Static Mechanical, Interfacial, and Water Absorption Behaviors of Alkali Treated Oil Palm Mesocarp Fiber Reinforced Poly(butylene succinate) Biocomposites

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In this work, oil palm mesocarp fiber (OPMF) was surface-treated with varying NaOH concentrations (1, 3, 5, 7, or 9%) and soaking times (1, 2, 3, or 4 h) at room temperature aiming to enhance its adhesion to the thermoplastic matrix for biocomposite application. The biocomposites from alkali treated OPMFs and poly(butylene succinate) at weight ratios of 70:30 were fabricated by a melt blending technique and hot-pressed moulding. The results indicate that NaOH treatment removed fiber's surface waxes, hemicellulose, and lignin, and produced fiber with rough surface morphology. The tensile results showed that OPMF treated in 5% NaOH solution for 3 h produced biocomposite with enhanced tensile strength (30%), tensile modulus (105%), and elongation at break (16%), as well as reduced water absorption (15%) and thickness swelling (13%) in comparison to that of untreated OPMF. Scanning electron microscopy showed improvement of interfacial adhesion between treated fiber and poly(butylene succinate). These results suggest that NaOH treatment could be an effective form of treatment for OPMF in biocomposites materials.

Keywords: Alkali treatment; Biocomposite; Oil palm mesocarp fiber; Poly(butylene succinate)

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INTRODUCTION

Utilization of natural fibers as filler or reinforcement in biocomposite material has gained increasing interest recently due to their relatively low cost, light weight, availability, renewability, and biodegradability in comparison to those of synthetic fibers (Wambua *et al.* 2003). These natural fiber-reinforced biocomposites showed both economic and environmental advantages over biocomposites reinforced with synthetic fibers (Herrera-Franco and Valadez-Gonzalez 2005; John *et al.* 2008). According to recent publications, natural fibers such as jute (Liu *et al.* 2009), coir (Islam *et al.* 2010; Nam *et al.* 2011), kenaf (Jonoobi *et al.* 2009; Ibrahim *et al.* 2010; Razak *et al.* 2014), and oil palm (Sreekala *et al.* 1997; Sreekala *et al.* 2000; Then *et al.* 2013; Teh *et al.* 2013; Then *et al.* 2014a) have been demonstrated to be effective reinforcements in various thermoplastic matrices. These biocomposites have been used successfully in many industries such as aerospace, automobile, marine, and military.

Oil palm mesocarp fiber (OPMF) is a lignocellulose material left in the palm oil mill after pressing of oil palm fruits to extract crude palm oil (Sreekala *et al.* 1997). Its major chemical components are cellulose, hemicellulose, and lignin (Sreekala *et al.* 1997). The OPMF is normally burned as boiler fuel to self-supply steam and electricity required for the operation in the palm oil mill (Lau *et al.* 2008). However, this method is detrimental to the environment. In this work, the OPMF is utilized in a more sustainable way, by compounding it with biodegradable thermoplastic to fabricate biocomposites. This could be a key role to overcome the environmental problems caused by burning OPMF while developing a value added product.

Poly(butylene succinate) (PBS) is a biodegradable thermoplastic synthesized *via* polycondensation of 1,4-butanediol and succinic acid (Kim *et al.* 2006). It possesses excellent mechanical properties, melt processing capability, and biodegradability (Liu *et al.* 2009). Currently, it is commercially available at prices lower than that of polylactic acid, a plant-based biodegradable thermoplastic (Nam *et al.* 2011). Many investigators have reported on natural fiber/thermoplastic biocomposites; however most of such biocomposites were fabricated using fiber content less than or equal to that of 50 wt.% (Sreekala *et al.* 2000; Herrera-Franco and Valadez-Gonzalez 2005; John *et al.* 2008; Liu *et al.* 2009; Ibrahim *et al.* 2010; Nam *et al.* 2011; Teh *et al.* 2013; Razak *et al.* 2014). These biocomposites may not be cost effective, as the price of thermoplastic is relatively higher than that of fiber. For this reason, biocomposite with 70 wt.% fiber content is fabricated in this study aiming to produce a price-competitive material.

The critical issues in natural fiber/thermoplastic biocomposites are poor interfacial adhesion between these two phases, owing to the dissimilarity in surface polarity, and poor dimensional stability resulting from the high moisture uptake of fiber itself (Kalia *et al.* 2009). Currently, various treatment methods such as silane (Sreekala *et al.* 2000; John *et al.* 2008; Eng *et al.* 2014), alkali (Sreekala *et al.* 2000; Xiao *et al.* 2001; Mwaikambo and Ansell 2002; Mohd Edeerozey *et al.* 2007; John *et al.* 2008; Ibrahim *et al.* 2010), alkali-peroxide (Eng *et al.* 2014; Razak *et al.* 2014), and grafting (Sreekala *et al.* 2000; Teh *et al.* 2013) are used in natural fiber surface modification. Among them, alkali treatment has proven to be one of the simplest, most economical, and most effective forms of treatment with the least environmental impact (Xiao *et al.* 2001). In this treatment, sodium hydroxide (NaOH) is preferred because of its low cost (Mohd Edeerozey *et al.* 2007). The NaOH treatment can remove the wax, oil, hemicellulose, lignin, and pectin that are present on the surface of the fiber cell (Mwaikambo and Ansell 2002). The removal of these substances can increase the surface roughness of fiber and promote the adhesion between thermoplastic and fiber, particularly *via* a mechanical interlocking mechanism (Mohd Edeerozey *et al.* 2007; John *et al.* 2008). Study done by Nam *et al.* (2011) revealed that alkali-treated coir fiber improved the tensile and flexural properties of the coir fiber-reinforced PBS biocomposite.

In this paper, OPMF was treated with NaOH, aiming at modification of the fiber's surface. The structural and chemical changes that occurred to the fiber upon NaOH treatment were characterized by means of Fourier transform infrared spectroscopy, scanning electron microscopy, and X-ray diffraction analysis. The influence of NaOH-treated OPMF on the mechanical properties and dimensional stability of OPMF/PBS biocomposite was reported. The interfacial property of the biocomposite was examined using scanning electron microscopy and short beam shear test.

EXPERIMENTAL

Materials

Poly(butylene succinate) (PBS), under the trade name of BIONOLLE[TM] 1903MD, was purchased from Showa Denko (Japan). It has a density of 1.26 g/cm^3 and a melting point of ~115 °C. Oil palm mesocarp fiber (OPMF) was obtained from FELDA Serting Hilir Palm Oil Mill (Malaysia). It was washed by soaking in distilled water for 24 h, rinsed with hot water (60 °C), and finally rinsed with acetone prior to drying in an oven at 60 °C. This process was carried out to remove dirt from the fiber surface. The dried fiber was then ground, sieved into a particle size of 150 to 300 μm, and stored in a sealed polyethylene bag for use in the chemical treatment process and biocomposites fabrication. The properties of OPMF were reported in our previous work (Then *et al.* 2014b). Analytical grade NaOH pellets were purchased from Merck (Germany), and used as received.

Methods

Modification of OPMF by NaOH treatment

The OPMF was oven dried at 60 °C prior to the modification process. The modification was carried out according to the method described previously (Ibrahim *et al.* 2010). In brief, the dried OPMF was soaked in 1, 3, 5, 7, or 9% NaOH solution for 3 h at room temperature. The ratio of OPMF/NaOH solution was fixed at 1:20. After the treatment, samples were filtered, washed several times with water, and finally dried in an oven at 60 °C. Another experiment was conducted with the same procedure as above except the OPMF was soaked in 5% NaOH solution for 1, 2, or 4 h at room temperature to determine the best soaking time for the treatment. The reaction between NaOH and OPMF is shown in Scheme 1.

$$\text{OPMF-OH} + \text{NaOH} \longrightarrow \text{OPMF-O}^-\text{Na}^+ + \text{H}_2\text{O}$$

Scheme 1. Reaction between NaOH and OPMF

Preparation of biocomposites

The PBS and fibers (OPMF or NaOH-treated OPMFs) were dried in an oven at 60 °C prior to use. The biocomposites were prepared by melt blending PBS and fibers in a Brabender internal mixer (Germany) at 120 °C with 50 rpm rotor speed for 15 min (Then *et al.* 2013). The weight ratio of OPMF/PBS was fixed at 70:30. In brief, the PBS pellet was first loaded in the mixer chamber for 2 min to melt. Next, fibers were added into the mixing chamber and mixing was continued for another 13 min. These compounded materials were then compressed into 1- and 3-mm thickness sheets with length of 150 mm and width of 150 mm by a hydraulic hot-press at 120 °C for 5 min under pressure of 14.70 MPa, followed by cold pressing at 30 °C for 5 min.

Fourier transform infrared (FTIR) spectroscopy

The functional groups and types of bonding in fibers were determined by a Perkin Elmer Spectrum 100 series spectrophotometer (USA) equipped with attenuated total reflectance (ATR). The FTIR spectra of the fibers were recorded in the range of frequency of 400 to 4000 cm^{-1}.

X-Ray diffraction (XRD) analysis

The crystallinity of the fibers was determined using a Shimadzu XRD 6000 diffractometer (Japan) with a nickel filtered Cu Kα (λ = 0.1542 nm) beam operated at 30 kV and 30 mA. The samples were scanned at the 2θ range of 10 to 30° with a scanning rate of 2°/min at 25 °C. The crystallinity index (CrI) was calculated from the XRD data and determined based on Eq. 1, as stated by Segal *et al.* (1959),

$$CrI\left(\%\right) = \frac{I_{002} - I_{am}}{I_{002}} \times 100 \qquad (1)$$

where I_{002} is the maximum intensity of diffraction peak at a 2θ of 22 to 23° and I_{am} is the intensity of diffraction of the amorphous material which was taken at a 2θ of 18°, where the intensity is at a minimum.

Scanning electron microscopy (SEM)

The microstructures of the fibers and the tensile fracture surface of the biocomposites were examined using a JEOL JSM-6400 scanning electron microscope (Japan) operated at a 15-kV accelerating voltage. All of the samples were coated with gold by a Bio-Rad coating system prior to analysis.

Interfacial properties measurement

A short beam shear (three point bending) test was conducted on the biocomposites according to the ASTM D2344 (2000) standard using an Instron Universal Testing Machine model 4302 (USA) equipped with a 1-kN load cell. The test specimens were cut into the dimension size of 25.0 mm × 12.7 mm × 3.0 mm. The test was performed at 25 °C with a constant crosshead speed of 1.3 mm/min and span length of 15 mm. The results were expressed in terms of apparent interlaminar shear strength. The test was performed on five specimens for each formulation, and the average values and standard deviations were reported.

Tensile properties measurements

A tensile test was carried out on the biocomposites using a Universal Testing Machine (Instron 4302), equipped with 1 kN load cell. The test specimens were cut from 1 mm sample sheets using a dumbbell shape cutter of ASTM D638-5 (2000) standard. A crosshead speed of 5 mm/min was used, and the tests were performed at 25 °C. The results were expressed in terms of tensile strength, tensile modulus, and elongation at break. The test was performed on five specimens for each formulation, and the average values and standard deviations were reported.

Flexural and impact properties measurements

A three-point bending test was conducted on the biocomposites according to ASTM D790 (2000) standard using a Universal Testing Machine (Instron 4302) equipped with 1kN load cell. The rectangular test specimens with dimensions of 127.0 mm × 12.7 mm × 3.0 mm were cut from the sample sheets for testing. The test was conducted at 25 °C with a crosshead speed of 1.3 mm/min and span length of 48 mm. The results were expressed in terms of flexural strength and flexural modulus.

An un-notched Izod impact test was carried out on the biocomposites using an IZOD impact tester equipped with a 7.5-J pendulum at 25 °C, based on ASTM D256 (2000) standard. The test specimens were cut into dimension size of 64.0 mm × 12.7 mm × 3.0 mm. The results were expressed in terms of impact strength.

The above tests were performed on five specimens for each formulation, and the average values and standard deviations were reported.

Water absorption and thickness swelling

Water uptake and thickness swelling tests were conducted on the biocomposites according to ASTM D570 (2005) standard and European Standard EN 317 (2003), respectively. Samples with a dimension size of 10.0 mm × 10.0 mm × 1.0 mm were cut from the 1 mm sample sheets and used for testing. The samples were oven-dried at 60 °C until a constant weight was reached prior to testing. The initial weight (W_0) and thickness (T_0) of the dried samples were measured using a microbalance and caliper, respectively. The samples were then immersed in distilled water for 24 h at 25 °C. After that, the samples were removed from the distilled water and wiped with tissue paper to remove excess water on the surface of the samples. The final weight (W_{24h}) and thickness (T_{24h}) of the samples were measured immediately. The tests were performed in duplicate, and the average values and standard deviations were calculated. The water uptake as well as the thickness swelling of the biocomposites was calculated based on Eqs. 2 and 3, respectively:

$$Water\ Absorption\ (\%) = \frac{W_{24h} - W_0}{W_0} \times 100 \qquad (2)$$

$$Thickness\ Swelling\ (\%) = \frac{T_{24h} - T_0}{T_0} \times 100 \qquad (3)$$

RESULTS AND DISCUSSION

Tensile Properties of Biocomposites

The tensile properties of biocomposite filled with OPMF-treated in NaOH solution of various concentrations for various soaking times are given in Table 1. It was reported that the tensile strength (TS), tensile modulus (TM), and elongation at break (EB) of neat PBS were 37.31 MPa, 248.90 MPa, and 470%, respectively (Then *et al.* 2013). However, the incorporation of 70 wt.% of OPMF in PBS (this biocomposite hereinafter referred to as OPMF/PBS) reduced the TS, TM, and EB to 13.86 MPa, 94.80 MPa, and 2.50%, respectively. The OPMF/PBS is taken as a reference sample for comparison.

As shown in Table 1, the tensile properties of the biocomposite were influenced by the NaOH concentration and soaking time used to treat the OPMF. It appears to be that the TS of the biocomposite increased gradually with increasing NaOH concentration, up to 5%, showing an increment of 31% as compared to that of OPMF/PBS. After that, it started to level off at 7% and then decreased at a higher NaOH concentration of 9%. In the meantime, the TM of the biocomposite also increased with increasing NaOH concentration, up to 5%, and it started to decrease at a higher concentration of NaOH. The OPMF treated in 5% NaOH solution produced biocomposite with the highest value of TM (194.80 MPa), showing an improvement of 105% as compared to that of OPMF

(94.80 MPa). The NaOH treated OPMFs also showed improvements in the EB of the biocomposites. The EB increased gradually with increasing NaOH concentration and reached its optimum value at 5%, showing 16% improvement in comparison to that of OPMF.

The increment in tensile properties of NaOH-treated OPMF/PBS biocomposites can be explained by the fact of alkali treatment gives rise to fibers with relatively clean and rough surfaces (Fig. 1d), which can provide additional sites for mechanical interlocking between fiber and thermoplastic, as well as increase effective surface area available for adhesion of thermoplastic matrix. These in turn improved the fiber/ thermoplastic interfacial adhesion and stress transfer efficiency. Hence, biocomposites with enhanced tensile properties were achieved (Herrera-Franco and Valadez-Gonzalez 2005; John *et al.* 2008). In a meantime, it can be noticed that at low NaOH concentrations of 1 and 3%, the percentage improvement was rather low. This may be attributed to the limited adhesion between fiber and polymer, resulting from ineffective removal of waxes and hemicellulose component from the fiber (Mohd Edeerozey *et al.* 2007). In contrast, at high concentration of NaOH (9%), degradation and rupture of fiber may occur and lead to decrease in tensile properties (Mohd Edeerozey *et al.* 2007; John *et al.* 2008).

It is clear that, at a soaking time of 3 h, the OPMF treated in 5% NaOH solution produced biocomposite with the highest values of TS, TM, and EB. Therefore this concentration is used to determine the optimum soaking time for the treatment. As shown in Table 1, it is evident that the soaking time also had an effect on tensile performance of the biocomposite. It can be seen that the TS, TM, and EB increased with increasing soaking time, up to 3 h, and started to decrease at longer soaking times. This decreasing trend is attributed to damage caused by the alkali over the fiber surface. From the tensile result, a short conclusion can be drawn that the best NaOH treatment conditions for OPMF/PBS system is at a NaOH concentration of 5% with a 3 h soaking time. The fiber treated at these conditions produced biocomposite with the highest values of TS, TM, and EB.

Table 1. Effect of NaOH Concentration and Soaking Time on the Tensile Properties of OPMF/PBS Biocomposite

Biocomposite	NaOH concentration (%)	Soaking time (h)	TS (MPa)	TM (MPa)	EB (%)
OPMF/PBS	-	-	13.86 (0.26)	94.80 (7.61)	2.50 (0.10)
NaOH-treated OPMF/PBS	1	3	14.28 (0.97)	131.20 (4.68)	2.55 (0.21)
	3	3	15.55 (0.39)	162.95 (5.16)	2.58 (0.15)
	5	1	15.86 (0.10)	117.20 (18.80)	2.87 (0.32)
		2	17.06 (0.16)	119.10 (11.88)	3.00 (0.17)
		3	18.11 (0.40)	194.80 (3.25)	2.90 (0.17)
		4	15.45 (0.45)	119.00 (8.70)	2.57 (0.12)
	7	3	18.21 (0.55)	163.70 (18.6)	2.60 (0.32)
	9	3	16.14 (0.38)	141.00 (8.1)	2.53 (0.12)

The standard deviation is in parentheses

Interfacial Properties of Biocomposites

From the results of the tensile testing, it can be seen that the biocomposite consisting of 5% NaOH treated OPMF (hereinafter referred to as NOPMF) and PBS exhibited the highest value of TS, TM, and EB among all of the biocomposites prepared.

Therefore, this biocomposite (hereinafter referred to as NOPMF/PBS) was selected for further characterizations. The interfacial adhesion between NOPMF and PBS was studied by viewing the tensile fracture surface of the NOPMF/PBS under a scanning electron microscope. The SEM micrographs of the NOPMF/PBS and the NOPMF can be seen in Fig. 1, along with the SEM micrographs of the OPMF/PBS and the OPMF for comparison.

It can clearly be seen that both the OPMF/PBS (Fig. 1a) and the NOPMF/PBS (Fig. 1b) had a heterogeneous structure. Fibers and thermoplastic can be easily distinguished in the micrographs. The dispersion of fiber in the OPMF/PBS was rather poor because of the formation of fiber agglomerates resulting from fiber-fiber interactions (Mohd Ishak *et al.* 2001). However, no agglomerate of fiber can be seen in the NOPMF/PBS, showing the dispersion of fiber was considerably improved. The presence of gaps between fiber and thermoplastic were also noticeable in the OPMF/PBS, but gaps were absent in the NOPMF/PBS. In addition, the surface of the NOPMF also seems to have been coated by a layer of thermoplastic after detachment from the PBS during tensile testing; this was not seen on the surface of the OPMF in the OPMF/PBS. This phenomenon can be explained in terms of the characteristics of the fiber itself. As can be seen in Fig. 1c, the external surface of the OPMF was covered by a layer of waxy substances. During biocomposite fabrication, PBS can only be adhered weakly to the external surface of fiber, as the waxy layer on its surface can restrict wetting of the fiber by thermoplastics. Therefore, detachment of fiber from PBS can easily occur during tensile testing and cavities are formed resulting from fiber being pulled out.
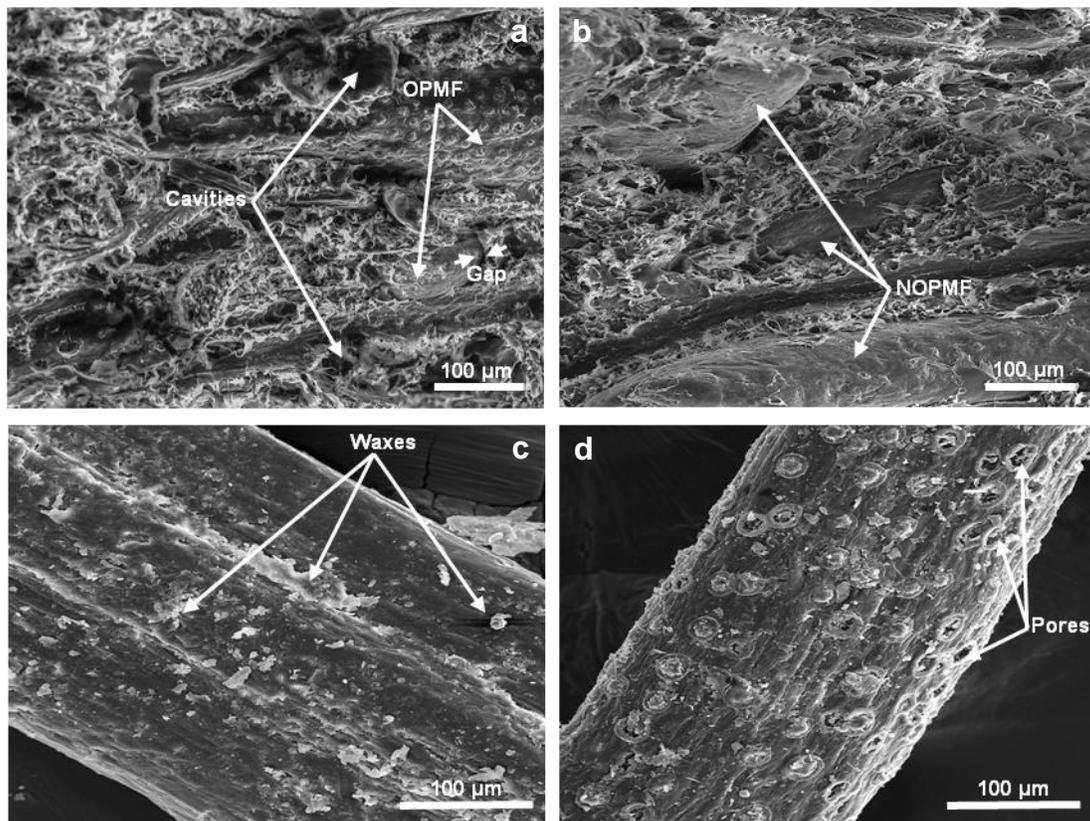
Fig. 1. SEM micrographs of (a) OPMF/PBS, (b) NOPMF/PBS, (c) OPMF, and (d) NOPMF

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The surface of OPMF, as seen in Fig. 1a, was relatively free from waxes as compared to that of virgin OPMF (Fig. 1c). This resulted from the peeling off of the waxy layer during the detachment process. In contrast to OPMF, the surface of NOPMF, shown in Fig. 1d, was relatively porous and rough. This will allow the PBS to adhere to the surface of NOPMF through mechanical interlocking, resulting in stronger NOPMF/PBS interfacial adhesion (Rosa *et al.* 2009). This explains the improvement of tensile properties in NOPMF/PBS.

The interfacial bonding strength between PBS and fibers (OPMF and NOPMF) can be measured by a short beam shear test. This test involves loading a short sample under three-point bending so that interlaminar shear failure is induced. The result of the test is normally expressed as apparent interlaminar shear strength (ILSS). The ILSS of OPMF/PBS and NOPMF/PBS is 1.64 and 2.56 MPa, respectively, as shown in Fig. 2. The use of NOPMF was found to improve the ILSS with an improvement of 56%. As shown previously in a SEM micrograph, the NOPMF (Fig. 1b) imparted better interfacial adhesion with PBS as compared to that of OPMF (Fig. 1a). The improved interfacial adhesion between PBS and NOPMF was able to increase their stress transfer efficiency and resulted in an improvement of ILSS. Conclusively, the enhancement in the biocomposite's tensile properties of NOPMF/PBS is attributed to the improved interfacial adhesion and interfacial bonding strength between PBS and NOPMF.
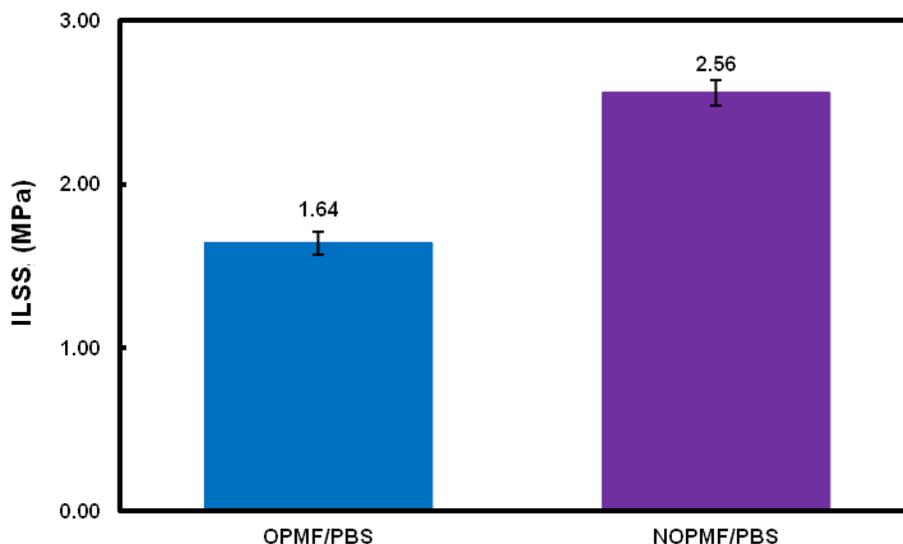
Fig. 2. Interlaminar shear strength (average ± SD) of OPMF/PBS and NOPMF/PBS

Structural and Chemical Composition Analysis of Fibers

The increment in tensile properties of natural fiber/thermoplastic biocomposite is related not only to the interfacial adhesion and bonding strength between fiber and thermoplastic, but also to the strength of fiber itself. In this work, the tensile properties of OPMF and NOPMF were not determined. However, XRD analysis was employed to study their crystallinity, because the strength of fiber can be influenced by its degree of crystallinity. Figure 3 shows the XRD patterns of OPMF and NOPMF. Both fibers show two main diffraction peaks in the 2θ range of 10 to 30° due to the monoclinic crystalline structure of cellulose type I in fiber (John and Thomas 2008). The diffraction peaks at 2θ of 16.5 and 22.1° correspond to the amorphous and crystalline region of fiber, respectively (Segal *et al.* 1959). The intensity (I) of diffraction peaks at 2θ of 18 and

22.1° for OPMF and NOPMF are tabulated in Table 2. These values were used to calculate the crystallinity index (CrI) or degree of crystallinity of fibers. It is noted that the CrI of NOPMF (42.4%) was relatively higher than that of OPMF (33.0%), showing a 28% increment in CrI. This result indicates increment in crystallinity of fiber after NaOH treatment. The increase in CrI of NOPMF is attributed to the removal of amorphous material, which includes hemicellulose, lignin, and wax. These materials are sensitive to alkali and thus can be removed during alkali treatment (Lai *et al.* 2008). This was confirmed in FTIR spectroscopy (discussed in the next section). Joonobi *et al.* (2009) have reported that fiber with a high degree of crystallinity can impart higher mechanical properties of its fiber and thus improve the mechanical properties of its corresponding biocomposite. Therefore, the enhancement of tensile properties in NOPMF/PBS can also be contributed from the relatively high CrI of NOPMF.

Table 2. Crystallinity Index of OPMF and NOPMF

Fibers	I_{am} (cps)	I_{002} (cps)	CrI (%)
OPMF	348	519	33.0
NOPMF	375	651	42.4
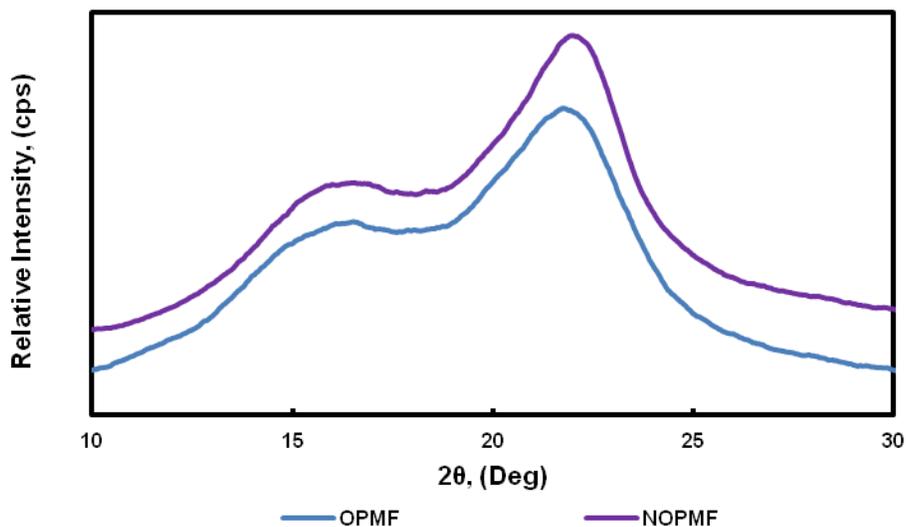
Fig. 3. XRD patterns of OPMF and NOPMF

The relatively clean and rough surfaces and high CrI of NOPMF are resulted from the elimination of waxy substances, hemicellulose, and lignin during the NaOH treatment as validated by FTIR spectroscopy. The FTIR spectra of OPMF and NOPMF are shown in Fig. 4. The peaks at 1730, 1510, and 1245 cm^{-1} are assigned to C=O stretching of the carboxylic ester or acetyl groups in hemicellulose and/or lignin (Sreekala *et al.* 2000), C=C vibration of the aromatic ring in lignin (Xiao *et al.* 2001), and C-O-C vibration of esters, ethers, and phenol groups of the waxes (Herrera-Franco and Valadez-Gonzalez 2005), respectively. In the NOPMF spectrum, the disappearance of a peak at 1730 cm^{-1} and relatively low absorbance of peaks at 1510 and 1245 cm^{-1}, as compared to that of the OPMF spectrum, indicate that hemicellulose, lignin, and waxes were eliminated during

the NaOH treatment. The spectrum of NOPMF also shows relatively low absorbance of peaks at 3391 and 1645 cm^{-1}, assigned to OH stretching and OH bending of absorbed water (Hosseinaei *et al.* 2012). This indicates that the hydrophilic natural of OPMF was reduced after NaOH treatment.
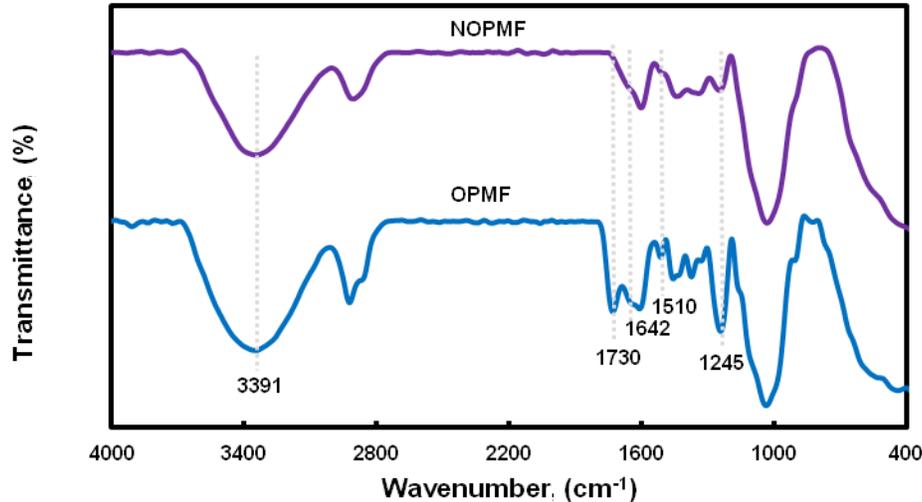
Fig. 4. FTIR spectra of OPMF and NOPMF

Flexural and Impact Properties

As discussed previously, the relatively strong interfacial adhesion and bonding strength between NOPMF and PBS resulted in biocomposite with enhanced tensile properties. Therefore, NOPMF was also used to produce biocomposite for the study of its effect on flexural and impact properties. The flexural strength (FS), flexural modulus (FM), and impact strength (IS) of NOPMF/PBS and OPMF/PBS are shown in Fig. 5.
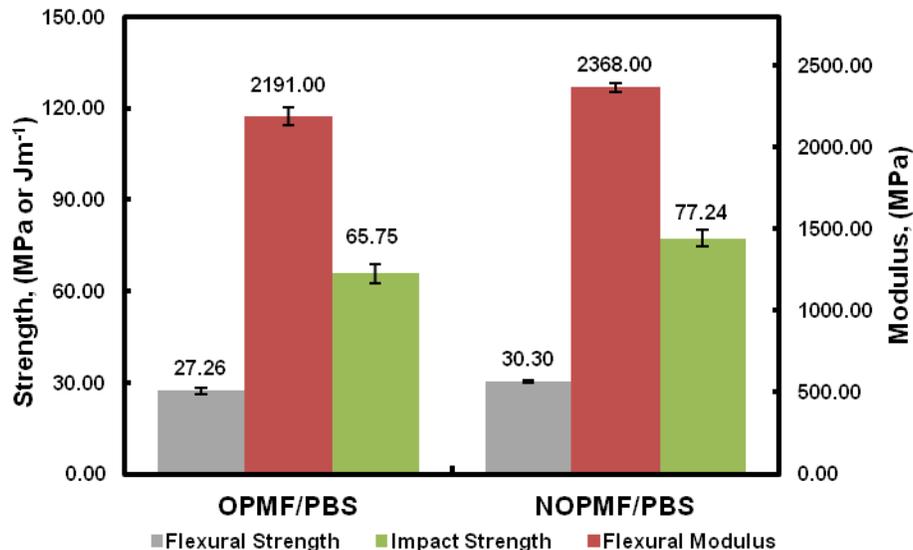
Fig. 5. Flexural strength, flexural modulus, and impact strength of OPMF/PBS and NOPMF/PBS

It can be seen that flexural and impact properties of NOPMF/PBS were relatively higher than the corresponding values for OPMF/PBS. The FS, FM, and IS of OPMF/PBS were 27.26 MPa, 2191.00 MPa, and 65.75 Jm^{-1}, respectively. These values increased to 30.30 MPa, 2368.00 MPa, and 77.24 Jm^{-1} for NOPMF/PBS. The NOPMF/PBS showed increments of 11, 8, and 17% in FS, FM, and IS, respectively, as compared to that of OPMF/PBS. There is no doubt that the improvement in flexural and impact properties of NOPMF/PBS was also a result of the relatively high interfacial adhesion, bonding strength, and CrI of NOPMF, which in turn produced biocomposite with better bending and crack propagation resistance.

Water Absorption and Thickness Swelling

The water absorption (WA) and thickness swelling (TS) of OPMF/PBS and NOPMF/PBS after 24 h of immersion in water are shown in Fig. 6. Both biocomposites showed increases in WA and TS after 24 h of immersion in water. This is attributed to the presence of hydroxyl groups in fiber which induce moisture absorption (Islam *et al.* 2010). However, NOPMF/PBS showed slightly lower percentages of WA and TS than that of OPMF/PBS with 15 and 13% reduction in WA and TS, respectively. It was reported that hemicellulose is the most hydrophilic component of fiber as compared to cellulose and lignin, and is the main contributor to the moisture absorption (Hosseinaei *et al.* 2012). Therefore, the elimination of hemicellulose during NaOH treatment can reduce the hygroscopicity of NOPMF. This also explains the reduction in percentages of WA and TS in NOPMF/PBS.
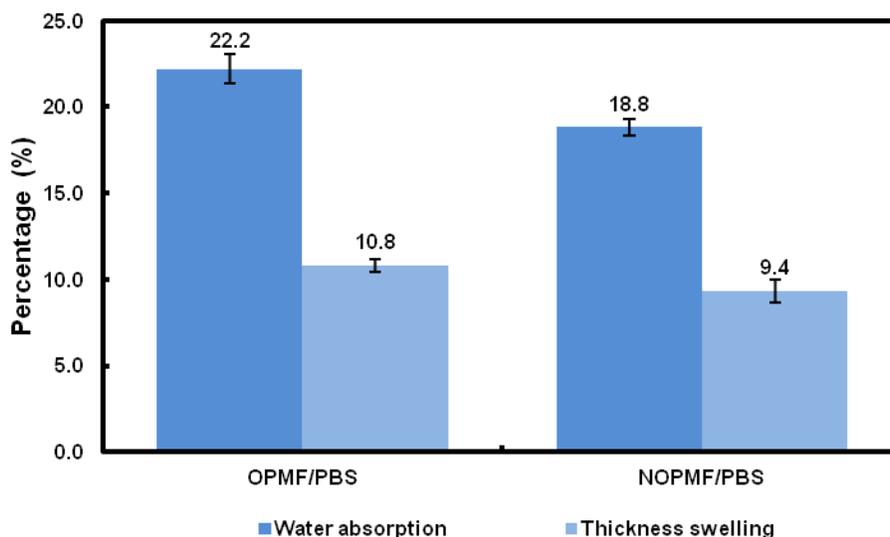
Fig. 6. Water absorption and thickness swelling of OPMF/PBS and NOPMF/PBS

CONCLUSIONS

1. The predicted best conditions for NaOH treatment of OPMF are 5% NaOH solution and 3 h soaking time.

2. The FTIR spectroscopy revealed that NaOH treatment eliminates hemicellulose, lignin, and wax from the fiber. This in turn produces fiber with clean and rough surfaces. Also, the CrI of fiber increases after NaOH treatment.

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3. The interfacial adhesion and bonding strength between fiber and PBS are improved after NaOH treatment. The resulted biocomposite shows an enhancement in tensile, flexural, and impact properties.

4. The dimensional stability of NOPMF/PBS improved due to the decrease in hygroscopicity of NOPMF.

ACKNOWLEDGMENTS

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