVM polyester composite products: engine guard of two-wheelers

CONCLUSION

In the present investigation, a comprehensive analysis was conducted to evaluate the impact of Nendran fiber rope mat and random fiber orientations on the mechanical and thermal properties of polyester composites. The study revealed several key insights and conclusions regarding the performance of these composites. Notably, the Nendran fiber rope vertical mat (NFRVM) reinforced polyester composites demonstrated superior mechanical strength, compared to the Nendran fiber random (NFR), Nendran fiber rope random (NFRR), and Nendran fiber rope horizontal mat (NFRHM) composites. This enhanced performance can be attributed to the mat orientation of the Nendran fiber rope, which facilitates a more uniform load distribution across the reinforcement, thereby improving the overall structural integrity and strength of the composite.

Scanning electron microscopy (SEM) analysis further supported these findings, showing that the adhesion between the Nendran fiber rope mat and the polyester matrix is notably effective. The interlocking of fibers within the mat structure enhances the bonding between the fiber and the matrix, contributing to the improved mechanical properties observed. The NFRVM composites not only exhibited better mechanical performance, compared to other natural fiber-reinforced composites, but also outperformed traditional glass fiber composites (GFC) in several aspects.

Thermal analysis revealed that the NFRVM composites have lower thermal conductivity compared to the other composite types, which can be attributed to the efficient packing arrangement of the Nendran fiber mat structure. This arrangement minimizes heat transfer, making the NFRVM composites more effective as thermal insulators. Additionally, the heat deflection temperature (HDT) of the NFRVM composites was slightly higher than that of the other composites. This improvement in HDT is due to the uniform distribution of fibers and strong adhesion between the Nendran fibers and the polyester matrix within the mat structure, which improves the material's ability to endure high temperatures without deforming.

Overall, the results of this investigation underscore the potential of Nendran fiber rope mat composites as a viable reinforcement material in polyester composites. These materials offer a combination of high strength, low thermal conductivity, and good heat resistance, which makes them suitable for applications such as industrial roof sheets and two-wheeler engine guards. The findings suggest that Nendran fiber rope mat composites not only provide a cost-effective alternative to traditional materials, but also contribute to sustainable manufacturing practices by utilizing eco-friendly natural fibers.

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