

Water Absorption and Dimensional Stability of Short Kenaf Fiber-Filled Polypropylene Composites Treated with Maleated Polypropylene

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ABSTRACT: The purpose of this research was to investigate the water absorption behavior and associated dimensional stability of kenaf-polypropylene-filled (PP/KF) composites. Composites with different fiber loadings, ranging from 0 to 40 wt %, were prepared with a twin-screw extruder followed by hot press molding. The influence of the compatibilizer was also studied for PP/KF composite with 5 wt % maleated PP (MAPP). Water absorption testing was carried out at room temperature for 7 weeks. Tensile, flexural, and impact tests were also performed on control, wet, and re-dried specimens. Increasing the fiber content resulted in higher water absorption and thickness swelling. The inferior mechanical properties of the wet composites were attrib-

uted to the effect of water, which deteriorates the interfacial properties of composites. On re-drying, all properties were almost recovered because of the recovery of interfacial area as evident in scanning electron micrographs. Incorporation of the MAPP significantly improved the compatibility between the fiber and matrix and the mechanical properties of the composites compared with those without MAPP. It also diminished the water absorption as well as the related thickness swelling in the composites. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 120: 563–572, 2011

Key words: kenaf-polypropylene composite; water absorption; dimensional stability; maleated polypropylene

INTRODUCTION

Lignocellulosic natural fibers such as sisal, coir, jute, ramie, pineapple leaf, and kenaf have the potential to be used as a replacement for glass or other traditional reinforcement materials in composites. These fibers have many properties that make them an attractive alternative to traditional materials. They have high specific properties such as stiffness, impact resistance, flexibility, and modulus.^{1–4}

Combining kenaf fibers (KF) with other resources provides a strategy for producing advanced composite materials that take advantage of the properties of both types of resources. It allows the scientist to design materials based on end-use requirements within a framework of cost, availability, recyclability, energy use, and environmental considerations.⁵

End-use applications of natural fiber composites for decking, flooring, outdoor facilities, window frames, various construction materials, and bathroom parts, for example, and their exposure to the atmosphere or contact with aqueous media has

made it necessary to evaluate their water uptake characteristics.⁶ Water absorption is one of the most important characteristics of KF-filled polypropylene (PP/KF) composite exposed to environmental conditions, which determines their end-use applications. Therefore, as a limiting parameter, water absorption has to be taken into account in the design of PP/KF composites for final applications. Similar to water absorption, fiber content and processing can affect thickness swelling and the dimensional stability of PP/KF composites, which is of great importance in outdoor applications such as decking and railing.⁷

In addition, lignocellulosic fibers used for reinforcement in nonpolar thermoplastics, such as polyethylene, PP, and polystyrene, have to be modified because effective wetting of fibers and strong interfacial adhesion are required to obtain composites with optimized mechanical properties.⁸ Good wetting of the fiber by the matrix and adequate fiber–matrix bonding can decrease the rate and amount of water absorbed in the interphase region of the composite. The water absorption behavior of natural fiber thermoplastic composites has been studied by a number of researchers, and the effectiveness of compatibilizers in reducing the amount and rate of water absorption has been well documented.⁹ Extensive research has been carried out with different kinds of coupling agents for surface modification of natural

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TABLE I
Designation and Composition of Materials

Designation	Materials	PP (wt %)	KF (wt %)	MAPP (wt %)
PP	PP	100	–	–
PP/KF20	PP + kenaf fiber	80	20	–
PP/KF30	PP + kenaf fiber	70	30	–
PP/KF40	PP + kenaf fiber	60	40	–
PP/KF30/M5	PP + kenaf fiber + MAPP	65	30	5
PP/KF40/M5	PP + kenaf fiber + MAPP	55	40	5

fibers to increase the adhesive action with the thermoplastic matrix. Maleated PP wax was used as a coupling agent to improve the properties of composites prepared from jute and kenaf-reinforced PP.¹⁰ All the studies indicated that there was a substantial increase in the surface properties of the fibers with the addition of the coupling agents.

The objectives of this study were to investigate the long-term water absorption of PP/KF composites at room temperature and its effect on mechanical properties such as tensile, flexural, and impact properties. In addition, the dimensional stability after water absorption was determined by indicating the degree of thickness swelling of samples. Besides studying the effect of fiber loading on PP/KF, the purpose of this study was also to explore the use of KF in PP-based thermoplastic composites both with and without a compatibilizer to address the weak interfacial bonding between natural fibers and polymer matrices.

EXPERIMENTAL

Materials

PP Titanpro[®] SM950, with a melt flow index of 21.67 g/10 min (tested at 190°C with 2.16 kg load) and a density of 0.9 g/cm³, was supplied by Titan Chemicals Corp. Bhd. (Kuala Lumpur, Malaysia), and was used as the polymer matrix. It is an impact copolymer and also a nucleated extra high-flow material, which possesses good toughness at low temperature and easy processing properties. In addition, commercially available pellets of maleic anhydride-modified homopolymer PP (MAPP), Polybond 3200 from Chemtura Corp. (Chemtura Gastonia, NC), were used as a compatibilizer to improve the compatibility and adhesion between KF fiber and the PP. The KF used was obtained from a herbaceous plant, *Hibiscus cannabinus*, and was supplied by Forest Research Institute Malaysia (FRIM) in the form of bundles.

Raw material preparations

Bundles of KF fibers were manually cut into 10 mm length with paper cutter and were crushed to 3–5 mm length by a crusher.

Compounding and molding

The KF, 3–5 mm in length, was initially dried in a vacuum oven at 80°C for 24 hr. PP, KF, and MAPP were extruded using a co-rotating twin-screw extruder (Model PSW30) according to the compositions given in Table I. The extrusion zone temperature ranged from 155°C to 175°C. The extrudate was then pelletized with the extruder pelletizer (Model PSH10).

After compounding, the tensile, flexural, and impact samples were prepared by melt pressing pellets of compounded material on a hot press machine from Kao Tieh GoTech Testing Machine Inc. (Taipei, Taiwan). Before molding, all compounded pellets were initially dried in a vacuum oven at 80°C for 24 hr to remove moisture entrapped in the materials. All PP/KF composites were compression molded at a temperature of 185°C and were preheated without pressure for 10 min, compressed under pressure of 10 MPa for 4 min, and cooled under pressure for 4 min.

Fiber length distribution

After compounding and molding, KF were taken from a small piece of sample using a chemical digestion technique where xylene was used as the solvent. The fiber length distributions of 100 fibers were determined with an image analyzer.

Water absorption and dimensional stability test

Water absorption tests were carried out according to ASTM D-570 specifications. Flexural specimens were cut from the compression-molded plates and used for the measurements of water absorption and thickness swelling. After vacuum drying at 80°C for 24 hr to a constant weight to a precision of 0.001 g, the weight of specimens before water immersion (W_d) were measured with a balance and thickness was measured with a thickness gauge (T_0). The specimens were immersed in water at room temperature for 7 weeks.

The weights of the specimens were measured at regular intervals using an analytical balance. The surfaces of these specimens were thoroughly dried with tissue papers, and they were weighed immediately to determine the weight of the specimens (W_w).

The percentage gain at any time t (M_t) as a result of water absorption was determined by eq. (1)¹¹:

$$M_t (\%) = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

where W_d and W_w denote the weight of the dry material (the initial weight of materials before water immersion) and the weight of materials after water immersion, respectively. The specimens were immersed until they were saturated. The diffusion coefficient (D) and the maximum water absorbed (M_m) can be obtained by considering the Fick's law diffusion model.

The equation of Fick's law has been simplified by Shen and Springer,¹² to show that the initial absorption is given by:

$$\frac{M_t}{M_m} = \frac{4}{h} \left(\frac{Dt}{\pi} \right)^{\frac{1}{2}} \quad (2)$$

where M_t is the percentage of weight gain at any time t , M_m is the maximum percentage of water absorbed at saturation, D is the mass diffusivity in the composite, h is the thickness of specimen, and t is the time of immersion.

The diffusion properties of composites described by Fick's laws were evaluated by weight gain measurements of predried specimen immersed in water by considering the slope of the first part of the weight gain curve versus square root of time by using the following equation. The coefficient of diffusion (D) is defined as the slope of the normalized mass uptake against $t^{1/2}$ and has the form:

$$D = \pi \left(\frac{kh}{4M_m} \right)^2 \quad (3)$$

where k is the initial slope of the plot of M_t versus $t^{1/2}$, M_m is the maximum weight gain, and h is the thickness of composite.

The thickness swelling (TS) was calculated according to the eq. (4):

$$TS (\%) = \frac{T_w - T_0}{T_0} \times 100 \quad (4)$$

where T_0 and T_w are the thicknesses (mm) of the sample before and after immersion, respectively.

Tensile test

Tensile tests were performed to verify the residual tensile properties of the composites. The tensile tests were performed at room temperature according to ASTM D 638-08, using a tensile tester, Instron model

3366, at a crosshead speed of 5 mm/min. Five samples of every composition were tested to obtain an average value.

Flexural test

Three-point bending flexural tests were conducted using an Instron model 3366 at a crosshead speed of 5 mm/min and a span length of 50 mm, according to ASTM D790-07. Five samples of every composition were tested to obtain an average value.

Impact test

Charpy impact tests were carried out using a Zwick Impact tester at room temperature, according to ASTM D6110-08 (notched samples) and ASTM D4812-06 (unnotched sample). Both the notched and unnotched samples were tested under impact energy of 7.5 joules.

Conditioning of specimens

Because of the hydrophilic nature of PP/KF composite, all testing specimens were placed in a vacuum oven at 80°C for 24 hr before testing. On removal from the oven, the specimens were allowed to cool to room temperature inside desiccators to maintain standard moisture content for all specimens. These specimens are then regarded to be in the as-received state. For the water absorption study, the specimens were immersed in distilled water at room temperature and regarded to be in the wet state. Once the water uptake in the specimens had reached a saturation limit, tensile, flexural, and impact tests were carried out. Further investigation into the extent of deterioration of these mechanical tests was carried out by re-drying the specimens in a vacuum oven at 80°C for 24 hr.

Scanning electron microscopy

Impact fracture surfaces of samples were examined with a field-emission Scanning Electron microscope model Zeiss Supra 35VP. To increase the conductivity of the samples and reduce the charging effects, the fracture surface was coated with a thin layer of gold using a VG Microtech-Polaron Sputter Coater before the scanning electron microscopy (SEM) examination.

RESULTS AND DISCUSSION

Fiber length distribution

Figure 1 shows the fiber length distribution of KF before and after compounding. It can be seen that the length of the fibers was shortened to an average

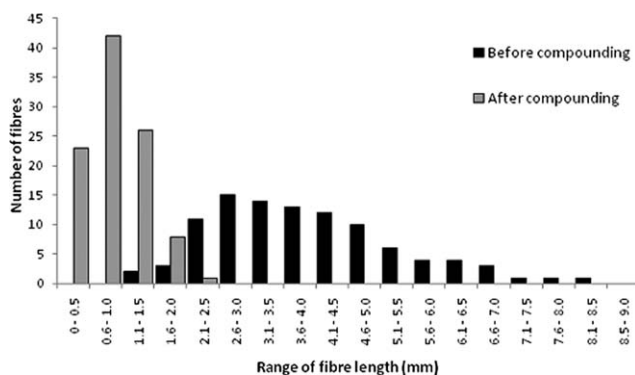


Figure 1 Fiber length distribution of KF before and after compounding and molding.

of 0.54 mm compared with the initial average fiber length, which was 3.4 mm. This may be attributed to shearing processes during twin-screw extrusion, which break down the fibers.

Water uptake curve

Figure 2 shows the percentage moisture absorption M_t of pure PP and PP/KF composites at different fiber loadings, as a function of the square root of time, $t^{1/2}$, at room temperature. An initial increase in M_t is observed in each case, followed by saturation or an equilibrium state indicated by a plateau region. This indicates that the water uptake behavior of PP/KF composites follow Fick's law for the of water absorption of composites.

The lowest water absorption was observed for pure PP, which is hydrophobic. As a nonpolar polymer, PP does not absorb water significantly.¹³ At 40% fiber loading, the composite exhibited the highest water absorption values for all immersion times, followed by 30% and 20% fiber loadings. This indicates that the amount of water absorbed increases with fiber loading. It is also obvious from Figure 2 that PP/KF20 composites reach saturation earlier (approximately after 22 days of water immersion) compared with 29 days for PP/KF30 composites and 35 days for PP/KF40. Other observations are the decrease in the initial rate and the level of water uptake with increasing KF content. The initial rate at which water molecules are absorbed and the level of water uptake of KF are largely dependent on the amount of accessible hydroxyl groups that can form hydrogen bonds with water molecules.¹⁴ The higher the amount of these hydroxyl groups, the higher the initial rate and the level of water uptake.

Natural fibers are prone to moisture and water absorption because of the presence of constituent materials such as cellulose and hemicelluloses, which are hydrophilic.¹⁵ Cellulose is a hydrophilic glucan polymer consisting of a linear chain of 1,4- β

anhydroglucose units, which contain hydroxyl groups. These hydroxyl groups form intermolecular and intramolecular hydrogen bonds with the macromolecule itself and also with other cellulose macromolecules or polar molecules. As a result, water, which is a polar molecule, can easily form hydrogen bond with the cellulose. Thus, higher fiber contents result in higher water absorption.¹⁶ In addition to the hydrophilic cellulosic fibers, another region that can hold water is the microgaps in the interface between the fiber and plastic phases. These can contribute to the subsequent water absorption of the materials because of increased porosity.¹⁷

It is also evident from Figure 2 that the formulations containing MAPP exhibit lower water absorption compared with the untreated ones. The presence of the MAPP compatibilizer enhances the fiber-matrix interface and causes better encapsulation of fiber by the plastic, which consequently results in lower water absorption.¹⁸ In detail, the hydrophilic -OH groups present in the KF react with the acid anhydride groups present in MAPP to form ester linkages.¹⁵ This reduces the water absorption capacity of the treated PP/KF composites.

Generally, water absorption increases with immersion time. A rapid moisture uptake was observed for all the specimens within the first few days of immersion. The absorption of water is related to its rate of diffusion into the composites. The maximum water absorbed, M_m , the apparent diffusion coefficient, D , and the maximum thickness swelling of composites are summarized in Table II.

According to Table II, both M_m and D values of PP/KF composites are higher than those of pure PP. The apparent diffusion coefficient, D , for composites increases with the fiber content. It is expected that the exposed fibers, which are located at or near the specimen's surface, absorb moisture faster than those in the interior parts (i.e., fibers that are entrapped or coated by the PP matrix).¹⁹ Thus, it is

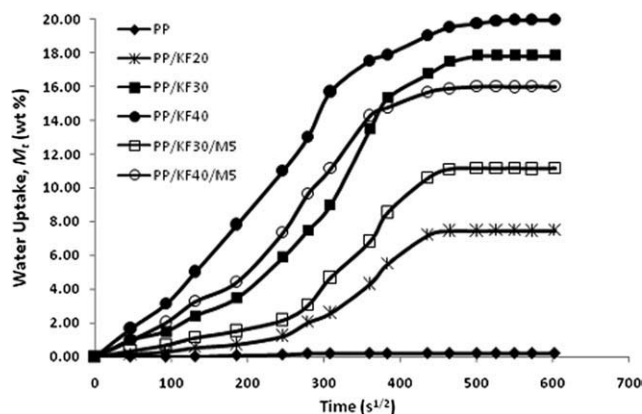


Figure 2 Water uptake curve of MAPP-treated and untreated PP/KF composites at different fiber loadings.

TABLE II
Maximum Water Absorbed, Apparent Diffusion Coefficient, and Maximum Thickness Swelling for PP and PP/KF Composites

Compounds	Maximum water absorbed, M_m (%)	Apparent diffusion coefficient, D (10^{-12} m ² /sec)	Maximum thickness swelling (%)
PP	0.10	0.10	0.20
PP/KF20	7.48	0.31	2.42
PP/KF30	17.82	1.26	15.33
PP/KF40	19.92	6.52	21.92
PP/KF30/M5	11.13	0.87	2.98
PP/KF40/M5	15.88	4.17	4.45

expected that the composite with 40% KF possesses more fibers on the surface to absorb water faster. On the contrary, fibers in PP/KF20 were mostly coated by the hydrophobic PP matrix, which acts as a barrier for the diffusion of water, and, therefore, their absorption rates were slower. The water molecules could saturate the surface of the PP/KF composite easily and also penetrate into the composites through voids, resulting in higher water absorption in a short exposure time.¹⁹ With the addition of MAPP compatibilizer, both PP/KF30/M5 and PP/KF40/M5 exhibit lower M_m and D compared with the uncompatibilized specimens.

Dimensional stability

The dimensional stability of a composite is related to its water absorption behavior. Figure 3 shows the thickness swelling of MAPP-treated and untreated PP/KF composites after water absorption.

The curves show an initial and rapid linear increase, followed by a decreased rate of increase, and finally reach a plateau region indicating the maximum thickness swelling. The KF change dimensions with changing moisture content because the cell wall polymers contain hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding.²⁰ The immersion of composites in water will cause swelling of the cell wall, and the fiber expands until the cell wall is saturated with water.

This maximum thickness swelling is achieved when the diffusion of water into composite reaches the saturation level. The maximum thickness swelling of PP/KF composites with different fiber loadings and pure PP can be seen in Table II. It can be seen that PP/KF at 40 wt % KF exhibits the highest swelling percentage (21.92%), which is 21.82% higher than that of PP. PP displayed the best dimensional stability because it was not prone to water absorption and thickness swelling because of its hydrophobic nature. Composites with lower fiber content also

possessed higher dimensional stability. As mentioned earlier, increasing the hydrophilic component, i.e., natural fiber, in the composite enhances the water uptake capacity and, therefore, resulted in higher degree of swelling of PP/KF composite with 40% of fiber. In addition, the results also clearly indicate that MAPP, chemically attached to KF, was able to prevent the water from going into the cell walls, and this reduced the degree of swelling.

Mechanical properties

Water absorption may affect the mechanical properties of PP/KF composites. The results of tensile, flexural, and impact tests of PP/KF composites, after being immersed in water for 7 weeks, are shown below.

Tensile and flexural properties

The tensile properties of PP and PP/KF composites with different fiber loadings in the as-received, wet, and re-dried states are shown in Table III. The tensile strength and modulus of PP was hardly affected by the absorption of water. This is a consequence of the negligibly small uptake of water exhibited by the material. In contrast, the tensile properties of the PP/KF composites were affected considerably. The tensile properties of natural fiber composites decreased after moisture uptake because of the plasticizing effect of the water molecules, which weaken the interfacial bond strength between PP and KF. Once the moisture penetrates inside the composite materials, the fibers tend to swell. Water absorption and their resulting effects contribute to the loss of compatibility between the fibers and matrix, which results in debonding and weakening of the interfacial adhesion. The retention ability, which is indicated by percentage retention, is the capability of wet sample to retain the strength of control sample. In other words, it is the ratio of strength of wet

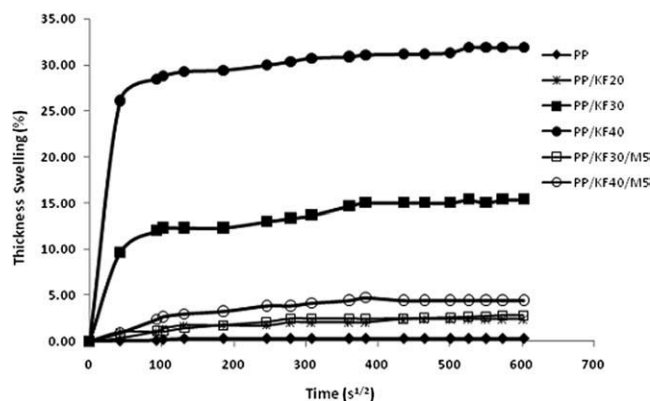


Figure 3 Thickness swelling of MAPP-treated and untreated PP/KF composites after water immersion.

TABLE III
Tensile and Flexural Properties of PP/KF Composites in the As-Received, Wet, and Re-Dried States

Composites	Properties	As-received	Water absorption properties	
			Wet	Re-dried
PP	Tensile strength (MPa)	17.39	17.05 (98.04)	17.51 [100.69]
	Tensile modulus (MPa)	967.5	951.6 (98.82)	903.4 [93.37]
	Flexural strength (MPa)	41.35	40.56 (98.09)	41.12 [99.44]
	Flexural modulus (MPa)	992.7	988 (99.53)	899 [90.56]
PP/KF20	Tensile strength (MPa)	12.66	11.25 (88.86)	12.16 [96.05]
	Tensile modulus (MPa)	1147	1049 (91.46)	1120 [97.65]
	Flexural strength (MPa)	26.22	21.60 (82.38)	23.23 [88.67]
	Flexural modulus (MPa)	1241	1024.3 (82.54)	1101 [88.72]
PP/KF30	Tensile strength (MPa)	10.59	8.37 (79.04)	9.46 [89.33]
	Tensile modulus (MPa)	1158	1057 (91.28)	1137 [98.19]
	Flexural strength (MPa)	23.05	20.31 (88.11)	20.34 [88.24]
	Flexural modulus (MPa)	1358	1059 (77.98)	1164 [85.71]
PP/KF40	Tensile strength (MPa)	10.33	7.24 (70.09)	8.47 [81.99]
	Tensile modulus (MPa)	1282	1104 (86.12)	1200 [93.60]
	Flexural strength (MPa)	19.67	12.80 (65.07)	13.69 [69.60]
	Flexural modulus (MPa)	1492	1154 (77.35)	1213 [81.30]
PP/KF30/M5	Tensile strength (MPa)	23.18	19.34 (83.43)	21.98 [94.82]
	Tensile modulus (MPa)	1774	1069 (60.26)	1354 [76.32]
	Flexural strength (MPa)	36.05	29.77 (82.58)	30.69 [85.13]
	Flexural modulus (MPa)	1678	1200.5 (71.54)	1331.5 [79.35]
PP/KF40/M5	Tensile strength (MPa)	19.84	14.52 (73.19)	17.66 [89.01]
	Tensile modulus (MPa)	1778	1244 (69.97)	1451 [81.61]
	Flexural strength (MPa)	24.01	17.16 (71.47)	19.15 [79.76]
	Flexural modulus (MPa)	1648	1351.0 (81.98)	1460 [88.59]

Values in parentheses indicate percentage retention of properties after water absorption at room temperature. Values in square brackets indicate percentage recovery of properties after re-drying.

sample over strength of control sample. As shown in Table III, the retention ability of tensile strength was observed to drop with increasing fiber loading. This is due to the higher hydrophilic character of fiber, which facilitates water absorption, promoting the degradation of the fiber–matrix interface, which, in turn, deleteriously affects the tensile strength of the composite.²¹ The reduction in tensile strength at higher fiber contents could be due to the lack of matrix that leads to inefficiency of stress transfer from the matrix to fibers and *vice versa*.²²

However, the reduction in tensile modulus after water absorption can again be attributed to the effect of the absorbed water molecules such that the interfacial bond strength between the KF and the PP matrix is weakened.²³ Following the normal trend for thermoplastic composites filled with solid fibers, the tensile moduli of the composites increased as the fiber loading increased.²⁴ This is due to the restriction of the mobility and deformability of the matrix with the introduction of mechanical restraint.

After re-drying the wet samples in an oven at 80°C for 24 hr, the tensile strengths and moduli for the PP/KF composites at all fiber loadings increased compared with those of the wet samples. As shown in Table III, percentage recoveries of 96.05%, 89.33%, and 81.99% were observed for the tensile strength of PP/KF with fiber loadings of 20%, 30%, and 40%,

respectively. High recoveries were also observed for the tensile modulus in Table III. The permanent loss in tensile properties exhibited by the composites suggests the irreversible effects of water absorption. The water molecules might have penetrated deep into the composite structures via mechanisms such as capillary action. In addition to inferior fiber properties, fiber swelling could also cause permanent damage to the composite structures such as micro-cracks. Such damage cannot be restored on drying and might affect the composite properties.¹⁴

The MAPP-treated composites had higher tensile strengths and tensile moduli than the untreated composites as can be seen in Table III, which seems to be due to the better interfacial bonding between the fiber and the matrix. The anhydride groups present in the MAPP were covalently bonded to the hydroxyl groups of the fiber surface.²⁵ The improved interaction and adhesion between the fibers and matrix through covalent bonding leads to better matrix to fiber stress transfer. The interaction between non-polar thermoplastics such as PP and any coupling agent, such as MAPP, is predominantly chain entanglement. Stresses applied to one chain can be transmitted to other entangled chains and distributed among many chains.

Flexural properties are important in assessing the resistance of composites to bending. It is evident

from Table III that the flexural strengths of PP/KF significantly decrease with increased fiber contents from 20% to 40%. Flexural strength is very dependent on many other factors such as the matrix–fiber interaction.²⁶ This observation may be attributed to the decrease in the interfacial bonding strength between the KF and the PP matrix. Polymers such as polyethylene and PP are nonpolar (hydrophobic) and, thus, are not compatible with polar (hydrophilic) fiber. As the fiber fraction in a composite increase, the weak interfacial region is also increased. As a result, the bonding strength of the whole composite is reduced.

There is a significant drop in the flexural strengths of PP/KF composites after water absorption, i.e., a reduction of 17.62%, 11.89%, and 34.93% in flexural strength for PP/KF with 20, 30, and 40 wt % KF, respectively. This is again due to the plasticizing effect of the water molecules. Absorbed water molecules fill into cavities and cracks within the composite and act as a plasticizer to the composite and render the structure more flexible and thus increase the mobility of the whole composite system.²⁷ On re-drying, the flexural properties of PP/KF composites were also highly recoverable, as evident from Table III. This was also attributed to the loss of degradation effect of water to PP/KF interface.

However, when MAPP was incorporated, the properties of the interface region markedly increased, which led to a higher efficiency of stress transfer from matrix to fiber. There was a slight increase in the flexural modulus for both MAPP-treated composites compared with the untreated composites, which were about 9.0% and 10.5%, respectively, for PP/KF reinforced with 30% and 40% fiber. This is due to the better interfacial adhesion between PP and KF that hindered the movement of most polymer chains. There was only a slight increase in the flexural modulus because of the change in the molecular morphology of the polymer near the fiber surface or in the bulk of the plastic phase after MAPP was added. Transcrystallization near the fiber surface and changes in the apparent modulus of the bulk matrix can result in changes in the contribution of the matrix to the composite modulus.²⁸

There were higher percentage recoveries of tensile properties observed in PP/KF30/M5 and PP/KF40/M5 in Table III. The excellent recoverability of MAPP-compatible PP/KF may be attributed to the improvement of the interfacial adhesion between PP matrix and KF by the addition of 5% MAPP. This can be explained by the fact that the better interfacial region prevents water molecules from penetrating deep into the composite structures as well as reduces fiber swelling that could cause permanent damage such as microcracks. Therefore, there will be

less water entrapped deep inside the composites because the number of microvoids has been reduced. The retention ability and recoverability of flexural strength and modulus were not significantly changed when compared between MAPP-treated and untreated samples.

Impact properties

The impact strength values for unnotched samples and notched samples are shown in Table IV. It can be observed that PP recorded the highest impact strength compared with the PP/KF composites. This is due to the ductile failure mode, which involved the plastic deformation of PP.

The addition of KF decreased the impact strength; this behavior increased with increasing fiber loading. As the fiber loading increased from 0% to 20%, 30%, and 40%, a noticeable reduction of 85.19%, 87.51%, and 90.57% was observed, respectively. As explained by Rowell et al.,⁹ the presence of the fibers decreases the energy absorbed by the specimens. The addition of the fibers creates regions of stress concentrations that require less energy to initiate a crack. Additionally, this result is in agreement with the mechanical properties of jute–PP composites studied by Doan et al.,²⁹ where the impact toughness decreased with increasing fiber content. This was attributed to the change in the fracture behavior from ductile to brittle and to the increase of the probability of fiber agglomeration at high fiber concentrations.

The unnotched impact resistance of polymers is usually far higher than the notched impact resistance. It is evident that at a fiber loading of 30%, impact strength of 5.43 and 3.39 kJ/m² were observed for unnotched and notched samples, respectively. According to De Armitt,³⁰ the impact resistance is composed of two distinct parts: first, the energy needed to initiate the crack and, second, the energy needed to propagate the crack through the sample. In the case of the unnotched test, the energy measured is the sum of two components, i.e., the energy needed to create a crack, often relatively high, plus the energy needed to grow the crack, usually much lower. However, the energy needed to form the crack is not required in the notched sample; therefore, the impact strengths for the notched samples were lower. The reduction in the impact strength from the unnotched to notched samples is higher for the pure PP sample compared with the PP/KF sample. This may be explained by the fact that PP is known to be a notch-sensitive material. In the case of the unnotched PP/KF sample, cracks are initiated at places of high stress concentration, such as fiber ends and defects, or at the interface region where adhesion between the two phases is poor.

TABLE IV
Impact Strengths of PP/KF Composites in As-Received, Wet, and Re-Dried States

Composites	Impact strength (MPa)	As-received	Water absorption properties	
			Wet	Re-dried
PP	Unnotched	43.48	44.30 (101.89)	44.1 [101.43]
	Notched	5.11	5.2 (101.76)	5.1 [99.8]
PP/KF20	Unnotched	6.44	9.3 (144.41)	9.28 [144.10]
	Notched	3.54	4.55 (128.53)	3.64 [102.82]
PP/KF30	Unnotched	5.43	8.7 (160.22)	6.74 [124.13]
	Notched	3.39	4.21 (124.19)	3.58 [105.6]
PP/KF40	Unnotched	4.10	5.25 (128.05)	4.07 [99.27]
	Notched	3.13	3.9 (124.6)	3.66 [116.93]
PP/KF30/M5	Unnotched	10.87	11.75 (108.10)	11.67 [107.36]
	Notched	4.08	5.13 (125.74)	4.59 [112.50]
PP/KF40/M5	Unnotched	8.52	9.61 (112.79)	9.53 [111.85]
	Notched	3.98	4.63 (116.33)	4.43 [111.31]

Values in parentheses indicate percentage retention of properties after water absorption at room temperature. Values in square brackets indicate percentage recovery of properties after re-drying.

On the absorption of water, there was a significant increase in the impact resistance of the notch and unnotched samples, as shown in Table IV. The improvement in the impact strength is related to the swelling of the fiber diameter after the absorption of water. The swelling of the fibers will enhance the frictional work from fiber pull-out from the PP matrix. This is in agreement with the impact results reported by Chow et al.²³ in the study of the moisture absorption of sisal fiber-reinforced PP.

According to Table IV, the impact strength of notched and unnotched re-dried samples dropped slightly compared with wet samples because the interfacial degradation was lessened due to the removal of water. In addition, less swelling of fibers resulted in less and harder fiber pull-out, which indirectly decreased the impact energy.

After the addition of MAPP, the impact strength values for unnotched composites improved nearly 100.2% and 107.8% for 30% and 40% fiber contents,

respectively. For the notched composite, the impact strength increases nearly 20.4% and 27.2% compared with that of untreated samples for PP/KF with 30% and 40% fiber loading, respectively. In contrast to the untreated composites, both fiber pull-out and matrix debonding in the MAPP-treated specimens were suppressed because fibers were well covered by MAPP. As explained by Rowell and Stout,²⁰ improving the fiber-matrix adhesion through the use of MAPP increases the resistance to crack initiation at the fiber-matrix interface, and the decrease in impact strength with the addition of fibers is not as marked.

Fractography analysis

A SEM micrograph of the fractured surface of PP/KF (40 wt %) is shown in Figure 4 in which a pull-out fiber can be seen clearly. In addition, there was some fiber debonding, as indicated by the circular as

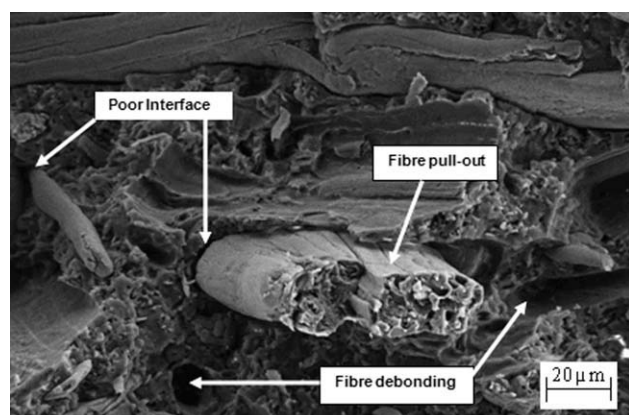


Figure 4 SEM micrograph of the impact-fractured surface of a PP/KF composite (as-received PP/KF40).

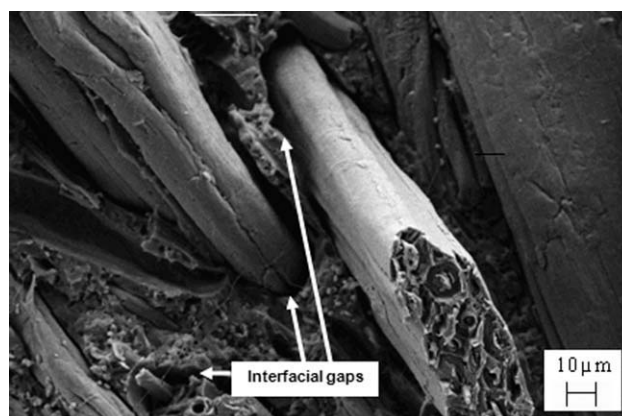


Figure 5 SEM micrograph of the impact-fractured surface of a PP/KF composite after water absorption (wet PP/KF40).

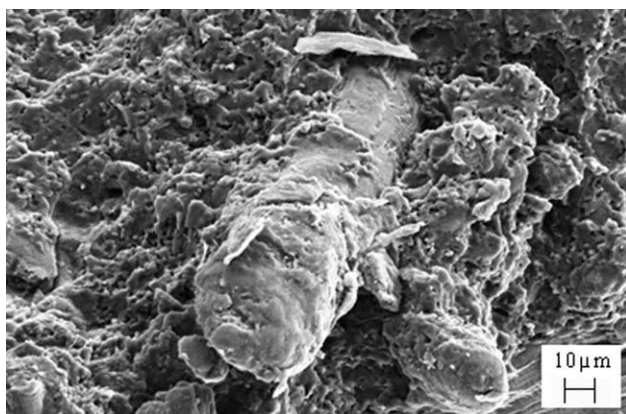


Figure 6 SEM micrographs of 5% MAPP-treated PP/KF composite (PP/KF40/M5).

well as the longitudinal voids caused by fiber pull-out on the other fracture plane. However, the fiber-matrix interaction was poor, which can be observed through the slightly loose interface where the fiber is protruding. The poor interfacial bonding accounts for the poorer mechanical properties of the composites.

The morphology of fracture surface, which shows fiber pull-out, swelling of fiber, and water absorbed in the loose interface, can be observed in the SEM micrograph of wet PP/KF40 shown in Figure 5. The interface between the fiber and matrix can be seen to be severely damaged, and there are large gaps around the fibers, which permit water to enter when sample is immersed in water.

The SEM micrographs of the fractured surfaces of MAPP-treated PP/KF at 40% fiber loading are shown in Figure 6. It can be seen that MAPP treatment has resulted in a clear morphological transformation of PP/KF composites. It reveals a good interaction between the KF and the PP matrix in the presence of MAPP. It is clear that there are very few gaps around the fiber surface and the matrix surface, and better adhesion can be observed in the form of a more cohesive interface between the matrix and fiber where MAPP-treated fibers were nicely embedded in the PP matrix.

CONCLUSIONS

The addition of KF affects the water absorption behavior of composites. The hydrophilic nature of natural fibers is responsible for the water absorption in such composites. The kinetics of water absorption of the PP/KF composites conforms to Fick's law of diffusion. The maximum water absorption, M_m , and the apparent diffusion coefficient, D , values are dependent on the KF content. The M_m and D values increase with increasing fiber content because there are more hydrophilic sites available for water absorption. Water absorption leads to a buildup of moisture in the fiber cell walls, which then results in

fiber swelling, and this adversely affects the dimensional stability.

The tensile and flexural properties decreased after water absorption because of the effects of water, which deteriorates the interfacial properties of composites. On the contrary, the impact strengths of notched and unnotched samples increase after water absorption as a result of the plasticization effect of water, which increases the energy absorption in the composite before break. On re-drying, all properties were recovered because of the recovery of the interfacial interaction.

The compatibility between fiber and matrix improved after adding the MAPP compatibilizer at 5 wt %. This causes higher water resistance, better dimensional stability, and better tensile, flexural, and impact properties of the composites.

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