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Plant-Drive Natural Fiber Reinforced Thermoplastic Composites by Film Stacking Method

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Abstract

Fiber reinforced polymer composites have a long history of being significant in a variety of applications because of their exceptional specific strength and modulus. An alternative to synthetic polymers that pollute the environment is provided by thermoplastic and vetiver fiber (VF) composites. In comparison to conventional reinforcing fibers (glass and carbon fiber), natural fibers (such as banana, sisal, coir, jute, vetiver, flax, hemp, and kenaf) have the following benefits: they are easier to obtain, renewable, noncorrosive, light density, biodegradable, have a high specific energy (strength of density ratio), and are less expensive. An inexpensive and ecologically friendly alternative to the costly chemical treatment of VF in polymer composites is VF length control. VF-reinforced low-density polyethylene (LDPE) composites were modified in the current study by utilizing the hot press compression molding technique in conjunction with the film process stacking method. A range of process parameters were employed, including VF condition (untreated and treated with sodium dodecyl sulfate (SDS)), VF sizes (short-VF is less than three centimeters and long-VF is greater than three centimeters), and VF percent (5, 10, and 15 weight %). The tensile modulus and modulus efficiency factor of the LDPE composite were examined in relation to the impacts of VF size, VF content, and SDS treatment. The results shown that, as a result of increased load bearing and interfacial adhesion, VF content up to 10 wt. %, processing temperature up to 160°C, and SDS treatment during processing for up to five hours, all increased a certain amount of tensile modulus and modulus efficiency factor. Long-VF load transfers have obviously had a positive effect, as seen by the improvement in tensile modulus and its efficiency factor as a result of efficient load transfer. The fibers' brittleness led to a decrease in their ductility.

Keywords: Composite, natural fiber, LDPE, sodium dodecyl sulfate-treatment, tensile properties

INTRODUCTION

The usage of synthetic fibers in polymer-based composites is decreasing due to their expensive cost and possible negative effects on human health and the environment. The use of natural fibers (NFs) as an alternative fiber reinforcement material has increased rapidly in several areas of polymer composites nowadays [1–4]. NF composites are now widely used in many different industries, including manufacturing, electrical and electronic equipment, civil and mechanical construction, auto factories, aircraft manufacturing, and many more [5–8]. The exceptional and distinctive blend of mechanical and physical properties possessed by these materials accounts for this. Synthetic composites, such as those made of glass, carbon, nylon, and Kevlar, and consisting of synthetic fibers and matrix bases, have been extensively studied [9, 10]. NF augmented composites are not as strong, durable, degradation resistant, or moisture resistant as synthetic fiber reinforced thermoset or thermoplastic composites. Because thermoplastic composites are less expensive to create and require less processing than

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thermosets, scientists prefer them. The use of synthetic fibers can harm the environment since they are unhygienic.

The matrix is being explored on a daily basis because lignocellulosic components are being created from fibers and thermoplastic/thermoset polymers as composites due to increased environmental consciousness. Compared to synthetic or traditional plastic components, NFs offer several advantages, such as low cost, low density, the necessary strength, renewability, recyclability, and biodegradability.

Crops used in agroforestry provide plant fibers, which are recyclable materials used in many engineering specialties. In addition to being thermally recyclable and renewable, plant fibers pose fewer dangers to the health and safety of employees. As an environment-friendly substitute for glass fibers in engineering composites, plant fibers such as jute, vetiver, flax, banana, and Calotropis gigantea make attractive reinforcement materials. When it comes to NFs, vegetable grass is one of the best options for use as an additional layer of reinforcement in polymer composites. Another name for the perennial grass *Chrysopogon zizanioides*, often known as vetiver, is *Vetiveria zizanioides*, which is a former scientific name. Vietnam, Thailand, Bangladesh, India, and other countries are the top producers of vetiver grass. Vegetable roots can grow up to five meters long and have strong mechanical properties. [11]. The lignocellulosic biofiber known as vetiver grass fiber contains hemicellulose, cellulose-type-I, lignin, and other low-molecular weight components. VFs can specifically take the place of glass fibers when cheap cost and low density are taken into account. VFs can be recycled, are nonabrasive, and can be used for energy recovery because of their high-calorific value and reduced health and safety risks when working with fiber products. They also possess good mechanical strength, low density, availability, biodegradability, safety from health risks, and affordability [12, 13]. To gain acceptance in extensive technical applications such as the automotive and construction sectors, NFs need to demonstrate an exceptional price–performance ratio, lightweight design, and environmentally friendly attributes [14].

It holds a leading position with respect to a range of materials utilized in the plastics sector, such as polythene (PE), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP) [15]. When these materials are burned or land filled after their useful lives, environmental problems arise [16]. This problem can be resolved by lowering the amount of NF mixes used in the creation of composite materials [17]. When employed in plastic composites, natural reinforcing fillers can be economical and have a big impact on helping to solve ecological problems that we might encounter in the future [18]. In this investigation, NFs and the polymers like low-density polyethylene (LDPE) and VF were used as the matrix to generate a plastic composite. LDPE is a common thermoplastic material that is molded into a range of laboratory equipment, bags, dispensing bottles, and cleaning bottles. LDPEs provide environmental problems when disposed of because of their long service lives and chemical stability. However, LDPE can be coupled with natural filler to create composites for the designated technological purpose without losing the materials' advantages in terms of cost and ecology. The addition of unaltered NFs typically highlights the weak points and irregularities of the composite because of the polarity mismatch between the hydrophilic natural filler and the hydrophobic polymer matrix [19–21]. By using wetting agents to increase the interfacial adhesion between VFs and the LDPE matrix, composites can have better mechanical properties. NFs are often chemically treated (e.g., alkaline treatment [22], silane treatment [23], and usage of compatibilizers [24] to increase the interfacial adhesion between fibers and polymers before the production of composites. In turn, this improves the composites' mechanical qualities. A strong coupling agent, sodium dodecyl sulfate (SDS), can be used to improve the coupling and contact between VF and the LDPE matrix. However, none of the studies that have been conducted on NF characteristics have examined the surface of VFs that have been treated with SDS.

In this investigation, the SDS was employed as a coupling agent to enhance the properties of the LDPE/VF composites. SDS is an anionic surfactant that is commonly utilized in the manufacturing of biomaterials [25]. According to certain studies, SDS was utilized as a coupling agent to improve the filler-matrix adhesion between recycled PP from coconut shells [26].

In this work, hot compression molding was used to create LDPE composites reinforced with vetiver fiber (VF) under varied processing conditions. The purpose of this study was to ascertain the effects of the manufactured composites' tensile modulus, modulus efficacy factor, and ductility on the amount of fiber utilized, the fibers' length, the processing temperature, and the processing time of the SDS treatment of VF.

EXPERIMENTAL PROCEDURE

Ingredients

As a polymeric matrix, LDPE with a melting flow index (MFI) of 4.0 g/10 min was provided by Polyolefin Company, Pvt. Ltd., Singapore.

The raw vetiver root was purchased from local vendors in Bangladesh. In Table 1 [27], the properties and ingredients of VFs are listed.

Table 1. Lists the traits and chemical composition of VFs [27].

Properties	**Value**
Density (g/cm^3)	1.5
Diameter (μm)	100–220
Tensile strength (MPa)	247–723
Young's modulus (GPa)	12.0–49.8
Failure strain (%)	1.6–2.4
Composition	
Cellulose	72.6%
Lignin	17%

METHODS

Manufacturing of VF-Reinforced LDPE Composites

VF was employed in a variety of shapes to strengthen the composites: untreated long fiber, or ULVF (more than 3 cm), and untreated short fiber, or untreated short VF (USVF; less than 3 cm). After being cleaned with distilled water and left to dry in the sun for 48 hours, the moisture content of the VFs was less than 4%. After being allowed to dry, the VFs were cut to the required lengths using scissors. Randomly distributed fibers with equivalent fiber volume contents of 0% (i.e., virgin resin), 10%, 20%, and 30%, respectively, were used to generate short and long fiber composites. The following relationship [28] is used to compute the volume fraction of fiber (V_f).

$$V_f = \frac{(W_f/\rho_f)}{(W_f/\rho_f)+(W_m/\rho_m)} \tag{1}$$

where W_f and W_m are the weights of the fiber and matrix (in g), respectively, and ρ_f and ρ_m are the reinforcement and matrix densities (in g/cm^3). With a minimum of 1.23 g/cm^3 and a maximum of 1.32 g/cm^3, the average density of 1.3 g/cm^3 was used to determine the fiber volume percent. VF had a different density than LDPE, which had a density of 0.92 g/cm^3.

Applying the modified rules of mixing as stated in Equation (2) will yield the tensile modulus of a composite material.

$$E_c = \alpha E_f V_f + E_m(1 - V_f) \tag{2}$$

$$or, \alpha = \frac{E_c - E_m(1 - V_f)}{V_f E_f} \tag{3}$$

The terms E_c, E_f, E_m, V_f, and stand for the tensile moduli of the composite material, the fibers, the matrix, the fiber volume fraction, and the modulus efficiency factor (MEF).

The fiber length, location, distribution, and resin wetting of the fibers are some of the elements that affect the MEF [29]. Although the minimum and maximum VF moduli were 10.1 GPa and 19.6 GPa, respectively, the tensile modulus of LDPE was 275 MPa. The VF MEF was calculated using the mean value of 14.5 GPa.

A hot press machine was used to create samples of LDPE/VF composite and LDPE sheets. Two metal plates that can be electrically heated, compressed by an air piston to produce pressure, and equipped with a cooling system make up the hot press machine. There were two procedures involved in the production of thermoplastic composites. After compressing the LDPE granules for about 10 minutes at 150°C and 8 MPa of pressure, the resulting sheets were cooled using a cooling water system for the necessary 10–15 minutes. The fibers were put at random between two polymeric sheets using the film stacking strategy, which was the second technique utilized to create the composite samples. The sheets were then heated using a hot press machine. Randomly organized short and long fibers were placed between two sheets of LDPE, hot pressed under the same processing conditions, and examined to see how fiber length and content affected the tensile features of composites.

To make SDS solution, 40°C was the temperature at which SDS powder was dissolved in ethanol. A quantity of SDS equal to 3% of the weight of the fiber was used. The mixture was then allowed to cool to room temperature.

To investigate the effect of SDS treatment on the tensile modulus of the resulting composites, short VFs were immersed in this solution for one, three, and five hours at room temperature. The same machine and processing configuration were then used to create short VFs-based composites treated with 10% weight percent SDS. The impact of processing temperature on the tensile modulus of the resulting composite was examined by preparing five samples, each containing 10 wt% of USVF, at various processing temperatures (120°C, 140°C, 160°C, 180°C, and 200°C).

Tensile Analysis of the Generated Samples

A Sinowon testing machine (ST series) was used to assess the samples’ tensile properties at room temperature at a steady speed of 4 mm/min.

Each composite was assessed using five specimens that measured 20 mm in width, 70 mm in length, and 2 mm in thickness. The industry standard test method for plastic tensile properties, ASTM D638-14, was followed in the performance of the test.

RESULTS AND DISCUSSION

Mechanical Properties of Composite Materials

The fiber–matrix interfacial bond strength, processing temperatures, fiber content, and fiber diameters were all highly impacted by the composites’ tensile characteristics. The interfacial bonding and dispersion between the hydrophilic filler and the hydrophobic matrix dictate the composite’s flexural characteristics. Figure 1 illustrates the impact of short fiber contents on the tensile modulus of the resulting composites. Figure 1 shows how the tensile modulus of the resultant composites increases with increasing fiber concentrations. It reaches its maximum value at 10 wt. %, after which it begins to decrease.

Since it is widely acknowledged that the strong interfacial adhesion and dispersion of reinforcements throughout the matrix is what causes the increase in tensile modulus, the mobility of polymer chains is limited under loading. These findings suggest that VFs have a strong strengthening and distributional impact.

Composites with higher VF content have a much lower tensile modulus as a result of improper mixing between LDPE and VF during the production process. Stress transfer between LDPE and VF is inhibited, for instance, in a composite with a 15 wt% VF content because of some weaker LDPE sections. Conversely, problems with mixing that occur during the manufacturing process can result in voids and defects that can act as a crack tip and accelerate the composite's premature failure [30].

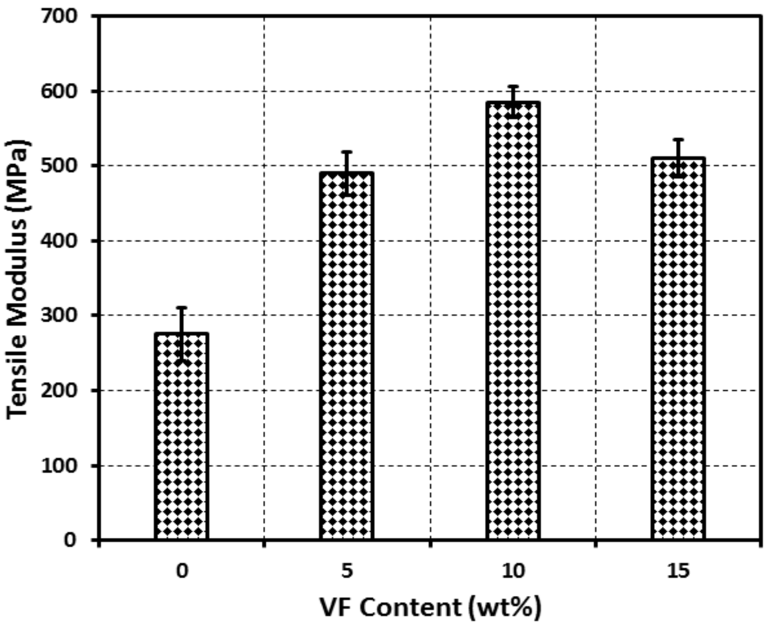

Figure 1. Effect of USVF content on the manufactured composite's' tensile modulus.

Figure 2 shows the MEF as a function of fiber volume percent (V_f) for LDPE composites reinforced with USVF. As the volume percent of the fiber grows, Figure 2 illustrates a decrease in the MEF, suggesting a decrease in interfacial adhesion. This phenomenon can be explained by the matrix's fibers failing to impregnate.

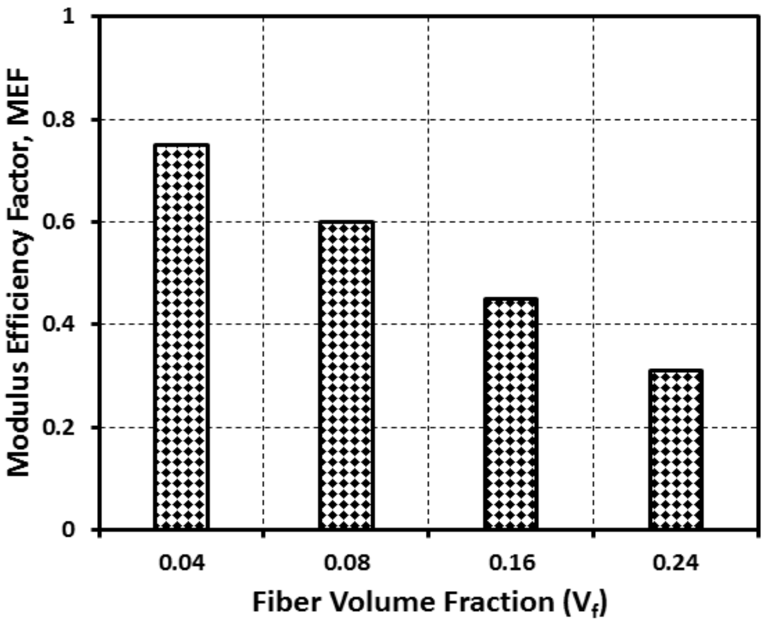

Figure 2. Effect of USVF content on the manufactured composite's MEF.

The ductility of composites was calculated as a percentage of elongation using Equation (4):

$$\%EL = \frac{L_f - L_o}{L_o} \times 100 \tag{4}$$

Where %EL, L_f, and L_0 are the sample's final and initial lengths, as well as the percentage of elongation.

Because the brittle nature of the VFs limits the composite's plasticity behavior in compared to the virgin LDPE matrix, Figure 3 shows that the ductility of LDPE diminishes as VF concentration grows.

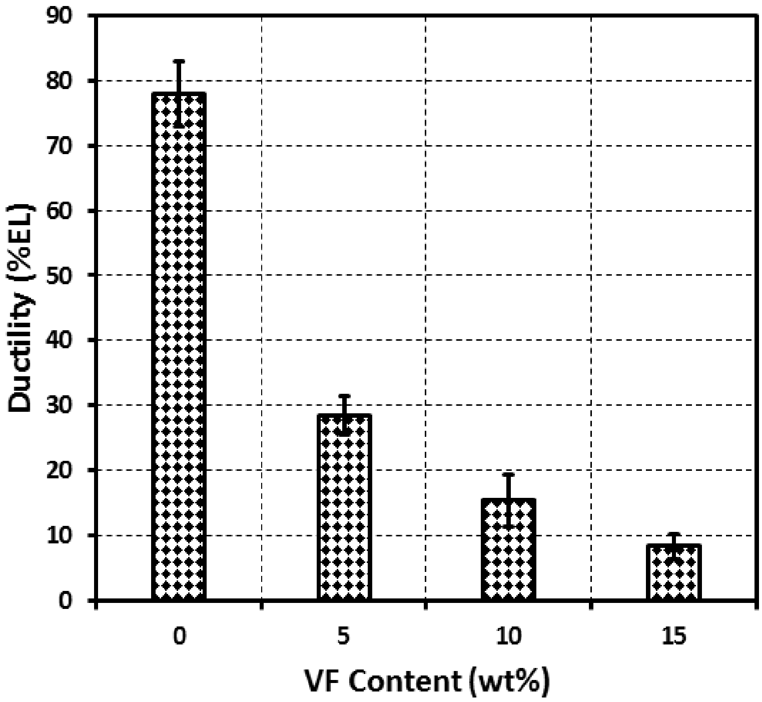

Figure 3. Effect of USVF content on the manufactured composite's ductility (%EL).

As seen in Figure 4, composites with long fibers have a higher tensile modulus than those with short fibers. This can be explained by the fact that the shearing process between the matrix and the fibers transfers the tensile load applied to discontinuous fiber composites to the fibers.

There is a dispersion of shear stress at the fiber–matrix interface because the polymeric matrix is under higher strain than the nearby fibers. When tensile stresses are applied to fibers, the shearing stress in the matrix that is utilized to do so is highest near the ends of the fibers. Tensile stresses, on the other hand, start at zero at the ends and increase gradually to a plateau value in the center of the fibers. Consequently, the fiber segments near their ends experience reduced tension in comparison to their middle region. Thus, the stress borne by the fibers increases as their length increases. This is commonly understood to mean the total length of fibers required for the tensile load to plateau or reach its maximum value. Fiber length has been shown to boost the tensile strength of composite materials [31].

When long fibers are used, Figure 5 demonstrates that the MEFs of the composites are larger than those of the composites with short fibers. This is related to the degree to which stress is transferred from the polymeric matrix to the fibers.

Because of their effects on the impregnation of reinforcements, processing temperature, pressure, and time have a significant impact on the mechanical properties of composite materials.

These factors were found to have a major effect on the unidirectional long Kenaf fiber-reinforced polylactic acid composite's tensile strength [32]. Figure 6 displays the tensile modulus of ULVF/LDPE composites made of untreated long VF as a function of processing temperature. Figure 6 illustrates how raising the processing temperature to 160°C improves the composite's tensile modulus. Volumetric flow is enhanced by raising the processing temperature, which is related to how LDPE melting viscosity is impacted by processing temperature. Improved compaction and fewer voids in the finished composite are the results of an LDPE melting rate brought on by a drop in the viscosity of the polymeric molten state. But as shown in Figure 6, increasing the processing temperature above 160°C lowers the tensile modulus of the resulting composites. This has to do with the fact that, due to structural degradation, cellulosic reinforcements begin to lose their strength at temperatures higher than 160°C.

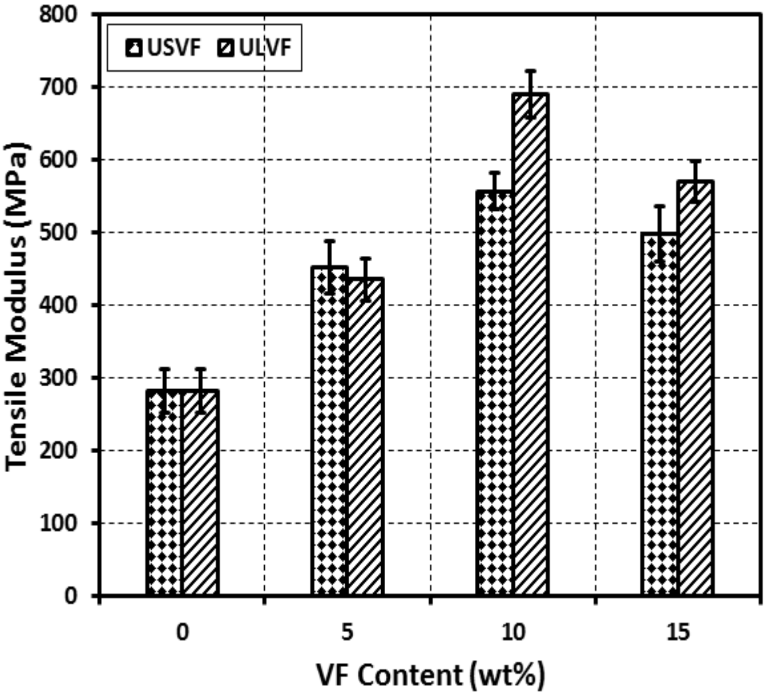

Figure 4. Effect of fiber length on produced composite's tensile modulus.

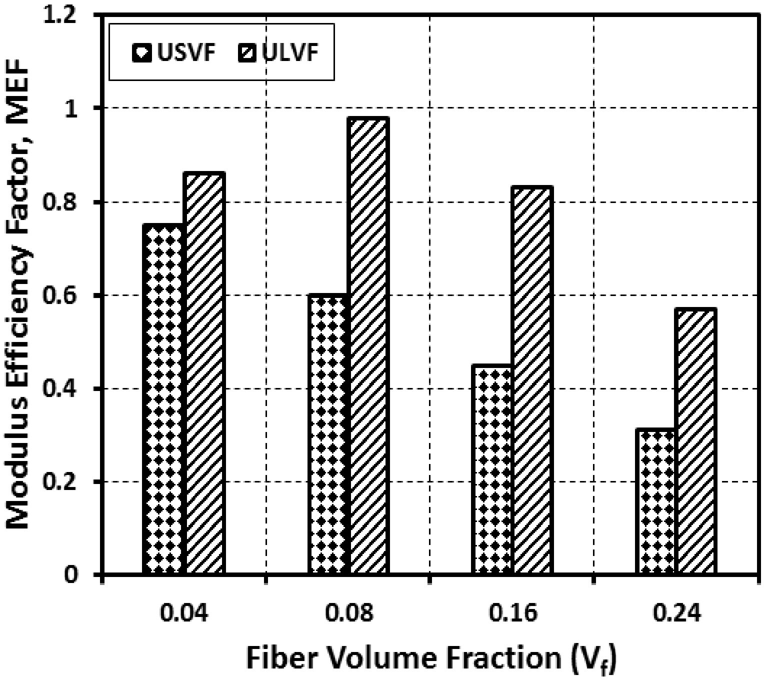

Figure 5. Effect of fiber length on produced composite's MEF.

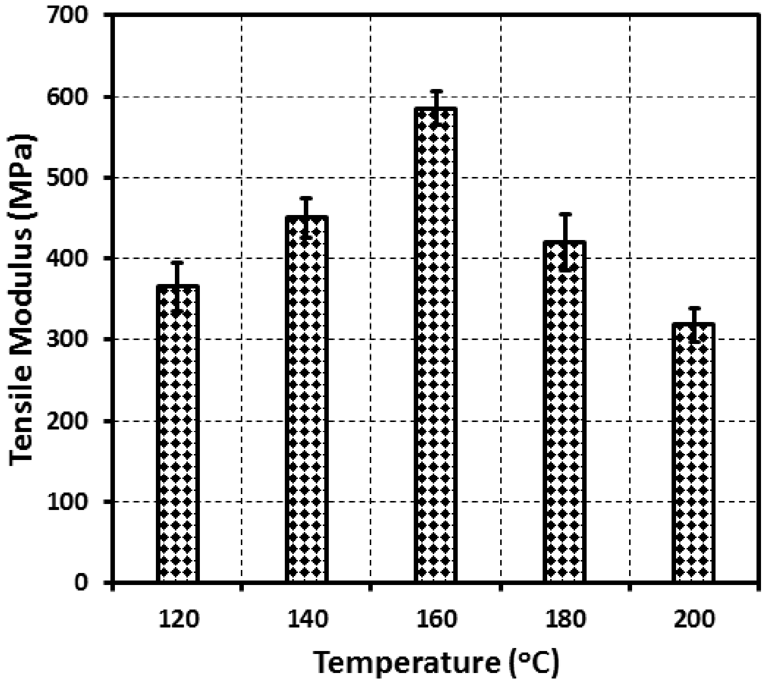

Figure 6. Tensile modulus impacts in relation to processing temperature.

Figure 7 illustrates how the MEF climbs until 160°C before starting to decrease as the processing temperature rises.

Raising the processing temperature causes the MEF to increase as well, which enhances the VF gestation rate and decreases the void content because VF loses mechanical characteristics at high temperatures.

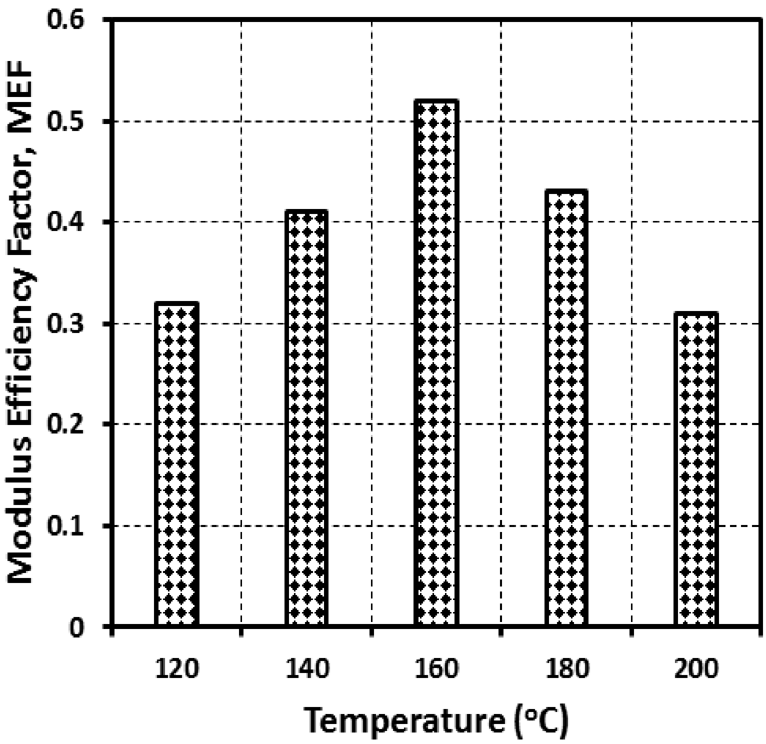

Figure 7. MEF effects as a function of processing temperature.

Figure panels 8(a) and 8(b) display, as functions of SDS treatment time, the tensile modulus and MEF of SDS treatment of VF-reinforced LDPE composites. The tensile modulus of the composites has increased as the SDS treatment period has increased, as shown in Figure 8(a). The impact of SDS treatment on the genesis of VF explains this.

NFs are produced by tiny fibril linkages that are attached to noncellulosic substances such as hemicellulose, lignin, pectin, wax, and oil coating material; consequently, the molecular structure of cellulosic materials is altered by SDS treatment by altering the configuration of densely packed crystalline cellulose. The fibers split into smaller fibrils as a result of the elimination of these components, improving the fiber size ratio (length/diameter) as a result of the decreased fiber diameter and enabling the fibrils to realign themselves in the direction of the applied flexible load. SDS treatment not only results in clean, coarse fibrils that aid in mechanical interlocking and bonding, but it also changes the hydrophilic characteristics of VF, improving their compatibility with the hydrophobic LDPE matrix. Consequently, there is improved contact adhesion between the VF and the LDPE matrix.

The MEF, which is seen in Figure 8(b) as rising with time during the SDS treatment, is linked to the expansion of the interfacial adhesion between the VFs and the LDPE matrix. The tensile and flexible properties of ramie fiber reinforced epoxy composite were found to be enhanced by the use of SDS-treated ramie fiber [33].

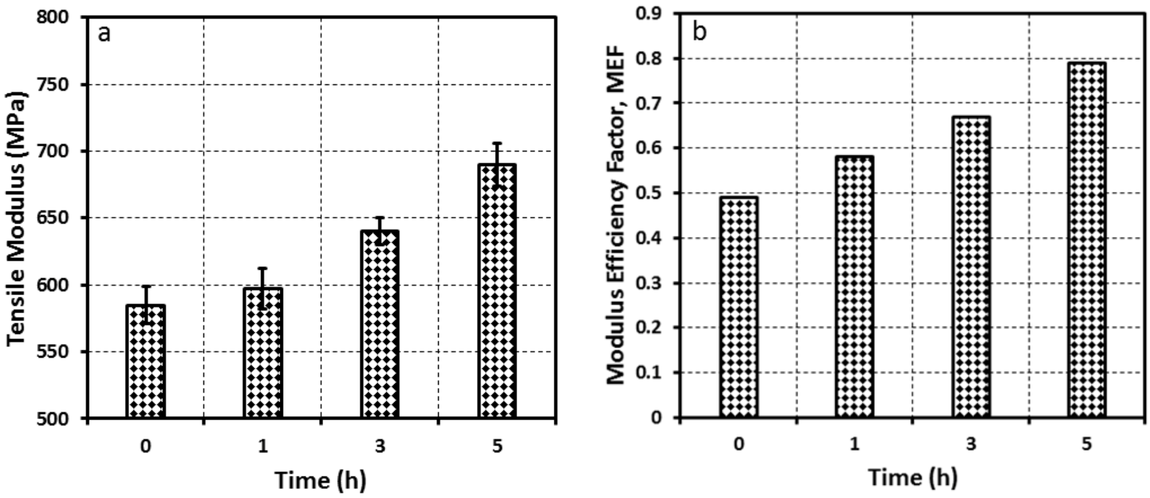

Figure 8. (a) Tensile modulus and (b) MEF of the produced composites as a function of the SDS treatment period.

CONCLUSIONS

The tensile modulus of VF–LDPE composites was found to be improved by adding up to 10% of short VFs, but it was shown to be decreased when high fiber contents were utilized because of inadequate impregnation, which raised the void content and lowered the MEF. Conversely, as a result of the brittle character of the fibers, increasing the ratio of short fibers reduced the ductility of the composites. Because long fibers transfer stress between the fibers and the matrix more effectively as they get longer, using long fibers improved the tensile modulus of the composites to a greater extent.

In comparison to composites made of short VFs, those made of long fibers have a higher MEF. Due to its effect on LDPE viscosity, which reduces void content through improved VF impregnation and raises the MEF, processing temperature was found to have an impact on the tensile modulus of the composites. All the same, the tensile modulus of the composites decreased at temperatures higher than 160°C, which might have something to do with the fibers breaking down. The MEF increases when the fibers and polymeric matrix have better interfacial adhesion due to the SDS treatment.

The tensile modulus of the composites was shown to increase due to the increase in interfacial adhesion; however, the extent of the improvement was found to be reliant on the duration of the SDS treatment.

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