Mechanical Properties and Dynamic Mechanical Analysis of Thermoplastic-Natural-Rubber-Reinforced Short Carbon Fiber and Kenaf Fiber Hybrid Composites

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ABSTRACT: The hybridization of thermoplastic natural rubber based on carbon fiber (CF) and kenaf fiber (KF) was investigated for its mechanical and thermal properties. Hybrid composites were fabricated with a melt-blending method in an internal mixer. Samples with overall fiber contents of 5, 10, 15, and 20 vol % were subjected to flexural testing, and samples with up to 30% fiber content were subjected to impact testing. For flexural testing, generally, the strength and modulus increased up to 15 vol % and then declined. However, for impact testing, higher fiber contents resulted in an increment in strength in both treated and untreated composites. Thermal analysis was carried out by means of dynamic mechanical analysis on composites with 15 vol % fiber content with fractions of CF to KF of 100/0, 70/30, 50/50, 30/70, and 0/100. Generally, the storage modulus, loss modulus, and tan δ for the untreated hybrid composite were more consistent and better than those of the treated hybrid composites. The glass-transition temperature of the treated hybrid composite was slightly lower than that of the untreated composite, which indicated poor damping properties. A scanning electron micrograph of the fracture surface of the treated hybrid composite gave insight into the damping characteristics. J Appl Polym Sci 107: 4043–4052, 2008

Key words: composite; glass transition; mechanical properties

INTRODUCTION

Hybrid reinforcement offers a range of properties that cannot be obtained with a single kind of reinforcement.[1] In addition, careful selection of fibers will substantially reduce the materials cost. Through hybridization, the advantages of one type of fiber could complement what is lacking in another fiber.[2] Thus, it is possible to design a material that has balance in cost, performance, and environmental advantages to better suit various requirements and applications through proper materials design.[2–4]

Thermoplastic natural rubber (TPNR) is a blend of natural rubber (NR) with any polyolefin. It properties lie between rubber and plastic. The advantage of TPNR is it can be processed with any thermoplastic machinery at comparable prices.[5] It is benefited by the addition of filler or reinforcement into the TPNR because this may reduce prices and somehow increase the performance as well.[6] Reinforcement can be done with either natural or synthetic fibers with pros and cons factors.

Carbon fibers (CFs) with high stiffnesses are preferable to glass fibers, especially where excellent mechanical properties combined with low density are required. Many attempts have been made to incorporate CFs into the thermoplastic matrix with an aim to upgrade the properties of plastics. Studies of short CFs reinforced with the thermoplastic elastomer ethylene/styrene butylene have revealed that there were improvements in modulus, hardness, and damping behavior.[7] However, traditional composite structures made of carbon, glass, and aramid fibers have contributed to an increase in environmental awareness. For this reason, renewable natural fiber reinforcement in composites is gaining attention by many researchers.

Kenaf fiber (KF), which is extracted from the *Hibiscus cannabinus L* plant, is receiving attention through the combination of its fibers with thermoplastics as a method for developing new types of composites. Apart from its lower cost, KF is also low in density, nonabrasive, and biodegradable and has fairly good mechanical properties.[8–14] KF, which is derived from renewable resources, is suitable for use in automo-

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tive applications, building, appliance, and so on. However, the enhancement of these applications is limited by some major drawbacks that need to be considered during blending, which include a lower processing temperature, high moisture uptake, and incompatibility between hydrophilic fibers and hydrophobic thermoplastic matrices.[8]

In this study, TPNR-reinforced short CF and KF hybrid composites were prepared to investigate the mechanical and thermal properties of the composites. A study on the effect of fiber loading, fiber fraction, and surface treatment applied on the tensile properties of TPNR-reinforced CF and KF hybrid composites was conducted and was discussed in an earlier article.[15] Thus, the objective of this article is to report recent studies of the hybrid composites (USA) with respect to their flexural and impact properties and dynamic mechanical analysis (DMA).

EXPERIMENTAL

Materials

Kenaf bast fibers (KFs) were obtained from Malaysia Agriculture and Research Development Institute (MARDI) (Serdang, Selangor, Malaysia). The density of KF measured was 1.13 g/cm^3. Polyacrylonitrile-type CF was procured from Toray (Tokyo, Japan). The density of CF was 1.95 g/cm^3, and the fibers were 6 mm in length. Polypropylene (PP) was supplied by Polipropilinas (Malaysia) Sdn. Bhd. (Ltd) and had a density of 0.905 g/cm^3. Maleic anhydride (MA) grafted polypropylene (MAPP) was purchased from Aldrich Chemical Co. (St. Louis, MO) and had a density of 0.95 g/cm^3. The MA content in MAPP was about 0.57%. NR-type Standard Malaysia Rubber-Light (SMR-L) with a density of 0.92 g/cm^3 was supplied by Guthrie Sdn. Bhd. (Ltd.), Perak, Malaysia, and liquid natural rubber (LNR) was prepared by a photochemical degradation technique in our laboratory.[16]

Preparation of KF

The KF obtained was harvested at 4 months of age. The fibers were then ground with an Ika Werke MF10 heavy-duty grinder (Staufen, Germany). Then, the fibers were sieved to obtain fibers 300–500 μm in size (the size chosen was based on optimum tensile strength).

CF surface treatment

Sulfuric acid surface oxidative treatment was used on CF. First, 1*M* sulfuric acid was heated to 70°C. This was followed by soaking of the fibers in the acid solution for 90 min. Refluxing of the CF was later followed with 1*M* sodium hydroxide for 60 min. Then, the CFs were resoaked in distilled water for another 5 days. Finally, the CFs were rinsed with distilled water and later dried for 3 h at 110°C. The dried CFs were kept in a dessicator to minimize the moisture content before use.

Preparation of the TPNR matrix

TPNR was prepared via the melt-blending of NR, LNR, and PP at volume ratio of 20/10/70 with a Thermo Haake 600p internal mixer. The samples were prepared at 180°C with a rotation speed of 50 rpm for a period of 12 min.

Hybrid composite preparation

The TPNR–KF–CF hybrid composite was compounded with the same internal mixer at 175°C at 9 rpm for 12 min of processing time. Before mixing, the TPNR and KF were handmixed into different loadings. TPNR and KF were allowed to mix for 5 min before CF was charged. The fiber contents were varied at 5, 10, 15, and 20 vol % for flexural testing, whereas up to 30 vol % was used for impact testing. For DMA studies, the overall fiber content was fixed at 15% loading with ratios of CF to KF of 100/0, 70/30, 50/50, 30/70, and 0/100 (Table I). Finally, the compound was transferred into a dumbbell-shaped mold for the compression-molding process for 16 min.

Composite characterization

Flexural strength was measured under a three-point-bending approach with a Testometric 350 instrument (Lancashire, UK) according to ASTM D 790. The distance between the spans was 100 mm, and the strain rate was 5 mm/min. Impact testing was carried out with a Ray Ran Pendulum Impact System (Warwickshire, UK) according to ASTM D 256-90b. All samples were notched before testing. Morphological observation of the tensile fracture surface of the hybrid composites with fibers at various ratios (CF/KF) was done by a scanning electron microscope (Philips XL 30, USA). The fracture ends of the samples were mounted on an aluminum stub and coated with a thin layer of gold to avoid electrostatic charging during examination.

TABLE I
Proportions of CF and KF in the Composites

Designation on the graph		Proportion of the fiber
UTK	TK	0% CF/100% KF
UTH 3C/7K	TH 3C/7K	30% CF/70% KF
UTH 5C/5K	TH 5C/5K	50% CF/50% KF
UTH 7C/3K	TH 7C/3K	70% CF/30% KF
UTC	TC	100% CF/0% KF

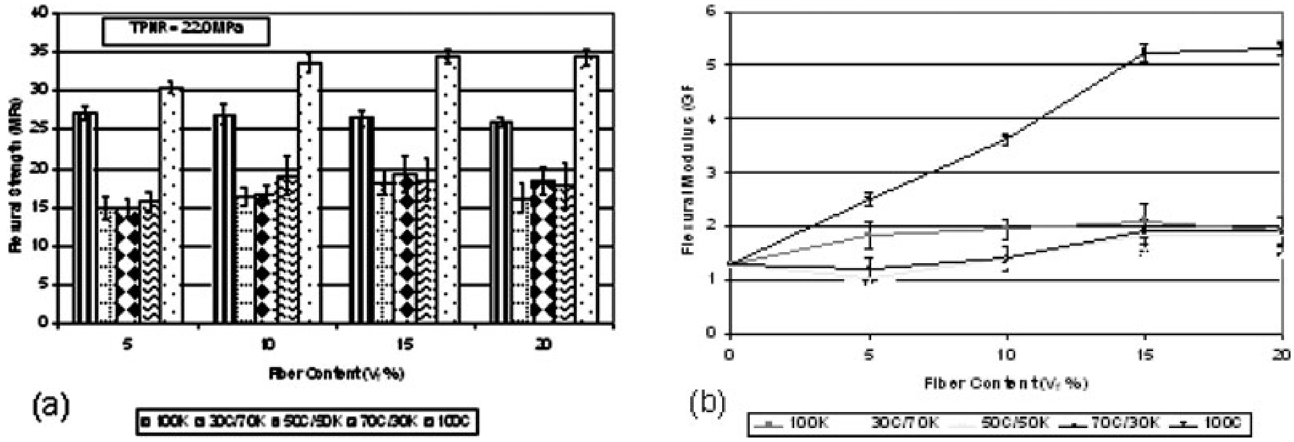


Figure 1 Effect of the fiber loading and variation in the fiber fraction on the flexural (a) strength and (b) modulus of the untreated hybrid composites.

DMA

DMA for the determination of the glass-transition temperature (T_g) was carried out with a DMA 2980 instrument (TA Instruments) operating in single-cantilever mode from −100 to 100°C at a constant frequency of 1 Hz and at a heating rate of 5°C/min. Sample dimensions were 30 × 12.5 × 3 mm^3. Liquid nitrogen was used to achieve subambient temperatures.

RESULTS AND DISCUSSION

Flexural properties

Untreated hybrid composites

Figure 1(a,b) shows the effect of the fiber content and variation of fiber fraction on the flexural properties of the untreated hybrid composite. As shown in Figure 1, an increase in the KF content from 5 to 20% did not much affect the flexural strength and modulus. This was as expected because it was known that KF was hydrophilic, whereas the TPNR matrix was hydrophobic. Thus, there would not be compatibility between the fiber and the matrix. Previous studies have reported that the flexural properties were affected by fiber–fiber interactions, the alignment of the fiber with the matrix, the presence of voids, dispersion, and the location of resin-rich areas.[17,18]

As for carbon composite, as shown in Figure 1, an increase in the fiber content from 5 to 20% slightly increased the flexural strength and obviously increased the flexural modulus of the carbon composite. The slight increase in flexural strength was due to the inert surface layer of CF, which caused no interaction with the matrix. However, the increment in flexural modulus was expected because CF was known to be very stiff. Hence, the higher the fiber content was, the higher the flexural modulus was obtained. However, at higher fiber contents, a reduction in modulus occurred. This was due to more dominant fiber-to-fiber interactions that hindered the stress transfer effectively from matrix to fiber.

As for the hybrid composites, as shown in Figure 1(a,b), the flexural strength and modulus were lower than the carbon composite and kenaf composite. Thus, this showed the incompatibility between CF and KF in the TPNR matrix. Other than incompatibility, the fiber aspect ratios also played a crucial role in the determination of the mechanical properties of the composites produced. This effect was amplified at higher fiber contents and agreed well with Rozman et al.[21] in his study on glass/empty fruit bunch fiber reinforced PP. However, it is interesting to note that at lower fiber contents (5 and 10%), the composite with a higher fraction of CF (70CF/30KF) exhibited a higher flexural strength. Nevertheless, at higher fiber contents (15 and 20%), the fraction of 50CF/50KF gave the highest strength, which responded to the synergistic effect of the hybrid composite. The synergism obtained may have been associated with better fiber arrangement and may have reduced the empty space between the fiber, matrix, and fiber. This effect may have increased the mechanical properties of the composites.

Treated hybrid composites

Figure 2(a,b) describes the effect of fiber loading and variation of the CF/KF ratios over the flexural strength and modulus ranges of the treated hybrid composites. As shown in Figure 2(a,b), as the KF content increased from 5 to 20%, the flexural properties were improved by about 21%. The increment in flexural properties with increasing fiber content was

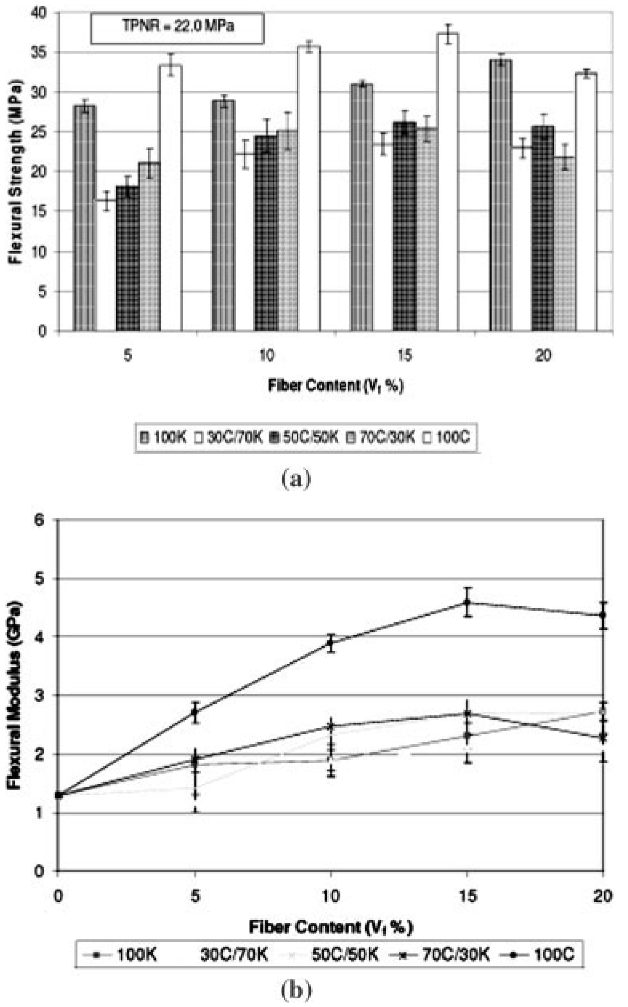


Figure 2 Effect of the fiber content and fiber fraction on the flexural (a) strength and (b) modulus of the treated hybrid composites.

expected and has been observed by other researchers.[9–14] This was attributed to the presence of MAPP, which promoted the interaction between TPNR and OH^- in KF. Good interaction, which led to better stress transfer, enhanced the properties obtained.

As shown in Figure 2(a,b), the enhancement of the flexural strength and modulus from 5 to 20% occurred with CF content. The improvement in flexural properties was due to the oxidative surface treatment applied on the CFs. The treatment applied on the shell of the inert surface layer and smooth surfaces of the CFs resulted in a roughened surface of the CFs. The roughened surface may have provided a mechanical interlocking mechanism with TPNR. However, at higher fiber contents, the graph showed a declination in flexural properties. This was ascribed to the fiber and more dominant fiber interaction, which failed to effectively transfer the stress from matrix to fiber.

As shown in Figure 1, similar trends were observed for the flexural strength and modulus of the treated hybrid composite. The treated hybrid composite displayed the lowest flexural strength and modulus compared to the kenaf composite and carbon composite. This showed that the incompatibility factor, nature of the natural and synthetic fibers, fiber aspect ratio, and consistency of fiber dimensions influenced the flexural properties of the hybrid composite. However, the strength and modulus of treated hybrid composite were slightly higher than that of the untreated hybrid composite. The same trend was also seen at lower fiber content, where the composite with a higher CF fraction demonstrated a higher flexural strength. Nevertheless, at higher fiber content fractions, 50CF/50KF showed comparable flexural strength and modulus values compared to the composite with a dominant CF fraction.

Impact properties

Impact strength is the measure of toughness, which is defined as the ability of materials to absorbed applied energy.[19] The effects of fiber content and variation fraction of KFs and CFs on the Izod impact strength of the hybrid composite are exhibited in Table II. Generally, increments in the fiber content from 5 to 30% increased the impact strength of the untreated and treated composite compared to that of the TPNR matrix. This showed that fibers incorporated acted as reinforcements in the composite and, thus, increased the impact strength.

As shown in Table II, the kenaf composite strength gradually increased with the addition of KFs from 5 to 30% fiber content. However, the impact strength slightly increased with the presence of MAPP as a coupling agent between KF and TPNR, as shown in Table II. This was expected, as reported by previous researchers.[9,11,14] This shows that MAPP had improved fiber and matrix interaction by the formation of chemical linkages and prevented the frictional force involved in fiber pullout.

TABLE II
Effect of the Fiber Volume Fraction and Fiber Loading on the Impact Strength of the TPNR–CF–KF Hybrid Composites

Untreated	0%	5%	10%	15%	20%	25%	30%
100K	3.3	3.4	4.4	4.4	4.8	5.2	5.7
30C/70K	3.3	3.9	7.5	9.8	11.4	13.1	15.3
50C/50K	3.3	6.1	12.2	14.8	14.9	17.9	24.3
70C/30K	3.3	6.4	13.1	19.3	20.5	20.8	30.1
100C	3.3	7.7	13.8	17.9	19.5	39.6	40.6
Treated	0%	5%	10%	15%	20%	25%	30%
100K	3.3	4.7	5.0	5.3	5.8	5.8	5.7
30C/70K	3.3	5.2	6.3	6.9	9.1	9.8	8.6
50C/50K	3.3	5.9	6.4	11.4	11.8	12.3	13.2
70C/30K	3.3	7.3	9.0	11.8	13.0	13.5	14.5
100C	3.3	7.7	12.8	17.1	19.3	21.3	26.0

For the untreated carbon composite, a significant improvement in the impact strength from 5 to 30% by almost 427% was observed, as exhibited in Table II. The same trend was observed for the sulfuric-treated carbon composites, as shown in Table II, with higher fiber content; the same was true for impact strength. However, the impact strength for treated carbon composites obtained was lower compared to that of the untreated carbon composites. This revealed that apart from the roughening the CF surface, the treatment applied caused the fiber to be brittle and easily fractured. It has been reported that even though the principal effects of CF surface treatment on composite properties are an increase the interlaminar shear strength and flexural and tensile strengths, surface-treated CFs usually undergo a loss of impact fracture toughness or notched tensile strength.[35]

As for the untreated hybrid composites, the expected trends were observed, where the impact strength for the hybrid composites were between the kenaf composite and the carbon composite. However, it is interesting to note that at 15 and 20% fiber content for the 70CF/30KF fraction, the impact strength obtained was even higher than that of the composite with 100% CF. This showed a positive hybrid effect of the TPNR–CF–KF hybrid composite that makes this composition viable for application as an impact modifier. As exhibited in Table II, the impact strength for the treated hybrid composite fell between the carbon composite and the kenaf composite. Generally, the impact strength obtained was slightly lower than that of the untreated hybrid composite. This could have been due to the effect of brittle CF, which resulted in a lower strength. Thus, this showed that the CF content significantly affected the impact properties.

DMA

DMA is a unique technique for studying composite structure and performance. Because the polymer was

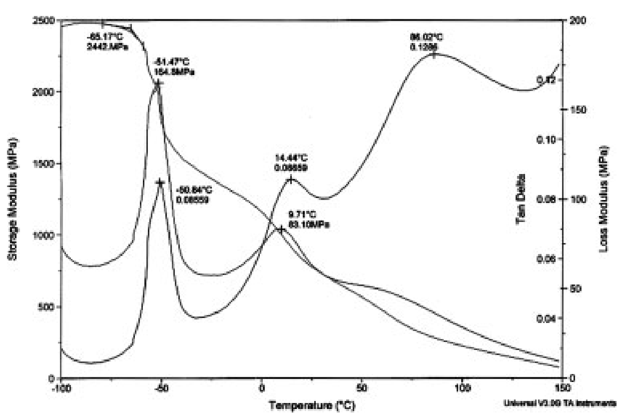


Figure 3 DMA thermogram of TPNR-toughened PP at a 30/70 ratio with 10% LNR.

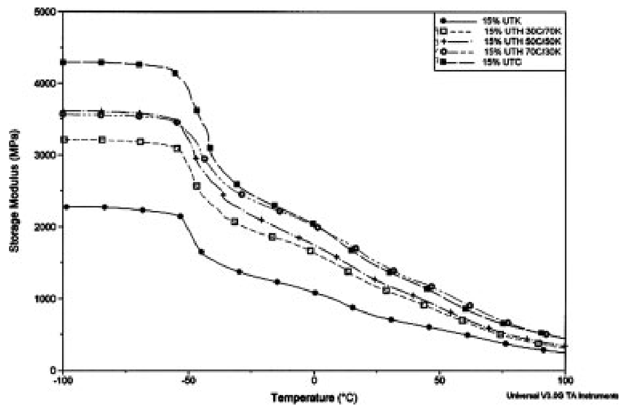


Figure 4 Effect of the fiber loading on E' of the hybrid composites.

viscoelastic, a complete description of the properties could be provided by dynamic experiments conducted over a range of time, temperature, and frequency.

Figure 3 shows the typical thermogram of the TPNR sample. The loss modulus (E'') decreased with increasing temperature. A sharp drop in storage modulus (E') occurred around −55°C, where TPNR experienced the glass transition to the rubbery state. T_g of TPNR was at −50.8°C due to the presence of NR. β-Relaxation refers to the movement of the amorphous segment, which occurred at 14.4°C. Another transition, the α-relaxation, refers to the mobility of the PP backbone in the crystalline phase, which was seen at 86.0°C. The thermogram of TPNR obtained was comparable to that found in previous work by Ibrahim and Dahlan.[20]

Effect of the fiber fraction

It is well known that incorporation of fibers or fillers may alter the composite mechanical properties. However, the properties obtained depend on the fiber factors, for example, low aspect ratios, fibers in bundle form, or defects in the fibers themselves. Figure 4 shows E' of the TPNR-reinforced short CF and KF hybrid composites. A variation in modulus occurred because of the effect of different fiber fractions incorporated into the hybrid system. At low temperature, E' for the untreated KF/TPNR was lower compared to that of the untreated CF/TPNR. This showed that KF contributed less stiffness to the composite in the glassy state. However, the addition of CF increased the E' value in the low-temperature region. A sharp drop was observed in the area of −55 to −45°C, which was associated with the T_g of NR. E' continued to drop after the glass-transition region.

Instead of the elastic E', DMA is capable of characterizing the viscous modulus or E'' of the polymer.

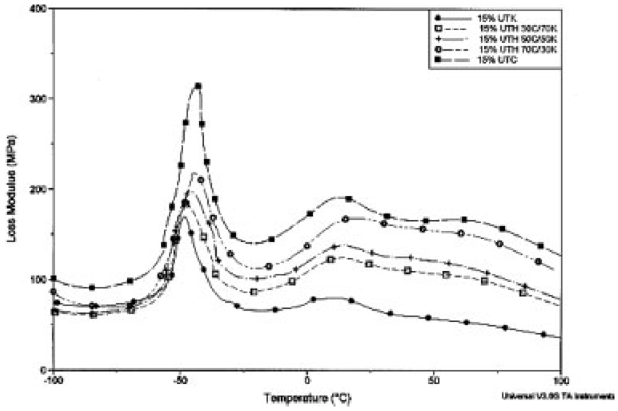


Figure 5 Effect of the fiber loading on E'' of the hybrid composites.

Figure 5 shows the thermogram of E'' of the TPNR-reinforced short CF and KF hybrid composites. The results show that the E'' value increased with the addition of CF from 30, 50, 70, to 100 vol % CF in the TPNR matrix. This indicates that heat dissipation increased with CF loading. Details of E'' and tan δ are summarized in Table III.

As shown in Figure 3, the TPNR showed an E'' peak at −51.5°C, which was associated with the mobility of the TPNR molecules. The peak almost coincided with the tan δ peak, which was considered the T_g of TPNR. In the composites incorporated with untreated fibers (Fig. 5 and Table II), the primary transition peak shifted to higher temperatures that were between −48.3 and −43.6°C for composites containing fibers from 0 to 100% CF fractions. The resulting higher temperatures could have been due to the immobilization of the polymer molecules near the surface of the fibers incorporated due to various molecular interactions. This was similar to the results of studies reported by Rana et al.[21] and Saha et al.[22] The E'' value corresponding to the E'' peak was lowest for TPNR (164.8 MPa) but substantially increased in the untreated hybrid composites (169.7, 183.6, 197.5, 217.3, and 312.6 MPa for the UTK, UTH3C7K, UTH5C5K, UTH7C3K, and UTC composites, respectively). Rana et al.[21] also reported a similar increase in the E'' temperature and E'' due to the incorporation of fibers. As also shown in Figure 5, a tiny hump was observed in the E'' versus temperature curves for all of the composites at temperature between −25 and 25°C. However, when the CF fraction was higher, the second peak (tiny hump) became rather nonprominent.

Tan δ, better known as a damping behavior, is related to the impact resistance of a material. A material will change from rigid to the elastic state with the movement of small groups and the chains of molecules within the polymer structure. In fiber-reinforced composites, damping is affected by the presence of fibers. Figure 6 shows the thermogram of tan δ of the TPNR-reinforced short CF and KF hybrid composites. In general, the increasing trend of T_g was observed with the presence of CF in TPNR/KF, which restricted the polymer chain mobility. It is interesting to note that T_g of the hybrid composite was between those of the TPNR/KF and TPNR/CF composite. As in TPNR/CF, the lower T_g obtained could have been due to the consistency of the aspect ratio as compared to the inconsistency of the KF aspect ratio. Thus, the incorporation of CF into the TPNR/KF composite showed a positive shift of T_g, which stressed the effectiveness of CF as a reinforcing agent. The T_g obtained was consistent with the E'' values, and this was similar to the result obtained by Ray et al.[23] on vinyl ester reinforced jute fibers; they reported that the increments of T_g and E'' were due to the incorporation of fiber. However, the magnitudes of tan δ for the TPNR/KF and TPNR/CF composites were higher as compared to that of the hybrid composite. This was due to the agglomeration of fibers or fiber–fiber contact.[24] The β-transition

TABLE III
Effect of the Fiber Loading on the Damping Behavior of the Composites

Sample		E''		Damping parameter	
		°C	MPa	°C	Tan δ_{max}
15UTK	Peak 1	−48.31	169.7	−47.68	0.0934
	Peak 2	10.34	79.98	17.27	0.0907
15UTH3C7K	Peak 1	−47.37	183.6	−46.42	0.0715
	Peak 2	13.81	124.2	14.05	0.0520
15UTH5C5K	Peak 1	−46.11	197.5	−44.53	0.0697
	Peak 2	14.44	138.4	15.23	0.0944
15UTH7C3K	Peak 1	−44.78	217.3	−43.52	0.0735
	Peak 2	17.78	168.2	25.83	0.1097
15UTC	Peak 1	−43.58	312.6	−42.95	0.0931
	Peak 2	12.54	191.3	15.48	0.1108

Tan δ_{max}, damping behavior at maximum peak.

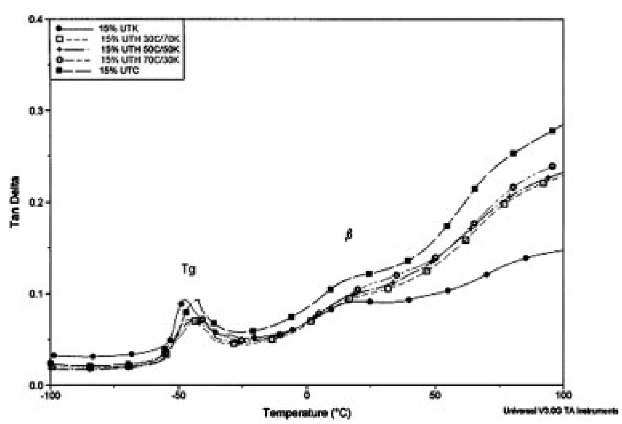


Figure 6 Effect of the fiber loading on tan δ of the hybrid composites.

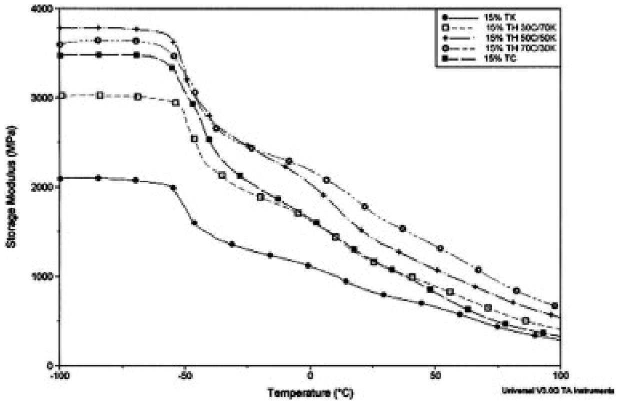


Figure 7 Effect of the applied treatment on E' of the hybrid composites.

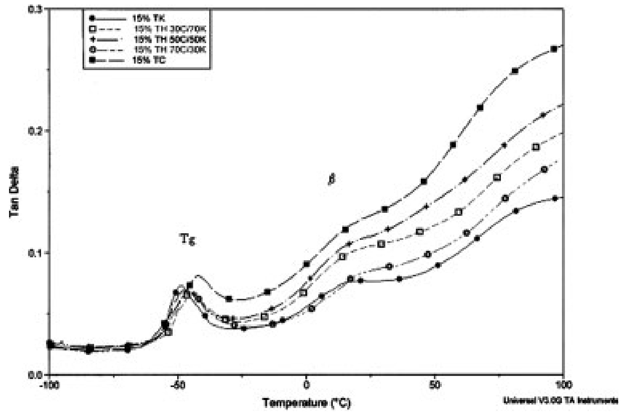


Figure 8 Effect of the applied treatment on tan δ of the hybrid composites.

was not very sharp, especially for the hybrid system. This indicates that the fibers masked the β-transition and, thus, changed the morphology; however, it was a minor transition and played no significant role. In reinforced TPNR, the β-relaxation was reflected in the amorphous phase of the PP segment.

Effect of the coupling agent and surface treatment

On the basis of Figures 3–6, the dynamic mechanical properties of TPNR and the series of TPNR composites was generally influenced by the fiber incorporated and the types of fibers. Rana et al.[21] reported that the dynamic mechanical properties of their composites were dependent on the fiber content; the presence of the additives such as filler, compatibilizer, and impact modifier; the fiber orientation; and the mode of testing. Thus, in this part, we discuss on the effect of the coupling agent and surface treatment used on the fibers incorporated. Figure 7 shows the thermogram of E' of the TPNR-reinforced treated short CF and KF hybrid composites. From the thermogram, one can see that E' increased with up to 50% CF fraction and then dropped at higher CF contents. E' for 15% treated CF was even lower than that of untreated TPNR/CF. The reduction in E' could have been due to the softening effect. As reported by Yang,[26] the softening effect refers to the softening phase that exists between the fiber and the matrix. This effect is more pronounced in the elastic microscopic properties of inorganic filler. On the other hand, E' for treated TPNR/KF was also lower than that of untreated TPNR/KF. Several factors could be associated with this system, as described by Sanadi et al.[27] for lignocellulosic reinforced PP on the lower β-transition obtained. This factor included the use of a coupling agent, MAPP, or a lubricating effect. MAPP may have interacted either with hydroxyl on the cellulose or between neighboring MAPPs, which could have altered the fiber orientation. We expected MAPP reacted with treated CF and, thus, affected CF as a reinforcing fiber.

The effect of the surface treatment on the damping behavior of the hybrid composites is depicted in Figure 8. The magnitude of peak height, as tabulated in Table IV, was slightly lower as compared to that of the untreated hybrid composite. However, T_g was slightly higher than that of the untreated hybrid composite. This reflects the better impact properties of untreated hybrids, as reported by Aziz and Ansell[28] in polyester-reinforced KFs. As for the β-transition, the temperature and magnitude decreased with KF content. However, the incorporation of CF increased the damping properties. This suggests that the phase separation that occurred between KF–MA–PP and CF–NR was due to the chemistry of the fibers and TPNR. This effect was decreased by different fiber aspect ratios of natural and synthetic fibers, as observed in the scanning electron microscopy (SEM) micrograph shown in Figure 9. A proba-

TABLE IV
Effect of the Applied Treatment on the Damping Behavior of the Composites

Sample		E''		Damping parameter	
		°C	MPa	°C	Tan δ_{max}
15TK	Peak 1	−49.58	126.2	−48.63	0.0731
	Peak 2	13.18	70.72	16.96	0.0763
15TH3C7K	Peak 1	−46.74	166.5	−45.79	0.0666
	Peak 2	13.49	130.7	17.14	0.1000
15TH5C5K	Peak 1	−48.31	214.1	−46.11	0.0689
	Peak 2	12.23	174.3	13.10	0.1040
15TH7C3K	Peak 1	−45.53	198.3	−44.78	0.0667
	Peak 2	18.79	149.1	24.88	0.0830
15TC	Peak 1	−43.58	217.1	−42.32	0.0811
	Peak 2	13.49	161.2	16.55	0.1204

Tan δ_{max}, damping behavior at maximum peak.

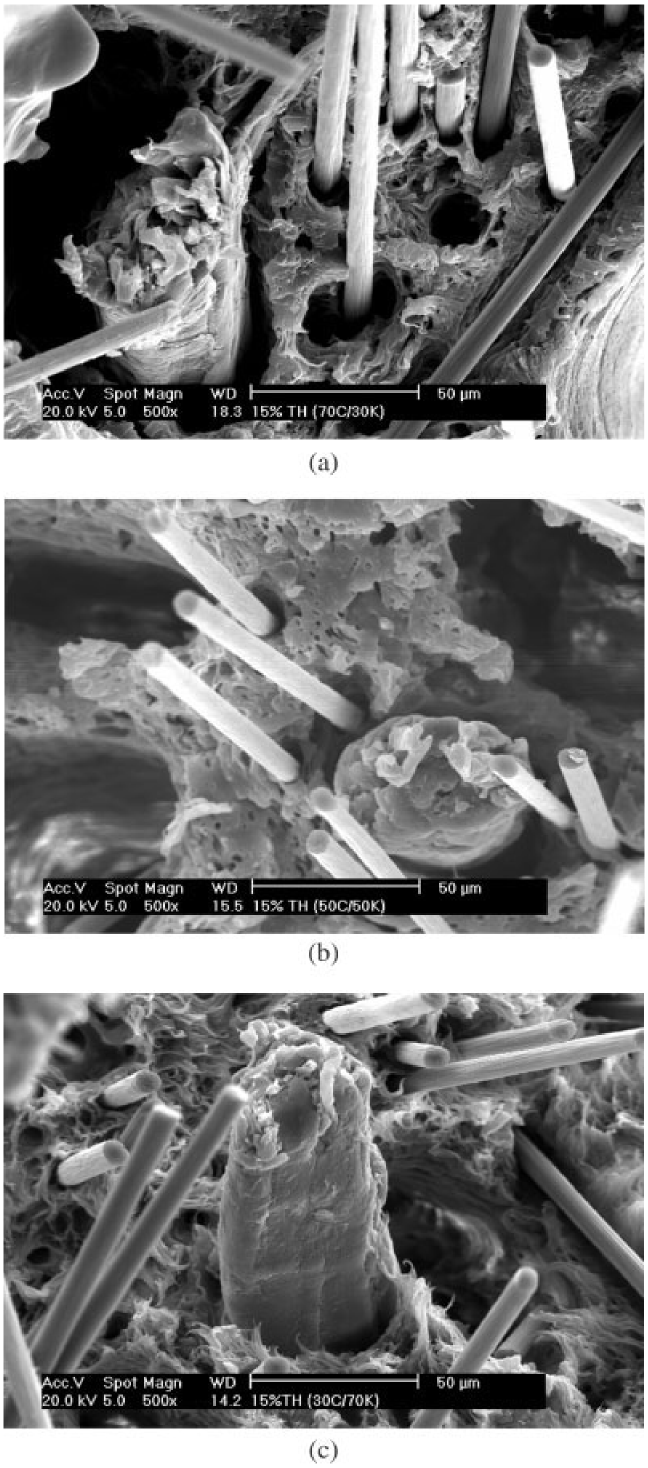


Figure 9 SEM micrographs of the composites with 15% fiber content at 500× magnification: (a) 70CF/30KF, (b) 50CF/50KF, and (c) 30CF/70KF.

ble problem arose in the treated hybrid, as described in Figure 10. (The functional group present in CF was determined via X-ray photoelectron spectroscopy and is not discussed in this article).

According to Finegan and Gibson,[29] there are two types of damping theories that have been developed: macromechanical and micromechanical damping. In this study, micromechanical damping was more prominent, which was due to the fiber aspect ratio, fiber orientation, fiber spacing, fiber–matrix interphase, and fiber and matrix properties. In another article, Chandra et al.[30] reported that the damping mechanism in composites is related to different sources of energy dissipation in fiber-reinforced composites, which are the viscoelastic nature of fibers and matrices; interphase; damage from fibers, matrices, or interphases; and viscoplastic or thermoelastic damping, which is associated with vibration and heat, respectively. Another attempt by Pothan et al.[31] on banana-fiber-reinforced polyester concluded that an improvement in interfacial bonding may have been achieved by a decrease in the tan δ values.

The preoxidative treatment applied on CF before blending in the internal mixer roughened and created pits on the fiber surface. This may have led to mechanical interlocking in the sulfuric-treated CF–TPNR. However, the presence of functional groups due to acid treatment interrupted this mechanical interlocking. This effect was more pronounced at higher fiber contents, as demonstrated in the tensile testing.[15] The topography of the CFs before and after treatment is shown in Figure 11. KF, on the other hand, was hydrophilic because of the presence of OH^- on its surface. Thus, the use of MAPP changed the nature of the kenaf and linkages to hydrophobic TPNR by an esterification reaction, as reported by many researchers.[25,32–34] Therefore, we expected there was no direct interaction in CF–TPNR–KF, as described in Figure 10. As shown in Figure 10, OH^- in KF was attracted to MA in MAPP through chemical linkages. However, the addition of treated CF with exposed functional groups attacked the backbone of NR in TPNR. This effect resulted in the phase separation of the NR and PP blends.

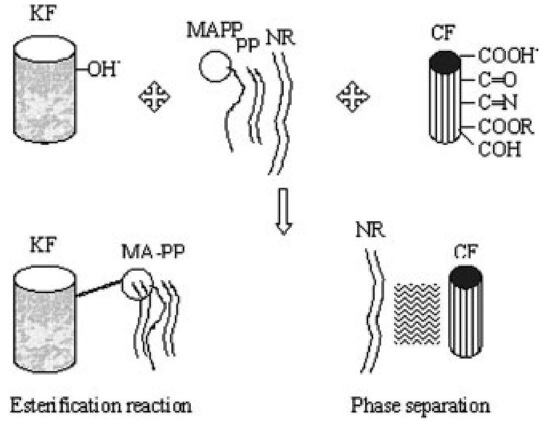
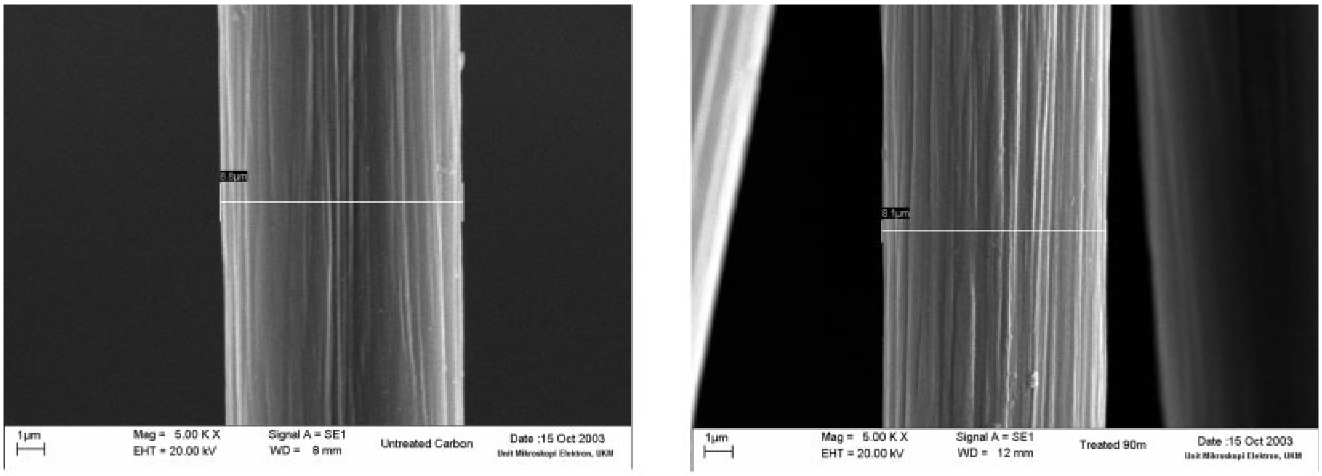


Figure 10 Probable phase separation in a treated hybrid composite.



(a) (b)

Figure 11 SEM micrographs at 5000× magnification of (a) CF before treatment and (b) CF after 90 min of sulfuric acid treatment.

CONCLUSIONS

Our studies showed that the flexural properties (strength and modulus) generally increased with fiber loading. However, the flexural properties for the composite with a single type of reinforcement were better compared to those of the hybrid composite. As for impact strength, the absorbed energy also increased with fiber loading. However, the untreated hybrid composite resulted in a higher strength than the treated one (Figure 12). DMA revealed the real behavior of the TPNR-reinforced short CF and KF hybrid composites. The untreated hybrid composites exhibited higher E' and E'' values and better tan δ values than the treated composites. The lower properties obtained in DMA were due to a low fiber aspect ratio, the random distribution of fibers (as observed in the SEM micrograph), the negative effect of treatment applied on the CFs, and the incompatibility between CF and KF. A problem arose that led to the phase separation of the fiber and matrix and affected the mechanical and thermal properties of the hybrid composites.

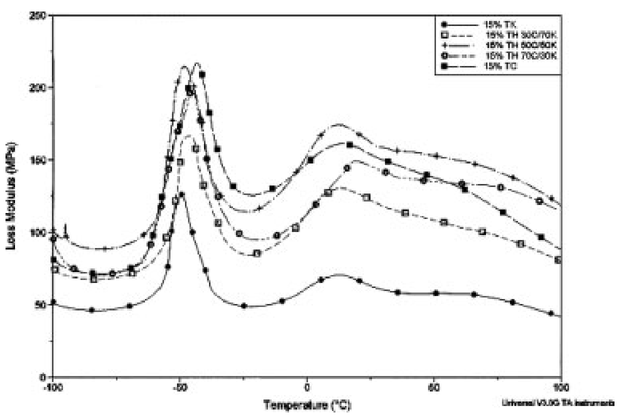


Figure 12 Effect of the applied treatment on E'' of the hybrid composites.

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