Hindawi
Advances in Materials Science and Engineering
Volume 2024, Article ID 8818030, 9 pages
https://doi.org/10.1155/2024/8818030

Research Article

Investigation of Mechanical and Thermal Stabilities of Tamarind Seed- and Peanut Shell Powder-Reinforced Vinyl Ester Composite

Ramakrishnan Kulasekaran Sathish Kumar,[1] Rathinasabapathy Sasikumar,[1] Nagaraj Nagaprasad ,[2] Rathinam Ezhilvannan,[3] and Ramaswamy Krishnaraj [4,5]

[1]*Department of Mechanical Engineering, Vinayaka Mission's Research Foundation (Deemed to be University), Salem 636308, Tamil Nadu, India*
[2]*Department of Mechanical Engineering, ULTRA College of Engineering and Technology, Madurai 625104, Tamil Nadu, India*
[3]*Department of Mechanical Engineering, Velammal College of Engineering and Technology, Madurai, Tamil Nadu, India*
[4]*Centre for Excellence-Indigenous Knowledge, Innovative Technology Transfer and Entrepreneurship, Dambi Dollo University, Dembi Dolo, Ethiopia*
[5]*Department of Mechanical Engineering, College of Engineering and Technology, Dambi Dollo University, Dembi Dolo, Ethiopia*

Correspondence should be addressed to Ramaswamy Krishnaraj; prof.dr.krishnaraj@dadu.edu.et

Received 21 October 2023; Revised 20 December 2023; Accepted 28 December 2023; Published 13 January 2024

Academic Editor: Kawaljit Singh Randhawa

Efficient exploitation of agricultural waste results in a more sustainable and ecofriendly environment since it lessens the burden of their disposal, which has become increasingly important in recent times. Due to their high mechanical strength and high thermal stability, these biodegradable low-value agrosolid wastes have the potential to successfully replace synthetic fibers and fillers in polymer matrices in the form of reinforcements. This work deals with the addition of low-cost and renewable hybrid natural fillers, tamarind seed filler (TMS), and peanut shell powder (PNS) as particulate reinforcements to the vinyl ester (VE) resin. Traditional compression molding creates TMS/PNS-VE hybrid composites with filler loadings ranging from 5% to 30%. After the composites were fabricated, they were tested for strength properties and heat deflection temperature. A detailed experimental analysis of the mechanical properties was conducted. According to the findings, 20 wt.% hybrid filler loading to the vinyl ester polymer exhibited peak tensile, flexural, and impact strengths of 40.3 MPa, 142 MPa, and 16 kJ/m^2, respectively, which is 1.52, 1.69, and 1.29 times the properties of the virgin polymer. However, the peak elongation at break 3.9% was obtained at 30 wt.%. Similarly, the heat deflection temperature (HDT) test of TMS/PNS-VE composites showed a maximum rise of 50.91% at 25 wt.% of filler loading. This is 1.51 times greater than the heat deflection temperature of the pure vinyl ester resin. The findings made it quite clear that adding 20 wt.% biosolid waste hybrid particulate fillers made out of tamarind seed and peanut shell to vinyl ester is the optimum weight, which improves the mechanical and thermal properties of the TMS/PNS-VE composite, making it suitable for making cost-effective materials for lightweight applications. This study also utilizes scanning electron microscopy (SEM) to investigate the microstructural characteristics of the composites, correlating these features with their mechanical performance.

1. Introduction

The existence of humanity is contingent on maintaining a pristine environment at all times. As a result, material scientists and technologists are working to develop cutting-edge commercial and environmentally friendly products that are both sustainable and biodegradable. The utilization of ecologically safe components contributes to the preservation of the ecosystem, and the speed with which these materials break down in the natural setting helps to promote this purpose. As an outcome, the number of items made from renewable resources has risen rapidly in recent years [1]. Natural wastes are by far the most prevalent material to be utilized in producing ecofriendly composites. Waste products derived from natural processes are both cost-effective and renewable. One of the most important aspects of natural waste is that biological processes can break it down. These wastes can potentially increase the biodegradability of the composite while improving its strength [2]. Therefore, the need to utilize such materials in the composite industry is inevitable. Natural fillers are renewable resources that can serve as reinforcing agents for various polymer matrices and are versatile enough to be utilized in different fields related to transport, construction, aviation, toy making, defense, sporting goods, and electronic industries [3]. These agrowastes are abundant in the form of kernels and shells. After being ground and sieved, they can be used as cellulosic biofuels or inexpensive polymer composite additives [4]. Adding fillers is the most effective strategy for increasing polymeric materials' mechanical and thermal aspects when these capabilities are not adequate for a particular application. Improved adhesion behavior between hydrophilic fibers and hydrophobic matrices can be attained through fillers. In situations where biocomposites are required, natural fillers are the better option. These composites are known for their little impact on the environment and their ability to be renewed. The natural fillers will produce satisfactory outcomes up to the optimal weight percentage, after which adding more could cause the composites' qualities to deteriorate [5].

Using these natural fillers in a polymer matrix helps reduce the manufacturing cost of the composites by minimizing resin requirements [6]. However, increased moisture absorption, low strength, uneven surface quality, and limited thermal stability are some of the critical challenges researchers face when working with these natural filler/fiber waste materials. Such challenges can be overcome by hybridization [7]. Hybrid composites show better tensile and flexural properties, improving their load-carrying capacity [8].

Tamarind is a massively produced agricultural commodity throughout the majority of the tropical nations of Asia, Africa, and Central America. The tamarind tree can flourish even on soil lacking fertility, has a shallow water requirement for its growth, and does not require any human labor for its care. With an annual output of 45,000 metric tons, Tamil Nadu is the top producer of tamarind among all Indian states. This estimate may account for about 98,000 metric tonnes (45.4% of the total subcontinent share). The fruit of the tamarind tree is the most cherished and costly part of the plant. The seed, which accounts for most of the fruit, namely, 25–40%, is thrown away as trash [9]. Similarly, like most other agricultural leftovers, peanut shells are produced in vast numbers each year and either dumped into the environment without the appropriate treatment or generally utilized to feed animals [10]. Prabhakar et al. experimentally explored whether or not the powder from peanut shells might be used to produce composite materials and found it feasible. The findings of the experiments demonstrated that it is possible to manufacture composites by employing peanut shell powder (PNS) as the reinforcement material. The incorporation of PNS significantly enhanced the thermal and mechanical characteristics. Despite the diversity of countries that produce groundnuts, utilizing waste products, such as shells, in manufacturing valuable components would appeal to the economy. To produce composites at an affordable cost, PNS-reinforced composites are a viable option, which may also lead to an increase in the scope of their application [11]. Hence, utilizing this agrowaste as hybrid reinforcement in a polymer matrix has much content in structural and other applications.

The most popular composite matrices are epoxies, unsaturated polyesters, and vinyl esters. Epoxies find use in high-performance applications, although unsaturated polyesters are the industry's leaders owing to their lower cost and greater ease of processing. However, they have low UV and temperature resistance. Due to its higher mechanical qualities and temperature resistance, epoxy is typically utilized when unsaturated polyesters no longer work. Epoxies are employed in high-cost areas because of their improved characteristics. Vinyl esters (VE) are chemically similar to unsaturated polyesters and epoxies and are frequently a compromise between the two. Epoxy has outstanding properties when it comes to mechanical or thermal stability. These properties were combined with the speed and ease of crosslinking of unsaturated polyesters to make this resin. Using fillers to reinforce the vinyl ester resin enhances the polymer composite's performance while decreasing production costs. Particulate fillers are the most significant way to support the vinyl ester resin in cast structural products [12].

By altering the percentage of filler addition in the polyester resin matrix, Jeyaprakash et al. created a composite out of powdered hybrid particulate reinforcing particles of tamarind seed (TS) and palm fiber (PF). The researchers demonstrated that the composite's maximum hardness in the Rockwell scale of about 90.2% and maximum impact resistance (1.066 J) could be achieved by using a 25 wt.% TS, 15 wt.% PF powders, and 60 wt.% polyester resin mix. The composite attained its maximum tensile strength of 18.3 MPa when 18 wt.% TS, 22 wt.% PF powder, and 60 wt.% polyester resin were combined [13]. The properties of epoxy composites made from groundnut shell powder (60 wt.%) and tamarind shell powder (60 wt.%) were studied by Santosh and Shetty. They also studied that tamarind shell fragments were tougher and brittler when compared to groundnut shell fragments and had better mechanical properties when added with epoxy [14]. Nagaprasad et al. fabricated hybrid filler-reinforced vinyl ester composites from tamarind seed and date seed wastes and then examined the mechanical properties after being altered. Mechanical tests (tensile, flexural, and impact) and Barcol hardness tests reveal that the best strength of the composites is achieved at a filler content of 10 wt.%. They claimed that hybrid filler composites are suited for use in the production of end products because the composite material has a low impact on the environment and can be applied to a variety of industrial applications as well as home applications [15]. Aradhyula et al. reinforced polypropylene (PP) biomaterials with biowaste catla fish scale (CFS) and proved that adding CFS content increased the flexural strength by 5%, density by 1%, and hardness by 11% of the PP/CFS composite. Also, CFS loading improved the composite's impact strength and melt flow index [16].

Abhishek et al. developed a hybrid epoxy composite from fish bone-derived nanofillers and *Phoenix pusilla* natural fiber. They identified a 22.5% rise in tensile strength and a 20% rise in flexural strength, and a 15.2% rise in hardness was achievable by incorporating bio-nanofillers into hybrid polymer composites [17]. According to the research of Olumuyiwa et al., a polymer composite can gain its hardness by including coconut shell particles in a low-density polyethylene matrix, which is a crucial property requirement in making automobile interior panels [18]. Studies conducted by Jagadeesh et al. examined the usage of corn husk flour, an agricultural byproduct, as reinforcement for thermoplastic polymers (polylactic acid). They proved this by adding the biofiller flexural modulus enhanced with increasing filler loading (10, 20, 30, and 40 wt.%) and mesh size (50~100, 100, and 300). They concluded that using materials derived from agrowaste as reinforcement in the manufacture of ecologically friendly composites is an attractive trend from the perspective of mechanical properties [19]. Saba et al. developed a kenaf/epoxy hybrid nanocomposite by dispersing the nanofiller comprising an empty fruit cluster of the nano-oil palm fibers, a material composed of layers of silicate called montmorillonite and biologically modified montmorillonite nanoclay. Mechanical testing revealed that compared to traditional kenaf fibers-reinforced epoxy composites, the nano-oil palm filler-reinforced composite showed a hike in tensile strength, impact strength, and elongation [20].

Research performed in the past makes it abundantly clear that incorporating a filler into a polymer matrix composite improves its mechanical and thermal properties. To utilize agricultural wastes efficiently to minimize the effort required to dispose of them, this work uses tamarind seed and peanut shell biosolid wastes as hybrid filler particle reinforcement in a vinyl ester matrix. This study explores the enhancement of vinyl ester composites' mechanical and thermal properties by incorporating tamarind seed and peanut shell powder as hybrid natural fillers. Additionally, SEM analysis was performed, providing information about the microstructural integrity of the composite and how it interacts with the matrix.

2. Materials and Methods

2.1. Materials. The primary raw materials used in this research are tamarind seed, peanut shell, and vinyl ester resin. Tamarind seeds and peanut shells were purchased from local sources, such as farmers from the nearby area. By using distilled water, they are cleaned to get rid of pulp, dust, and soluble impurities. Water droplets settled on the top surfaces of the objects were wiped with the help of a tissue paper. After that, they were baked in an electrical furnace in the 60°C heat range for one whole day. A pebble mill was used to grind up dried tamarind seeds with peanut shells to 30 and 60 μm particle sizes. HORIBA SZ100 particle analyzer was used to determine the average grain size of crushed tamarind seeds and peanut shells.

In this study, in addition to the untreated vinyl ester resin, the matrix was formed of bisphenol-A-epoxy-derived resin (styrene-45%), which is nothing but a vinyl ester. It measured 400 cps in viscosity and 1.09 in specific gravity, and its density was 1.145 g/cm^3. In addition, it had a promoter called N,N-dimethylaniline ($C_8H_{11}N$), a catalyst called methyl ethyl ketone peroxide ($C_8H_{18}O_6$), and the element cobalt. Sathyam Fibertex, Coimbatore, India, supplied these chemicals for the study.

Table 1 summarizes the properties of the materials used in the study. The particle size of both tamarind seed powder and peanut shell powder was taken in the range of 30 μm–60 μm and measured using a HORIBA SZ100 particle analyzer. The tamarind seed powder and peanut shell powder were prepared by cleaning, baking, and grinding. The vinyl ester resin, a bisphenol-A-epoxy-derived resin, was used with a density of 1.145 g/cm^3 and a viscosity of 400 cps. These properties are integral to understanding the behavior of the composite materials studied.

2.1.1. Material Preparation. The usual method of compression molding is utilized during the fabrication of hybrid fillers in addition to VE resin. In this research, tamarind seed and peanut shell additives are blended as a mixed type of filler with a combined percentage of weight. To prepare vinyl ester specimens with variable filler loadings ranging from 5% to 30%, a specific mold is designed ($200 \times 200 \times 3$ mm). Carbon black-made mold release wax was initially applied on the surface of the mold and on the cover plate to make it easier to remove the plates, which are cured as soon as they achieve their final state [15]. Then, the promoter (10% N,N-dimethylaniline) of about 1.5 wt% was added to a known volume of VE resin. To remove any air bubbles that had crept in during the stirring process, the liquid was made to pass through a vacuum chamber to remove gases after being stirred for an additional 2 minutes. After adding an equal amount of accelerator and catalyst (1.5 wt.%), the mixture was stirred for two minutes before degassing in a vacuum chamber [21]. The catalyst is methyl ethyl ketone peroxide with a wt.% of 50, while the accelerator is 3 wt.% cobalt naphthenate. The use of methyl ethyl ketone peroxide (MEKP) at 50 wt.% as a catalyst is chosen to effectively initiate the curing process in vinyl ester resins, balancing safety and reactivity. Cobalt naphthenate is used as an accelerator at 3 wt.% to enhance the curing rate without compromising the composite's properties. This combination is standard in the industry for efficient and reliable curing of vinyl ester resins.

After that, the prepared mixture was put into the mold, which was then secured using a cover plate. After curing the sample for 24 hours at room temperature, it was taken out of the mold for postcuring of about 2 hours at 80°C. After the composite plate had utterly hardened, the mold was split loose and removed. Similarly, the hybrid composite consisting of variable filler loadings has been synthesized.

2.2. Testing Methods

2.2.1. Mechanical Testing. Assorted test specimens' composite plates were trimmed to the required size with the help of a saw cutter. At room temperature, tensile and flexural

Table 1: The properties of tamarind seed powder, peanut shell powder, and vinyl ester resin used in the study.

Material	Particle size range (μm)	Density (g/cm^3)	Other properties
Tamarind seed powder	30–60	—	Cleaned, baked, and ground
Peanut shell powder	30–60	—	Cleaned, baked, and ground
Vinyl ester resin	—	1.145	Bisphenol-A-epoxy-derived, viscosity: 400 cps, and specific gravity: 1.09

tests were performed on a (Tinius Olsen H50K) universal testing machine. Three samples were analyzed for each wt.% of body weight to provide consistent results. Crosshead with the speed setting of 1 mm/min was set and employed in tensile tests to ensure compliance with the requirements of the ASTM D638 standard with a specimen size of about 165 mm × 10 mm × 3 mm [22]. The flexural test is performed on specimens (127 × 12.7 × 3 mm) according to the ASTM D790-10 standard. The three-point bending method was applied with a 50 kN capacity with a crosshead speed of 2 mm/min [23]. Later, the impact strength test results evaluated (Charpy approach) as per the standards of ASTM D256 using a specimen size of 65 × 13 × 3 mm^3 were analyzed.

2.2.2. Heat Deflection Temperature Test. An HDT-TSP type analyzer (60 × 12 × 3 mm^3) was used to test HDT for composites with a hybrid filler loading of 0 to 30 wt.% as specified by ASTM D648 (60 × 12 × 3 mm^3). The constant temperature range in this experiment was 2°C/min, and the loading pressure was 455 kPa. The HDT was measured after the deformation of the test specimen under flexural force, which is a typical behavior [24].

3. Result and Discussion

3.1. Tensile Test. In terms of its tensile properties, the behavior of a material is determined by three different elements. These are the material's tensile strength, the elongation of the material at the point of the break, and its tensile modulus. Figures 1 and 2 show how increasing the filler quantity changes the concentration of hybrid filler reinforcement, which directly affects the tensile properties of the vinyl ester composite. Figure 1 depicts such effects that the factor had on the tensile strength property, and Figure 2 illustrates what effect the factor had on the tensile modulus. Pure vinyl ester resin has a tensile strength of 26.5 MPa, so its tensile modulus is 1.17 GPa. In the tensile test, the composite showed an interesting trend. The tensile strength peaked at 40.3 MPa at 20 wt% filler content, indicating improved stress distribution and load-bearing capacity at this concentration. Concurrently, the tensile modulus, which reflects the material's stiffness, achieved its maximum value of 2.14 GPa at a slightly higher filler concentration of 25 wt%. This difference illustrates how the composite's flexibility and rigidity balance varies with filler content, highlighting the tradeoff between strength and stiffness in composite materials. At 20 wt% filler, the tensile strength increases due to optimal filler dispersion and stress distribution. In contrast, the tensile modulus decreases because the natural fillers add flexibility to the composite, reducing its stiffness. The tensile property of the composite material falls when an extra hybrid filler is introduced to the mixture of materials [15, 21, 25–28]. This is because the mixed filler has a lower tensile modulus. Also, this is due to the TMS/PNS filler concentration in the composite being higher than 10 wt.%, which caused the surface contact of the fillers to begin getting structured. As a result of this, the composite exhibited the characteristics described above. The SEM images in Figure 3 provide a microstructural perspective of the tensile fracture surfaces of the TMS/PNS-reinforced vinyl ester composites. These images reveal crucial details about the filler distribution and interfacial bonding quality at varying filler contents. At the optimal 20 wt% filler concentration, where the tensile strength peaked at 40.3 MPa, the SEM image in Figure 3(a) shows an even distribution of fillers with minimal evidence of filler pull-out or voids. This suggests a strong filler-matrix adhesion, contributing to the improved stress distribution and load-bearing capacity. In contrast, at a higher filler concentration of 25%, the image in Figure 3(b) shows increased instances of voids and filler pull-out, indicating weaker interfacial bonding and explaining the observed decrease in tensile strength beyond the 20 wt% filler content. These microstructural observations correlate well with the mechanical test results, highlighting the importance of optimal filler content for maximizing tensile strength. The development of connections became noticeably more extensive if the TMS/PNS filler addition was higher than 20 wt.%. It was discovered that the TMS/PNS hybrid filler-reinforced composites saw a considerable drop in their strength and stiffness when they were treated to a concentration of filler equivalent to or higher than 25 wt.%. The clustering of hybrid fillers, which are prone to be easily removed by an applied force and ultimately result in the failure of the material, was the primary cause of this phenomenon. In Figure 4, the elongation at the break of the vinyl ester composite shows a continuously rising trend until 15 wt.% of filler loading, after which it starts to drop and stays at that level until 25 wt.%. However, the maximum allowable 3.9% was reached when the hybrid filler loading was 30 wt.%.

3.2. Flexural Test. The material demonstrated its capacity to withstand bending loads during the flexural test. The flexural strength of the composite increased significantly, reaching 142 MPa at 20 wt% filler content, which is 1.69 times higher than that of pure vinyl ester resin. The influence of filler loading on the flexural strength of the TMS/PNS-VE composite is depicted in Figure 5. This increase is attributed to this concentration's enhanced bonding and load transfer capabilities. Regarding flexural modulus, which indicates the

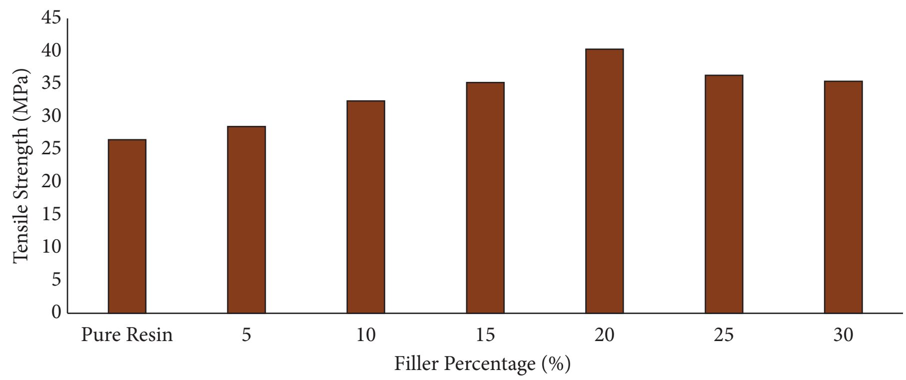

Figure 1: Influence of filler loading on the tensile strength of the TMS/PNS-VE composite.

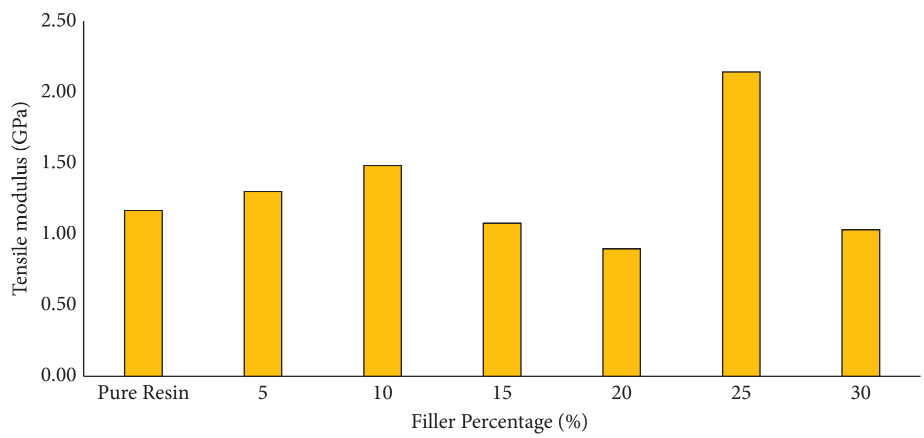

Figure 2: Influence of filler loading on the tensile modulus of the TMS/PNS-VE composite.

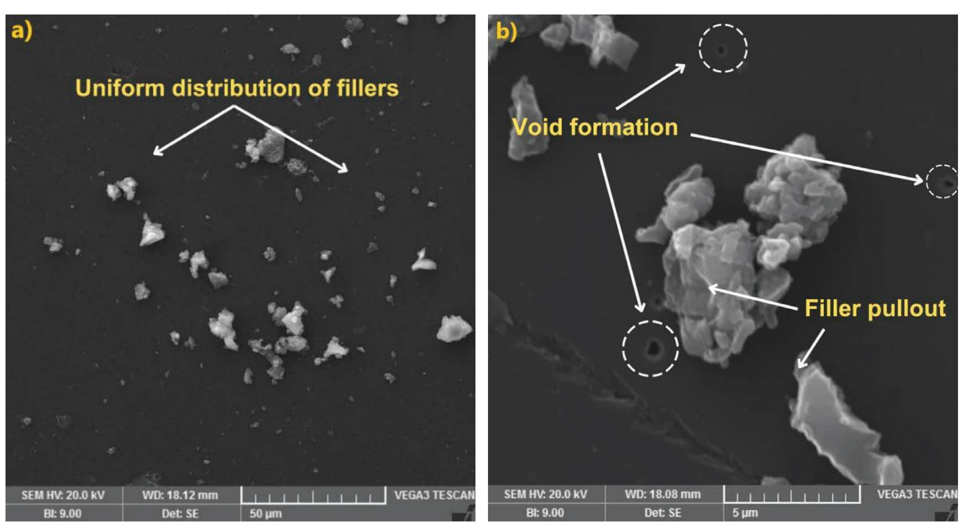

Figure 3: SEM images of the fractured tensile surfaces of TMS/PNS vinyl ester composites at filler loadings of (a) 20% and (b) 25%.

rigidity under bending, the composite also showed improved performance, correlating with the increase in strength. This simultaneous enhancement in both flexural strength and modulus underscores the efficacy of the TMS/PNS hybrid filler in reinforcing the composite for structural applications. This is because the hybrid filler has a larger elasticity modulus than pure resin [29–34]. The flexural resistance of the material improves when there is excellent adhesion between the filler and the resin at the interface. Further addition of filler particles increases void content due to particle agglomeration, which reduces the dispersion of particles, creating weak interfacial bonding. An increase in

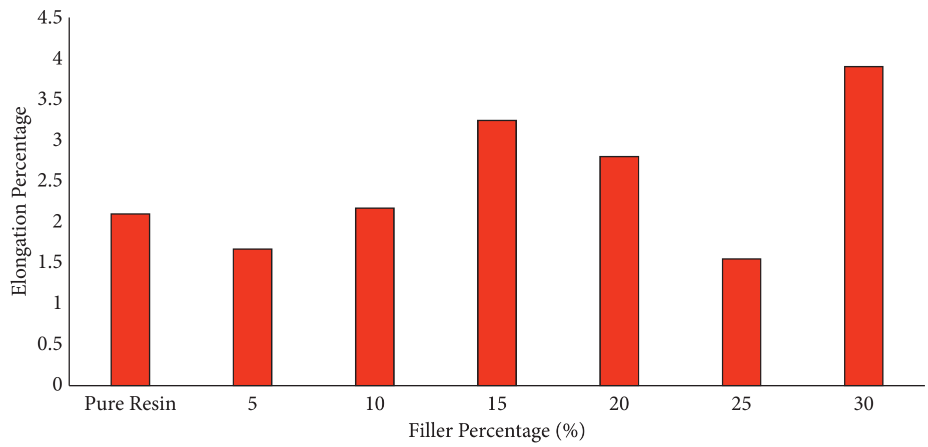

Figure 4: Influence of filler loading on the elongation of the TMS/PNS-VE composite.

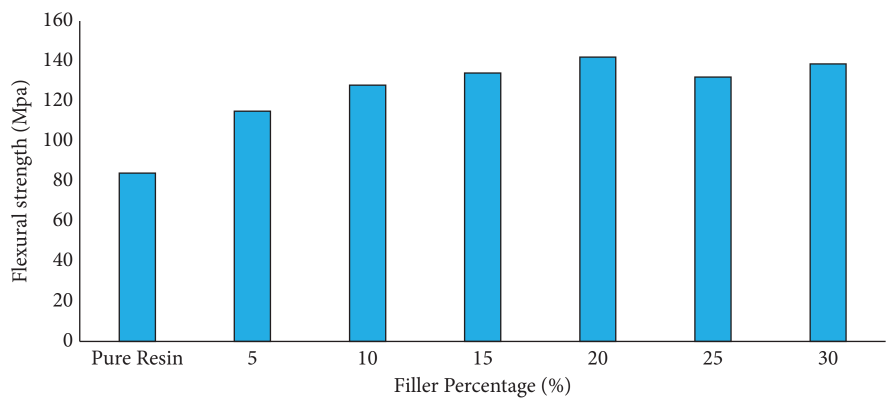

Figure 5: Influence of filler loading on the flexural strength of the TMS/PNS-VE composite.

particle reduces matrix weight, affecting the stress distribution rate between the matrix and filler [35]. The SEM images in Figure 6 examining the flexural fracture surfaces provide insights into the composite's ability to withstand bending loads. At 20 wt% filler content, where the flexural strength reached its maximum (142 MPa), the SEM micrograph in Figure 6(a) shows a cohesive and well-bonded filler-matrix interface. The absence of significant voids or debonding at this concentration underscores the efficacy of the TMS/PNS hybrid filler in reinforcing the composite. This is reflected in the enhanced bonding and load transfer capabilities, as observed in the mechanical test results. However, with further increase in filler content, the SEM image in Figure 6(b) reveals more pronounced voids and poor interfacial bonding, contributing to a decrease in flexural strength. This observation supports the findings that beyond 25% filler concentration, the mechanical properties tend to deteriorate due to factors such as particle agglomeration and reduced matrix weight, affecting stress distribution between the matrix and filler.

3.3. Impact Test. The impact test was continued until all of the impact samples were shattered. The impact strength findings that were achieved from using different filler weight percentages in TMS/PNS-VE composites are depicted in Figure 7. As a result of increased hybrid filler loading, the TMS/PNS-VE specimens' impact strength increased between 12.6 kJ/m^2 and 16 kJ/m^2, going from 5 to 20 wt.%. This increased the value range by varying the filler loading between 0 and 5 wt.%, and there is an increase in the strength from 12.4 kJ/m^2 to 12.6 kJ/m^2. Compared to the effect of energy caused by pure resin, the impact caused by a composite containing 5 wt.% of hybrid filler vinyl ester increases by 1.02 times. A possible reason for this is that only a tiny amount of the filler was used to make the composites. Compared to the impact strength of the TMS/PNS-VE hybrid composite with a filler content of 5 wt.%, the material's impact strength is somewhat diminished when the filler level is increased to 10 wt.%. If the weight content was increased by about 20 wt.%, the impact resistance of the TMS/PNS-VE composite was measured at 16 kJ/m^2, owing to the increase in load transfer between the filler and matrix. Compared with the impact strength of pure resin, an increase in TMS/PNS of 20 wt.% resulted in a factor of 1.29 percent increase in impact strength. After increasing the filler percentage load from 20 to 25 wt.%, the resistance to the impact of the TMS/PNS-VE composite material shows a significant decline, going from 16 kJ/m^2 to 14 kJ/m^2, suggesting a drop in performance. This decrease can be seen when comparing the two values. When there is a larger

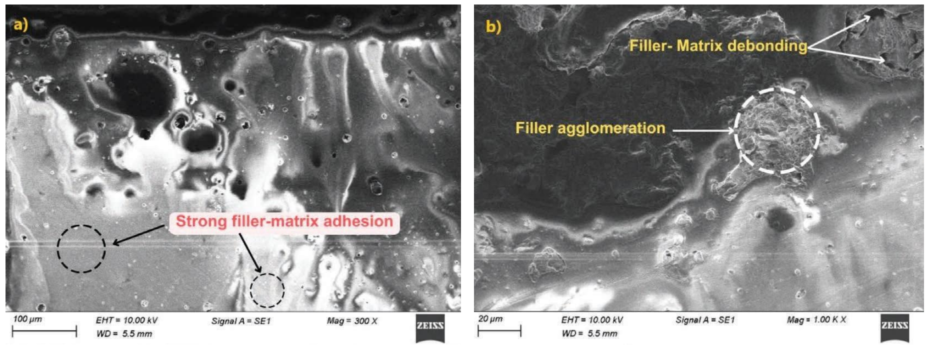

Figure 6: SEM images of fractured flexural surfaces of TMS/PNS vinyl ester composites with filler contents of (a) 20% and (b) 25% illustrating the microstructural differences.

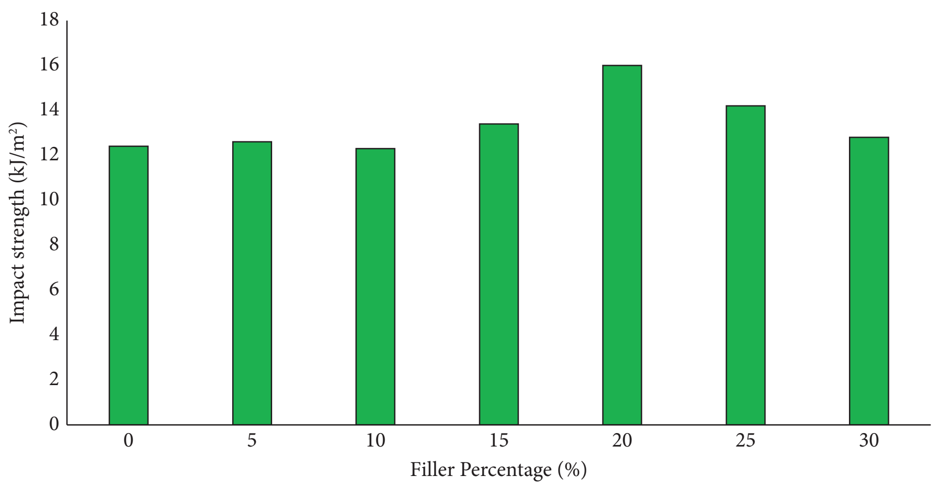

Figure 7: Effect of filler loading on the impact strength of the TMS/PNS-VE composite.

quantity of the filler, this occurrence will take place. When the volume of filler addition is increased in the range of 25–30 wt.%, the impact strength of the TMS/PNS-VE composite gets lowered by as much as 12.8 kJ/m^2, depending on the specific situation. This will likely occur if the filler is not dispersed equally throughout the matrix.

3.4. Heat Deflection Test (HDT). The heat deflection temperature is an important parameter to consider when determining whether or not a material can withstand high temperatures and conditions without becoming deformed; hence, a heat deflection temperature test (HDT) is carried out. Figure 8 illustrates the HDT of the TMS/PNS-VE composites at various weight ranges. The findings of the graph demonstrate that the HDT value of transparent resin is 55°C. The data also indicate that an increasing concentration of pure resin in TMS/PNS increases HDT values. This is shown by the fact that the HDT values have increased, which demonstrates the point. Despite increasing filler content to 25 wt.%, after that, the temperature rose to its actual capacity of 83°C, which is 1.51 times that of the efficiency of pure vinyl ester resin. This is the case even though the value had

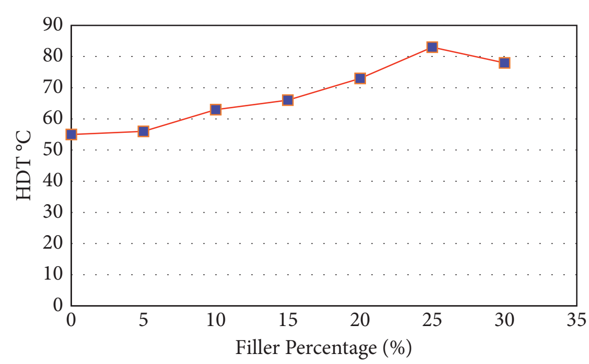

Figure 8: Variation in heat deflection temperature of the TMS/PNS-VE composite due to filler loading.

previously decreased. Compared with the performance of unaltered vinyl ester resin, which is only 0.75 times more remarkable, this is a highly significant difference. These data make it abundantly evident that the TMS/PNS filler possesses the most favorable thermal properties of the numerous natural fillers. This is the filler that includes acceptable thermal characteristics.

4. Conclusion

Waste TMS/PNS filler-reinforced hybrid vinyl ester composites were created as part of this work, and their consequent mechanical properties were studied. Following are the conclusions drawn from the findings of the experiments as a result of the data collected:

(1) According to mechanical test results performed on the specimen, the optimal strength in tensile, flexural, and impact was attained with a filler loading of 20 wt.%.

(2) The SEM analysis confirmed that the optimal filler content not only enhances mechanical properties but also ensures uniform filler distribution and strong filler-matrix bonding, which is critical for the structural integrity of composites.

(3) The HDT of the composites reaches its maximum value when they have a filler content of 25 wt.%.

(4) A weight ratio of 20 wt.% of the TMS/PNS hybrid filler to VE composites is the optimal weight ratio, as determined by the peak tensile strength value of 40.3 MPa.

(5) The highest bending stress in the fabricated composite, around 142 MPa, is attained when 20 wt. % of hybrid filler is utilized; similarly, the impact strength reaches its peak at this wt.%, which is 16 kJ/m^2.

According to these findings, the hybrid filler composite can fabricate lightweight load-carrying applications in structural and domestic fields. Our findings demonstrate the effectiveness of tamarind seed and peanut shell powder in enhancing the mechanical and thermal properties of vinyl ester composites and highlight the potential of these biowastes in paving the way for more sustainable and environmentally friendly material solutions in various industrial applications.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

This study was performed as a part of the employment of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. K. Thomas, J. Parameswaranpillai, S. Krishnasamy et al., "A comprehensive review on cellulose, chitin, and starch as fillers in natural rubber biocomposites," *Carbohydrate Polymer Technologies and Applications*, vol. 2, Article ID 100095, 2021.

[2] O. Das, K. Babu, V. Shanmugam et al., "Natural and industrial wastes for sustainable and renewable polymer composites," *Renewable and Sustainable Energy Reviews*, vol. 158, Article ID 112054, 2022.

[3] S. M. Rangappa, S. Siengchin, J. Parameswaranpillai, M. Jawaid, and T. Ozbakkaloglu, "Lignocellulosic fiber reinforced composites: progress, performance, properties, applications, and future perspectives," *Polymer Composites*, vol. 43, no. 2, pp. 645–691, 2022.

[4] M. Barczewski, D. Matykiewicz, A. Piasecki, and M. Szostak, "Polyethylene green composites modified with post agricultural waste filler: thermo-mechanical and damping properties," *Composite Interfaces*, vol. 25, no. 4, pp. 287–299, 2018.

[5] P. Jagadeesh, M. Puttegowda, Y. G. Thyavihalli Girijappa, S. M. Rangappa, and S. Siengchin, "Effect of natural filler materials on fiber reinforced hybrid polymer composites: an Overview," *Journal of Natural Fibers*, vol. 19, no. 11, pp. 4132–4147, 2022.

[6] K. R. Srinivas, T. Achamyeleh, B. Somanath, and K. B. Murali, "Experimental investigation of mechanical properties for tamarind shell particles as filler in epoxy composite," *International Journal of Engineering Research & Technology*, vol. 3, pp. 40–49, 2017.

[7] H. Singh and T. Singh, "Effect of fillers of various sizes on mechanical characterization of natural fiber polymer hybrid composites: a review," *Materials Today: Proceedings*, vol. 18, pp. 5345–5350, 2019.

[8] R. Garadimani, G. U. Raju, and K. G. Kodancha, "Study on mechanical properties of corn cob particle and e-glass fiber reinforced hybrid polymer composites," *American Journal of Materials Science*, vol. 5, no. 3, pp. 86–91, 2015.

[9] C. Hemalatha and S. Parameshwari, "The scope of tamarind (*Tamarindus indica* L.) kernel powder in diverse spheres: a review," *Materials Today: Proceedings*, vol. 45, pp. 8144–8148, 2021.

[10] O. Oulidi, A. Nakkabi, F. Boukhlifi et al., "Peanut shell from agricultural wastes as a sustainable filler for polyamide biocomposites fabrication," *Journal of King Saud University Science*, vol. 34, no. 6, Article ID 102148, 2022.

[11] M. N. Prabhakar, A. U. R. Shah, K. C. Rao, and J. I. Song, "Mechanical and thermal properties of epoxy composites reinforced with waste peanut shell powder as a bio-filler," *Fibers and Polymers*, vol. 16, no. 5, pp. 1119–1124, 2015.

[12] H. Ku, M. Prajapati, and M. Trada, "Fracture toughness of vinyl ester composites reinforced with sawdust and postcured in microwaves," *International Journal of Microwave Science and Technology*, vol. 2012, Article ID 152726, 8 pages, 2012.

[13] P. Jeyaprakash, A. Arul Marcel Moshi, S. Rathinavel, and A. G. Babu, "Mechanical property analysis on powderized tamarind seed-palm natural fiber hybrid composites," *Materials Today: Proceedings*, vol. 43, pp. 1919–1923, 2021.

[14] G. Santosh and V. Shetty, "Comparative study on mechanical properties of tamarind shell and groundnut shell particles reinforced epoxy composite," *International Research Journal of Engineering and Technology*, vol. 52, p. 2395, 2017.

[15] N. Nagaprasad, V. Vignesh, N. B. Karthik Babu, P. Manimaran, B. Stalin, and K. Ramaswamy, "Effect of green hybrid fillers loading on mechanical and thermal properties of vinyl ester composites," *Polymer Composites*, vol. 43, no. 11, pp. 7928–7939, 2022.

[16] T. V. Aradhyula, D. Bian, A. B. Reddy et al., "Compounding and the mechanical properties of catla fish scales reinforced-polypropylene composite–from biowaste to biomaterial," *Advanced Composite Materials*, vol. 29, no. 2, pp. 115–128, 2020.

[17] S. Abhishek, M. R. Sanjay, R. George, S. Siengchin, J. Parameswaranpillai, and C. I. Pruncu, "Development of new hybrid Phoenix pusilla/carbon/fish bone filler reinforced polymer composites," *Journal of the Chinese Advanced Materials Society*, vol. 6, no. 4, pp. 553–560, 2018.

[18] A. J. Olumuyiwa, T. S. Isaac, and S. O. Samuel, "Study of mechanical behaviour of coconut shell reinforced polymer matrix composite," *Journal of Minerals and Materials Characterization and Engineering*, vol. 11, no. 8, pp. 774–779, 2012.

[19] D. Jagadeesh, P. Sudhakara, C. V. Prasad, H. Kim, J. I. Song, and J. I. Song, "A study on the mechanical properties of bio composites from renewable agro-waste/poly (lactic acid)," *Journal of Biobased Materials and Bioenergy*, vol. 7, no. 1, pp. 163–168, 2013.

[20] N. Saba, M. T. Paridah, K. Abdan, and N. A. Ibrahim, "Effect of oil palm nano filler on mechanical and morphological properties of kenaf reinforced epoxy composites," *Construction and Building Materials*, vol. 123, pp. 15–26, 2016.

[21] N. Nagaraj, S. Balasubramaniam, V. Venkataraman, R. Manickam, R. Nagarajan, and I. Sikiru Oluwarotimi, "Effect of cellulosic filler loading on mechanical and thermal properties of date palm seed/vinyl ester composites," *International Journal of Biological Macromolecules*, vol. 147, pp. 53–66, 2020.

[22] V. Vignesh, A. N. Balaji, and M. K. V. Karthikeyan, "Effect of wood sawdust filler on the mechanical properties of Indian mallow fiber yarn mat reinforced with polyester composites," *International Journal of Polymer Analysis and Characterization*, vol. 22, no. 7, pp. 610–621, 2017.

[23] B. Stalin and A. Athijayamani, "The performance of bio waste fibres reinforced polymer hybrid composite," *International Journal of Materials Engineering Innovation*, vol. 7, no. 1, pp. 15–25, 2016.

[24] B. Stalin, N. Nagaprasad, V. Vignesh, and M. Ravichandran, "Evaluation of mechanical and thermal properties of tamarind seed filler reinforced vinyl ester composites," *Journal of Vinyl and Additive Technology*, vol. 25, no. 2, pp. E114–E128, 2019.

[25] V. Mahesh, R. Gobinath, M. S. Kırgız, R. P. Shekar, and M. Shewale, "Global trends of research productivity in natural fibre reinforced composites: comprehensive scientometric analysis," *Journal of Natural Fibers*, vol. 19, no. 16, pp. 13088–13105, 2022.

[26] J. Sridhar, R. Gobinath, and M. S. Kırgız, "Comparative study for efficacy of chemically treated jute fiber and bamboo fiber on the properties of reinforced concrete beams," *Journal of Natural Fibers*, vol. 19, no. 15, pp. 12224–12234, 2022.

[27] H. Y. B. Katman, W. J. Khai, N. Bheel, M. S. Kırgız, A. Kumar, and O. Benjeddou, "Fabrication and characterization of cement-based hybrid concrete containing coir fiber for advancing concrete construction," *Buildings*, vol. 12, no. 9, p. 1450, 2022.

[28] J. Sridhar, R. Gobinath, and M. S. Kırgız, "Evaluation of artificial neural network predicted mechanical properties of jute and bamboo fiber reinforced concrete along with silica fume," *Journal of Natural Fibers*, vol. 20, no. 1, Article ID 2162186, 2023.

[29] N. Bheel, M. O. Ali, M. S. Kırgız, N. Shafiq, and R. Gobinath, "Effect of graphene oxide particle as nanomaterial in the production of engineered cementitious composites including superplasticizer, fly ash, and polyvinyl alcohol fiber, ICRAMM-2022," *Materials Today: Proceedings*, vol. 13, 2022.

[30] K. Ramaswamy, L. T. Jule, and K. Subramanian, "Seenivasan and others, Reduction of environmental chemicals, toxicity and particulate matter in wet scrubber device to achieve zero emissions," *Scientific Reports*, vol. 12, pp. 1–10, 2022.

[31] K. Thirumalai Raja, N. Jayanthi, J. Leta Tesfaye, N. Nagaprasad, R. Krishnaraj, and V. S. Kaushik, "Using an artificial neural network to validate and predict the physical properties of self-compacting concrete," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 1206512, 10 pages, 2022.

[32] A. Saka, L. T. Jule, L. Gudata et al., "Preparation of biobutanol via coffee bean harsh extracts by zinc oxide nanoparticle as catalyst," *Biomass Conversion and Biorefinery*, vol. 52, pp. 1–10, 2022.

[33] A. Saka, L. T. Jule, S. Soressa et al., "Biological approach synthesis and characterization of iron sulfide (FeS) thin films from banana peel extract for contamination of environmental remediation," *Scientific Reports*, vol. 12, pp. 10486–10488, 2022.

[34] K. U. Maheswari, M. Thilak, N. SenthilKumar et al., "Regression analysis on forward modeling of diffuse optical tomography system for carcinoma cell detection," *Scientific Reports*, vol. 13, no. 1, p. 2406, 2023.

[35] V. K. Shravanabelagola Nagaraja Setty, G. Govardhan, S. Mavinkere Rangappa, S. Siengchin, and S. Siengchin, "Raw and chemically treated bio waste filled (Limonia acidissima shell powder) vinyl ester composites: physical, mechanical, moisture absorption properties, and microstructure analysis," *Journal of Vinyl and Additive Technology*, vol. 27, no. 1, pp. 97–107, 2021.