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Tensile Modulus of Film Stacked Palm Fibers-LDPE Sheet Composites

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ABSTRACT

Palm fiber-LDPE composites were prepared by a film-stacking method studying the effects of fibers content, their length, processing temperature and alkaline treatment on tensile modulus and modulus efficiency factor. It was found that up to 5 wt.% and processing temperature to 160°C in addition to alkaline treatment improved the tensile modulus and modulus efficiency factor to a certain limit due to an enhancement in load carrying and interfacial adhesion, also it was obvious that long fibers play a positive role in load transfer; improving the tensile modulus and its efficiency factor due to effective load transfer. Ductility was decreased due to the brittle behavior of the fibers.

摘要

采用薄膜堆积法制备了棕榈纤维 LDPE 复合材料, 研究了纤维含量、长度、加工温度和碱处理对拉伸模量和模量效率因子的影响。结果表明, 高达5wt%的长纤维, 经碱处理后, 加工温度达到 160°C时, 由于承载力和界面结合力的提高, 拉伸模量和模量效率因子提高到一定程度, 长纤维对载荷传递起到了积极的作用; 通过有效载荷传递提高拉伸模量及其效率因子。由于纤维的脆性, 塑性略有下降。

KEYWORDS

Palm fibers; alkaline treatment; processing temperature; modulus of elasticity; ductility; modulus efficiency factor

关键词

关键词; 棕榈纤维; 碱性处理; 加工温度; 弹性模量; 延展性; 模数效率系数

Introduction

Synthetic polymers are used in many applications due to their low cost and lightweight, but they have low mechanical properties, so the best method to improve their mechanical properties is to reinforce them with suitable reinforcements. Organic and inorganic reinforcements were used to improve the mechanical properties of polymeric matrices such as polypropylene, polyethylene, and polystyrene. Inorganic reinforcements such as talc, carbon black, fly ash and calcium carbonate were used to reinforce both low-density polyethylene (LDPE) and high-density polyethylene (HDPE) (Parvin, Ullah, and Mina 2013, Kumar et al. 2012; Ahmad and Mahanwar 2010). The tensile strength of LDPE was found to decrease with the increase of talc and carbon black, whereas, the modulus of elasticity, hardness, and flexural strength was found to increase (Parvin, Ullah, and Mina 2013). The addition of fly ash was found to improve the mechanical, thermal and electrical properties of HDPE (Kumar et al. 2012, Ahmad and Mahanwar 2010). The effects of calcium carbonate content, its size and the use of stearic acid as a coupling agent on the tensile and thermal properties of recycled LDPE and calcium carbonate particles were investigated, the addition of calcium carbonate particles up to 15 wt.% was found to enhance the tensile properties of the produced composites. It was found that the addition of small filler particles resulted in a noticeable improvement of tensile strength and modulus of elasticity of composite materials compared with large filler particles (Ma'ali et al. 2018).

Natural reinforcements are derived from renewable resources and they have many advantages such as low cost and moderate mechanical properties, olive solid waste and wood flour were used to reinforce polyethylene, it was found that the contents and size of olive solid waste particle content had a big effects on the mechanical and thermal properties of the produced composites (Sawalha et al. 2018), while the impact energy, the hardness and the water absorption of HDPE were strongly affected by wood flour contents (Ma'ali et al. 2015).

Different types of natural fibers were used to improve the mechanical properties of different types of synthetic and natural polymers, the effects of fiber types and their contents and chemical treatments on the properties of the produced composites were investigated (Chun et al. 2017; Das, Adhikary, and Ray 2010; Miao and Hamad 2013; Satyanarayana 2015; Wang and Sain 2007). Increasing the natural fiber contents and the use of alkaline treated fibers were found to improve the mechanical properties of banana-epoxy resin, banana-vinyl ester resin and sisal fibers-epoxy resin-based composites, the effects of alkaline treatment were related to removal of the noncellulosic materials from the fibers (Somashekar and Shanthakumar 2014, Santhosh et al. 2014)

Sawalha et al. (2019) studied the effects of cellulosic materials extracted from different agricultural wastes such as corn stalks, olive solid waste and wood, and their contents on the mechanical and thermal properties of LDPE-based composites, it was observed that there is an increase in the modulus of elasticity of the produced composites and a decrease of ductility with the increase of cellulosic material content. The addition of cellulosic materials was found to affect both the melting temperature of LDPE and its degree of crystallinity, depending on the cellulosic material source.

AlMaadedd et al. (2012) studied the mechanical and thermal properties of date palm wood flour/glass fiber-reinforced hybrid composites of recycled polypropylene. It was found that the tensile properties of recycled polypropylene were increased by the addition of wood flour, the tensile strength of wood flour-reinforced recycled polypropylene was increased significantly by the addition of 5 wt.% glass fibers.

In this work, palm fibers which were extracted from an abundant agricultural waste emerge from palm trees planted in Palestinian fields were used to reinforce low-density polyethylene, the effects of fibers content, their length, the processing temperature and the time of alkaline treatment of palm fibers on the modulus of elasticity, modulus efficiency factor, and ductility of the produced composites were investigated.

Materials and methods

Materials

Low-density polyethylene (LDPE), which was supplied by Qapco Qatar, with a melt flow index (MFI) of 4.0 g/10 min, was used as the polymeric matrix. Palm fibers were extracted from palm leaf stalks which are abundant agricultural waste available in Palestine fields, were used to reinforce LDPE. Palm fibers were extracted and prepared at both short (less than 3 cm) and long fibers (greater than 3 cm), they were extracted by retting and mechanical processing like handpicking. The fibers were cleaned with freshwater and then dried under sunlight for 48 h to reduce moisture to less than 5%.

Sample preparation

A homemade thermal press machine was used to prepare the polymeric sheets and the samples of the composite materials, the thermal press consists of two metallic plates which can be heated electrically, the pressure was applied by using air-pressurized pistons, it is equipped with a water-cooling system. Firstly, LDPE granules were pressed at 160°C for about 10 min under a pressure of 5–6 bar, after that, the produced sheets were cooled to room temperature by using a cooling water system, the required cooling time was between 10 and 15 min. Secondly, the composite materials were prepared using the film stacking method in which fibers were randomly distributed and placed between the two polymeric

sheets, and then pressed by the thermal press machine. In order to investigate the effect of fiber contents and their length on the tensile properties of the composite materials, randomly distributed untreated short fibers (0–25 wt.%) and randomly distributed untreated long fibers (0–10 wt.%) were placed between two sheets of LDPE and then the samples were pressed by using thermal press machine under the same processing conditions.

In order to investigate the effect of alkaline treatment on the tensile modulus of elasticity of the produced composites, short palm fibers were immersed in a solution of 0.05 M of sodium hydroxide at room temperature for 2, 4, 6 and 8 h. Then, 5 wt.% alkaline short palm fibers-based composites were produced by using the same machine under the same processing conditions. While six samples containing 5 wt.% untreated short fibers were produced at different processing temperatures (120°C, 140°C, 160°C, 180°C, 200°C, and 220°C) in order to investigate the effect of processing temperature on the modulus of elasticity of the produced composites.

Tensile testing of the produced samples

Tensile testing of the samples was carried out by using a Sinowon testing machine ST series, at a constant speed of 4 mm/min at room temperature. For each composite, five specimens of 70 mm gauge length, 20 mm width and 2 mm thickness were tested. The test was carried out according to the standard test method for tensile properties of plastic ASTM D638–14.

Results and discussion

In general, the tensile properties of composite materials are affected by several factors such as the reinforcement type, its content, dimensions, and orientations. The effect of short fiber contents on the modulus of elasticity of the produced composites is shown in Figure 1.

It can be observed from Figure 1 that the modulus of elasticity of the produced composites increases with increasing the fiber contents to reach its maximum value at 5 wt.% after which it starts to decrease. It is generally known that the improvement of the tensile modulus is caused by the good dispersion of reinforcements and good interfacial adhesion between the reinforcements and the matrix; therefore, the mobility of polymer chains is restricted under loading. This result indicates that palm fibers have a strong reinforcing effect and that there is a good distribution of the fibers. At higher percentages of the palm fibers, the modulus of elasticity decreases significantly due to the presence of voids in the polymeric matrix which is ascribed to poor impregnation (Sawalha et al. 2018).

The modulus of elasticity of a composite material can be estimated based on the modified rule of the mixture as shown in Equation 1:

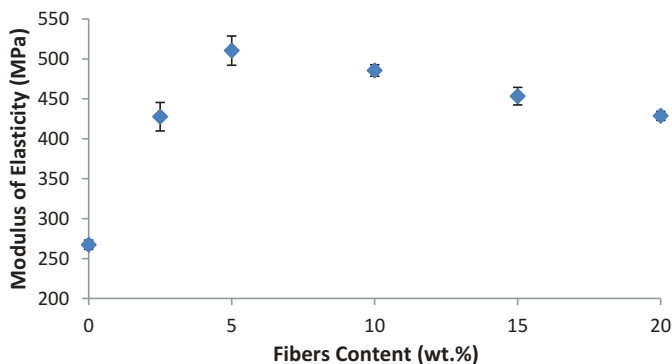


Figure 1. Effect of short palm fiber contents on the modulus of elasticity of the produced composites.

$$E_c = \alpha E_f v_f + E_m (1 - v_f) \quad (1)$$

where E_c , E_f , E_m , v_f , and α represent the modulus of elasticity of the composite material, the modulus of elasticity of the fibers, the modulus of elasticity of the matrix, the fiber volume fraction and the modulus efficiency factor, respectively. The modulus efficiency factor depends on many variables such as the fibers length, their orientation, their distribution, and the wetting of the fibers by the resin (Capela et al. 2017).

The fiber volume fraction (v_f) and the modulus efficiency factor (α) of the prepared composites can be calculated by using the following equations, respectively:

$$v_f = \frac{m_f / \rho_f}{m_f / \rho_f + m_m / \rho_m} \quad (2)$$

$$\alpha = \frac{E_c - E_m (1 - v_f)}{v_f E_f} \quad (3)$$

where m_f , m_m , ρ_f , and ρ_m are the mass of the palm fibers, the mass of LDPE, the density of palm fibers and the density of LDPE, respectively. The density of LDPE was 0.91 g/cm^3 while the minimum and maximum densities of palm fibers were reported to be 0.45 g/cm^3 and 0.57 g/cm^3 , respectively (Djebbloun et al. 2019), the average value, 0.51 g/cm^3 , was used to calculate the fiber volume fractions. The modulus of elasticity of LDPE was found to be 267.3 MPa while the minimum and maximum modulus of elasticity of palm fibers were reported to be 3.30 GPa and 9.86 GPa , respectively (Djebbloun et al. 2019), the average value, 6.58 GPa , was used to calculate the modulus efficiency factor.

It can be seen from Figure 2 that the modulus efficiency factor decreased with increasing the fiber volume fraction which is an indication of the decrease in interfacial adhesion which could be explained by the disability of the matrix to impregnate the fibers.

The ductility of the composites was calculated as percentage of elongation by using the following equation:

$$\%EL = \frac{l_f - l_0}{l_0} \times 100 \quad (4)$$

where $\%EL$, l_0 , and l_f represent the percentage of elongation, the initial and final lengths of the samples, respectively.

Figure 3 shows that the ductility of LDPE decreased gradually with increasing fiber content, this is due to the brittle behavior of the fibers which limits the plasticity behavior of the composites compared to the virgin polymer matrix.

It can be observed from Figure 4 that the modulus of elasticity of long fibers-based composites is higher than the modulus of elasticity of short fibers-based composites. This can be related to the fact

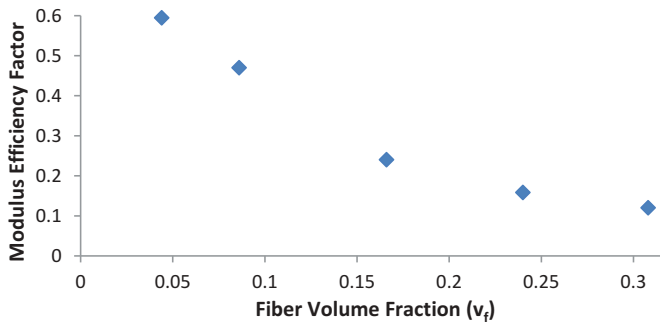


Figure 2. Effect of palm fiber volume fraction on the modulus efficiency factor.

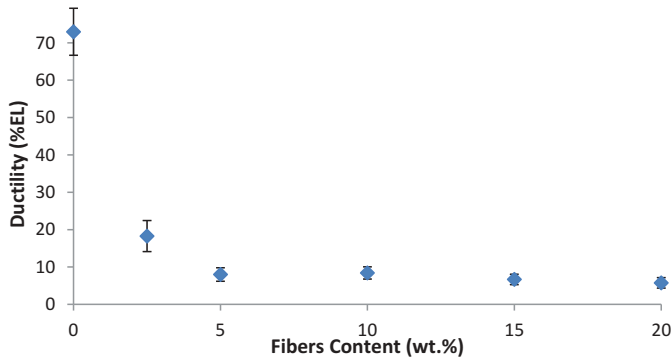


Figure 3. Effect of short palm fiber content on the ductility of the produced composites.

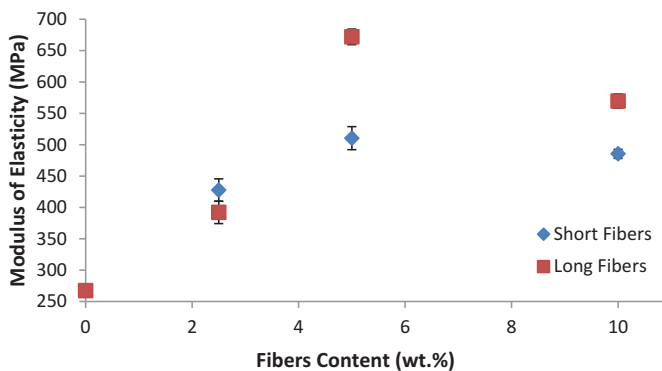


Figure 4. Effects of palm fiber length on the modulus of elasticity of the produced composites.

that the tensile load applied to discontinuous fiber composites is transferred to the fibers by the shearing mechanism between the matrix and the fibers. The polymeric matrix has higher strain than the adjacent fibers which creates a shear stress distribution across the fiber–matrix interface. The tensile stresses are applied to the fibers through the shearing stress in the matrix, these shearing stresses have their maximum value near the fiber ends, while the tensile stresses are zero at the fibers ends and they gradually increase to a plateau value in the central of the fibers. Thus, the parts of the fibers near the ends carry less stresses than the middle section. The sum of the lengths of the fibers on each end require for the tensile load to reach its plateau or maximum value is often called the fibers' critical length, so the stress carried by the fibers increases with increasing their length. An improvement in the tensile strength of composite materials with increasing the fiber length was reported (Sankar et al. 2014).

It can be seen from [Figure 5](#) that the modulus efficiency factors for composites containing long fibers are higher than those containing short fibers which is related to the effectiveness of stress transfer between the polymeric matrix and the fibers when long fibers were used.

Processing temperature, pressure and time have a big effect on the mechanical properties of composite materials due to their effects on the impregnation of reinforcements, it was reported that these variables had a big effect on the tensile strength of unidirectional long Kenaf fiber-reinforced polylactic acid composite (Tharazi et al. 2017).

It can be observed from [Figure 6](#) that increasing the processing temperature up to 160°C improves the modulus of elasticity of the produced composite, this is related to the effect of the processing temperature on the viscosity of LDPE melt, increasing the processing temperature improves the volumetric flow rate of the LDPE melt due to the reduction in the polymeric melt viscosity which results in good impregnation and low

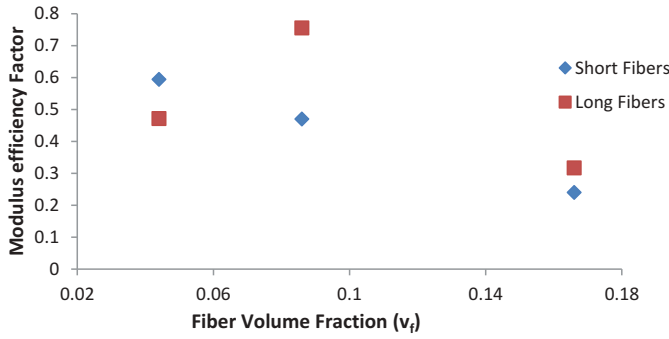


Figure 5. Effects of palm fiber length on the modulus efficiency factor.

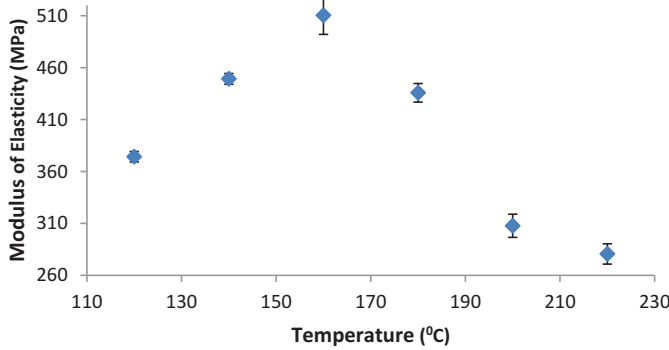


Figure 6. Effects of processing temperature on the modulus of elasticity of the produced composites.

void content in the produced composite. But it can be observed from Figure 6 that increasing the processing temperature above 160°C results in a reduction in the modulus of elasticity of the produced composites which is related to the fact that the cellulosic reinforcements start to lose their strength at temperatures above 160°C due to their structural degradation (Mizera et al. 2017).

Figure 7 shows that the modulus efficiency factor increases with increasing the processing temperature up to 160°C then it starts to decrease, the increase in the modulus efficiency factor with increasing the processing temperature is attributed to the improvement in the degree of impregnation of palm fibers which reduces the void content, while the reduction in the modulus efficiency factor at higher temperatures is related to the degradation of palm fibers which reduces their mechanical properties.

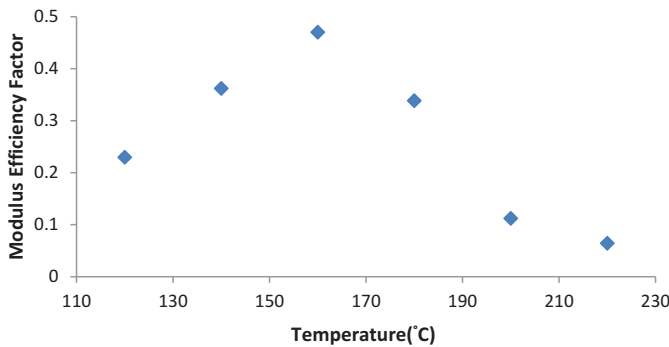


Figure 7. Effects of processing temperature on the modulus efficiency factor.

It can be observed from [Figure 8](#) that the modulus of elasticity of the composites improved with increasing the time of alkaline treatment. This is attributed to the effect of alkaline treatment on the structure of palm fibers. Natural fibers consist of small fibrils bonding together by noncellulosic materials such as hemicelluloses, lignin, pectin, wax and oil covering material, so alkaline treatment modifies the cellulosic molecular structure, it changes the orientation of highly packed crystalline cellulose order and forming an amorphous region due to the extraction of noncellulosic which makes the fibrils more capable to rearranging themselves along the direction of the applied tensile load, the extraction of these materials also separates the fibers into small fibrils which increases the fiber aspect ratio (length/diameter) due to the reduction of the fiber diameter. The alkaline treatment produces clean and rough fibrils which facilitates both mechanical interlocking and bonding, the alkaline treatment also modifies the hydrophilic characteristics of the fibers which makes them more compatible with the hydrophobic polymeric matrix. This results in the improvement of interfacial adhesion between the polymeric matrix and the reinforcement.

[Figure 9](#) shows that the modulus efficiency factor increases with increasing the alkaline treatment time which is related to the improvement in the interfacial adhesion between the fibers and the polymeric matrix. It was reported that the use of alkaline treated sisal natural fibers improved the tensile and flexural properties of sisal fibers reinforced epoxy polymer matrix (Somashekar and Shanthakumar 2014).

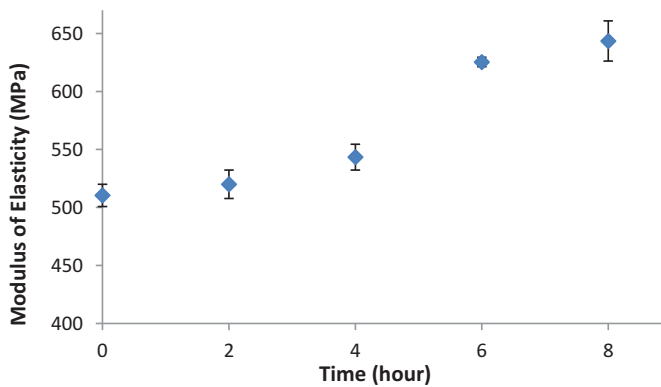


Figure 8. Effects of alkaline treatment time on the modulus of elasticity of the produced composites.

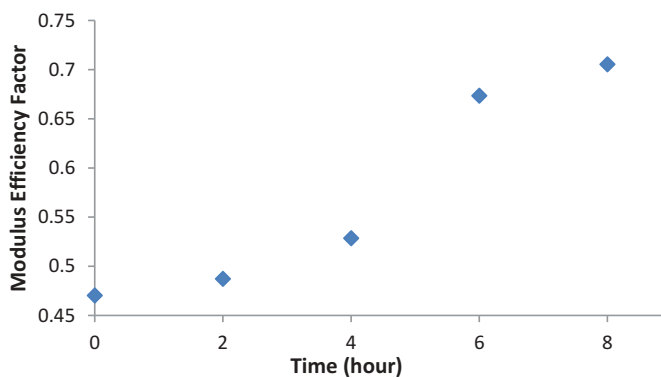


Figure 9. Effects of alkaline treatment time on the modulus efficiency factor.

Conclusions

It can be concluded that the modulus of elasticity of palm fiber-LDPE composites was improved by the addition of short palm fibers up to 5 wt.% while it decreased when high fiber contents were used due to poor impregnation which leads to increase the void content which reduces the modulus efficiency factor. On the other hand, the ductility of the composites was reduced by increasing the short fiber content due to the brittle behavior of fibers. The degree of improvement in the modulus of elasticity of the composites was improved when long fibers were used due to the effectiveness of stress transfer between the matrix and the fibers as the fiber length increases, the modulus efficiency factor for long palm fibers-based composites is higher than that for short palm fibers-based composites. The processing temperature was found to affect the modulus of elasticity of the composites due to its effect on the viscosity of LDPE which reduces the void content due to the improvement in the degree of impregnation of palm fibers, this resulted in the increase in the modulus efficiency factor, but the modulus of elasticity of the composites was reduced when temperatures above 160°C were applied which may be attributed to the degradation of the fibers. Alkaline treatment was found to improve the modulus of elasticity of the composites due to the improvement in the interfacial adhesion between the fibers and the polymeric matrix, but the degree of improvement was found to be dependent on the time of alkaline treatment, the improvement in interfacial adhesion improves the modulus efficiency factor.

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