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A Comparative Study on Some Properties of Wood Plastic Composites Using Canola Stalk, Paulownia, and Nanoclay

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ABSTRACT: In this research, the reinforcing effect of fillers including canola stalk, paulownia and nanoclay, in polypropylene (PP) has been investigated. In the sample preparation, 50 wt% of lignocellulosic materials and 0, 3, and 5 wt% of nanoclay particles were used. The results showed that while flexural and tensile properties were moderately enhanced by the addition of nanoclay in the matrix, notched Izod impact strengths decreased dramatically. However, with increase in the nanoclay content (5 wt%), the flexural and tensile properties decreased considerably. The mechanical properties of composites filled with paulownia are generally greater than canola stalk composites, due to the higher aspect ratio. The thickness swelling and water absorption of the composites significantly decreased with the increase in nanoclay loading. Except tensile modulus, the differences between the type of fibrous materials and nanoclay contents had significant influence on physicomechanical properties. Morphologies of the composites were analyzed using transmission electron microscopy (TEM) and X-ray diffraction (XRD), and the results showed increased *d*-spacing of clay layers indicating enhanced compatibility among PP, clay, and lignocellulosic material. TEM micrographs also confirmed that the composites containing 3 wt% nanoclay had uniform dispersion and distribution of clay layers in the polymer matrix. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 129: 1491–1498, 2013

KEYWORDS: canola stalk; mechanical properties; nanoclay; paulownia; thickness swelling

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INTRODUCTION

Accelerated deforestation and forest degradation, in addition to a growing demand for wood-based products, have raised an important issue regarding the sustained supply of raw materials.[1] Consequently, there is a need for alternative resources to substitute wood raw material. Therefore, researchers, both in industry and academia, are looking for new sources of lignocellulosic materials.[2] Among the possible alternatives, fast-growing tree species and agro-waste fibers could play a major role in providing the balance between supply and demand for the manufacturing of composite panels such as wood plastic composites (WPCs).[3]

Paulownia (*Paulownia fortune* L.) is one of the most successful fast-growing and high-yield plantation species in tropical and sub-tropical regions. Its worldwide importance is growing. Paulownia is a deciduous species native to the south east of China and has been used for the production of high quality timber as far back as 1049 BC.[4] It could be considered as a low demand water plant, in spite of not growing in barren zones. Paulownia trees grow to 10–20 m in height and 30–40 cm in diameter within 7–10 years. Most species of paulownia are extremely fast growing, and each tree could produce 1 m^3 of wood at the age of 5–7 years. It may grow in intensive plantations with about 2000 trees per ha. Then, it has an annual production of 330 t/ha.[5]

Agro-waste fibers as natural lignocellulosic materials could be attractive alternatives due to their low cost and ready availability. One of the most promising agricultural residues is canola stalk. Canola (*Brassica napus* L.) is widely cultivated throughout the world as the third most important oilseed crop after soybean and palm. As the result of high demand for vegetable oils and biodiesel, the worldwide planted area for canola increases continuously. In addition, the leaves of canola can be used as animal feed. Approximately, 34 Mt of canola stalks were harvested in the world in 2009, corresponding to $\sim$ 62 Mt of plant oil.[6] It is estimated that about 0.5 Mt of canola stalk is produced in Iran annually.[7] It is worth mentioning that canola stalk is considered as an underutilized agricultural by-product and currently it has no commercial use in Iran.

Table I. Chemical Compositions and Morphological Characteristics of the Used Materials

Property	Canola stalk	Paulownia
Chemical		
Holocellulose (%)	66.9	58.7
Cellulose (%)	43.0	50.0
Lignin (%)	19.3	27.0
Extractives (%)[a]	6.5	12.1
Ash (%)	7.3	2.2
Anatomical		
Fiber length (mm)	0.82	1.11
Fiber width (μm)	23.0	36.8
Aspect ratio	27.9	33.4

[a] Alcohol-acetone.

Using organo-modified montmorillonite (MMT), commonly called nanoclay, to reinforce WPCs has attracted great attention in academic and industrial sectors. This is because the addition of small amount of nanoclay could substantially enhance the physical and mechanical properties of both thermoplastic and thermoset polymers.[8,9] MMT is a member of the smectite mineral group; naturally occurring layered materials having high aspect ratio and specific surface area. MMT is composed of aluminum silicate layers, which are organized in a parallel fashion to form stacks with a regular van der Waal gap in between them called interlayer spacing or gallery.[10] Clays are in nature organophobic, but they can be changed into organophilic by replacing the Na^+ or Ca^{2+} cation originally present in the galleries with one organic cation such as alkylammonium ions via an ion-exchange reaction.[11]

The overall goal of this study was to explore and compare the potential of paulownia and canola stalk for producing WPCs. The specific objectives of this study were to (a) prepare WPCs from above-mentioned lignocellulosic materials and nanoclay as reinforcing agent, and (b) characterize physical, mechanical, and morphological properties of WPCs.

EXPERIMENTAL

Materials

Injection molding grade polypropylene (PP), with trade name V30S, was supplied by Arak Petrochemical (Iran). The PP was in the form of pellets with a melt flow index of 18 g/10 min and density of 0.92 g/cm^3.

Maleated anhydride grafted polypropylene (MAPP), in the form of pellets with a density of 0.91 g/cm^3, a melt flow index of 64 g/10, and maleic anhydride of 2%, was obtained from Kimia Javid Sepahan, Iran.

The organophilic montmorillonite (OMMT), with trade name of Cloisite 15A, in powder form was used as nanoparticle. Natural montmorillonite modified with a dimethyl, dehydrogenated tallow, 2-ethylhexyl quaternary ammonium (CEC = 125 meq/100 g clay, d_{001} = 31.5 Å) was obtained from Southern Clay Products, USA.

Two types of lignocellulosic materials were investigated in this study: paulownia and canola stalk. The materials were ground into flour using a Thomas-Wiley mill. The particles were sifted with a vibrating screen. Particles that pass through 40-mesh and remained on the 60-mesh screen were used. Selected particles were oven dried at 105°C to reduce the moisture content to less than 3%. The important chemical components and fiber morphology of the canola stalk and paulownia are given in Table I.

Sample Preparation

Formulation of the mixes and abbreviations used for the respective mixes prepared are given in Table II. Composites were produced in a two-stage process. In the first stage, lignocellulosic flour, MAPP, PP pellets, and nanoclay powder were premixed mechanically at various formulations, and the mixtures were then fed into a laboratory corotating twin screw extruder. The temperature profile in the extruder was 165/170/175/180/185°C and the screw speed was set at 40 rpm. In the second stage, the extruded strand was passed through a water bath and pelletized. The resulting granules were then placed in hot press at 190°C for 10 min and finally cooled to room temperature under pressure. The pressure for heating was controlled at 3.5 MPa.

Mechanical Testing

Specimens were tested following ASTM standard D 638 for tensile properties, ASTM D 790 for flexural properties and D 256 for notched Izod impact strength. The flexural properties were measured in three-point bend tests. Tensile and bending tests were conducted using a Universal Testing Machine (Schenk-Trebel) at a speed of 2 mm/min. Impact test was performed with a pendulum apparatus (Santam model SIT20D) using conventional V notched specimens. The hammer weight and the impact energy were 0.818 kg and 5 J, respectively. Six replicates were tested for every property under each formulation.

Physical Testing

Physical properties, namely, thickness swelling and water absorption were tested in accordance with ASTM D 570. Before testing, the weight and thickness of each specimen were measured. Conditioned samples of each type of composite were soaked in distilled water at room temperature for 2 and 24 h. Samples were removed from the water, patted dry and then measured again. Each value obtained represented the average of six samples.

Table II. Compositions of the Studied Formulations

Code	Formulation	WF (wt %)	PP (wt %)	MAPP (wt %)	Nanoclay (wt %)
A1	CS50/PP46/M4/N0	50	46	4	0
A2	CS50/PP43/M4/N3	50	43	4	3
A3	CS50/PP41/M4/N5	50	41	4	5
B1	PW50/PP46/M4/N0	50	46	4	0
B2	PW50/PP43/M4/N3	50	43	4	3
B3	PW50/PP41/M4/N5	50	41	4	5

CS, canola stalk; PW, paulownia; PP, polypropylene; M, MAPP; N, nanoclay.

Statistical Analysis

Statistical analysis was conducted using SPSS programming (version 18) method in conjunction with analysis of variance (ANOVA) techniques. Duncan's multiple range test (DMRT) was used to determine the statistical differences among the variables investigated at the 95 and 99% confidence levels.

X-Ray Diffraction

An X-ray diffractometer was used to measure the basal spacing between silicate layers in the nanocomposites. The XRD was performed in a Bruker X-ray diffractometer (D8 Advanced) using Cu Kα radiation (λ = 1.54 nm). The samples were scanned in 2θ ranges 2–10° at a rate of 0.3°/min. The generator was operated at 40 kV and 30 mA. The interlayer spacing (d_{001}) of clay was calculated in accordance with Bragg's law[12]:

$$2d \sin \theta = n\lambda \tag{1}$$

where d is the spacing between planes, θ is half of the angle of diffraction, n is the order of diffraction ($n = 1$), and λ is the X-ray wavelength ($\lambda = 1.54$ nm).

Scanning Electron Microscopy

Studies on the morphology of the composites were carried out using Scanning Electron Microscope (Hitachi HHS-2R). The fracture surfaces of the specimens after tensile test were sputter-coated with gold before analysis, in order to eliminate electron charging.

Transmission Electron Microscopy

The dispersion of nanoparticles in WPC was studied using Transmission Electron Microscope (Zeiss EM 900) at an accelerated voltage of 50–80 kV.

RESULTS AND DISCUSSION

Mechanical Properties

As mentioned earlier, the two investigated lignocellulosic materials are clearly distinguishable by differences in their chemical compositions, and a different mechanical behavior can therefore be expected. PP was filled with various mixtures of materials and nanoclay to produce WPCs. Statistical results of mechanical properties demonstrate the influences of type of fibrous materials and nanoclay loading (Table III). On the basis of the statistical analysis no significant differences in tensile modulus values of the composites were observed. However, tensile, flexural, and impact strengths resulted in significant differences at 95 and 99% confidence levels. Results indicate that fibrous materials, nanoclay content and their interaction had significant influence on the mechanical properties.

Flexural Properties

Figure 1(a) elucidates results of the flexural strengths and moduli of WPCs with varying amounts of fiber and nanoclay. Composites made with paulownia show the highest modulus of flexural, whereas canola stalk filled composites exhibit the lowest properties. Maximum flexural modulus was 2.7 GPa for canola stalk-filled composites, while maximum modulus of paulownia is ~ 3.2 GPa. The strength of fiber reinforced composites depends on the properties of constituents and the interface interaction. However, when considering the flexural properties, homogeneity of the overall composite needs to be taken into account.[12]

Comparison of the results for composites with varying nanoclay contents shows that the flexural moduli of the composites increase with increase in nanoparticles content. When an amount of 3 wt% nanoclay was added, the flexural modulus showed the highest values, increasing by about 44 and 28% for paulownia and canola stalk, compared with samples without nanoparticles. However, with increase in the nanoclay content (5 wt%), the flexural moduli decreased considerably. Various parameters influence the mechanical properties of WPCs including the fiber aspect ratio, fiber-matrix adhesion, stress transfer at the interface and mixing temperatures.[13] The canola fiber, which had a low aspect ratio (Table I), showed inferior flexural moduli to the paulownia-filled composites. In other words, aspect ratio is a good indicator for showing the load-carrying capability of natural fibers. It is also noteworthy that the flexural moduli of composites are significantly greater than the pure PP (1.5 GPa). Researchers who have measured flexural properties of wood fiber thermoplastic composites have reported similar trends.[13,14]

Tensile Properties

The trend of tensile properties of the WPCs as function of lignocellulosic material types and nanoclay contents was similar to that of flexural properties discussed earlier. Figure 1(a) shows the results of tensile strength and modulus of WPCs with varying lignocellulosic materials and nanoclay loading. The tensile strength of the WPCs varies significantly with fiber type. The paulownia-filled composites showed superior strength and modulus compared to canola stalk-filled composites. Cellulose, lignin, and extractive contents of the lignocellulosic materials have strong influences on the mechanical properties of WPC.[15] Aspect ratio, rather than particle size, has the greatest effect on strength and stiffness.[16] The higher aspect ratio of paulownia fibers permits better stress transfer between the matrix and the fibers. As can be seen from Table I, paulownia has higher fiber length and aspect ratio compared with the canola stalk. Various parameters influence the mechanical properties of fiber-reinforced composites including the fiber aspect ratio, fiber–matrix adhesion, stress transfer at the interface and mixing temperatures.

The composites made using 3 wt% nanoclay and paulownia fibers had the highest tensile strength and modulus values amongst the composites evaluated (15.4 MPa and 3.92 GPa, respectively), whereas composites without nanoclay (A1) exhibited the lowest properties. Similar to the flexural properties, with increasing nanoclay content up to 5 wt% in the formulations, the tensile strength and modulus moderately decreased. The decrement of tensile properties at 5 wt% of nanoclay is related to the agglomeration of nanoparticles.

Impact Strength

Figure 1(b) illustrates the notched Izod impact strengths of the composites made with different types of fibrous materials and nanoclay contents. The impact properties of the WPCs varied significantly with fiber type. Composites made with paulownia fiber exhibited the highest impact strength; whereas

Table III. Analysis of Variance on the Effects of Lignocellulosic Material and Nanoclay Contents and Their Interaction on Some Physical and Mechanical Properties

		Source of variations				
Properties		A	B	A × B	Error	Total
Tensile strength	df	2	2	8	18	27
	SS	12.447	92.659	108.666	25.576	4003.305
	MS	6.223	46.329	13.583	1.421	
	F	4.380^{*}	32.606^{**}	9.560^{**}		
Tensile modulus	df	2	2	8	18	27
	SS	1.461	2.67	4.739	10.49	345.733
	MS	0.731	1.335	0.592	0.583	
	F	1.254	2.291	1.016		
Flexural strength	df	2	2	8	18	27
	SS	145.733	488.766	667.12	222.876	26407.27
	MS	72.866	244.383	83.39	12.382	
	F	5.885^{*}	19.737^{**}	6.735^{**}		
Flexural modulus	df	2	2	8	18	27
	SS	0.827	0.288	1.127	25.576	4003.305
	MS	0.413	0.144	0.141	1.421	
	F	3.851^{*}	1.34	1.313		
Impact strength	df	2	2	8	27	36
	SS	8.395	3.658	13.932	9.648	156.319
	MS	4.197	1.829	1.741	0.357	
	F	11.746^{**}	5.119^{*}	5.047^{**}		
Water absorption 2 h	df	2	2	8	45	54
	SS	30.255	150.260	188.143	72.698	836.689
	MS	15.128	75.130	23.518	1.616	
	F	9.364^{**}	46.505^{**}	14.558^{**}		
Water absorption 24 h	df	2	2	8	45	54
	SS	185.255	143.483	355.020	79.207	2613.800
	MS	92.627	71.741	41.878	1.760	
	F	52.625^{**}	40.759^{**}	23.893^{**}		
Thickness swelling 2 h	df	2	2	8	45	54
	SS	0.971	0.732	1.763	0.715	9.446
	MS	0.452	0.366	0.220	0.016	
	F	28.831^{**}	23.034^{**}	13.864^{**}		
Thickness swelling 24 h	df	2	2	8	45	54
	SS	15.566	11.595	27.694	18.991	189.678
	MS	7.783	5.798	3.462	0.422	
	F	18.442^{**}	13.738^{**}	8.203^{**}		

A, lignocellulosic material; B, nanoclay; df, degree of freedom; MS, mean of squares; SS, sum of squares; *F*, *F* value.
*Significant difference at the 5% level ($P \leq 0.05\%$), **Significant difference at the 1% level ($P \leq 0.01\%$).

canola stalk-filled composites showed the lowest properties. As mentioned earlier, the strength of WPCs is dependent on the properties of fibers such as aspect ratio and length of individual fibers. As it can be seen from Table I, the aspect ratio of the paulownia fibers is higher than that of the canola stalk, which permits better stress transfer between the matrix and the fibers. In contrast to flexural and tensile properties, incorporation of nanoclay content produced an insignificant decrease in the impact strength. In general, with increasing nanoclay content in the mixture, the impact strength decreases.[17] The decline in the impact strength at higher nanoclay loading is probably due to stiffening of polymer chains and agglomeration of nanoclay particles, which result in absorbing less impact energy.[18]

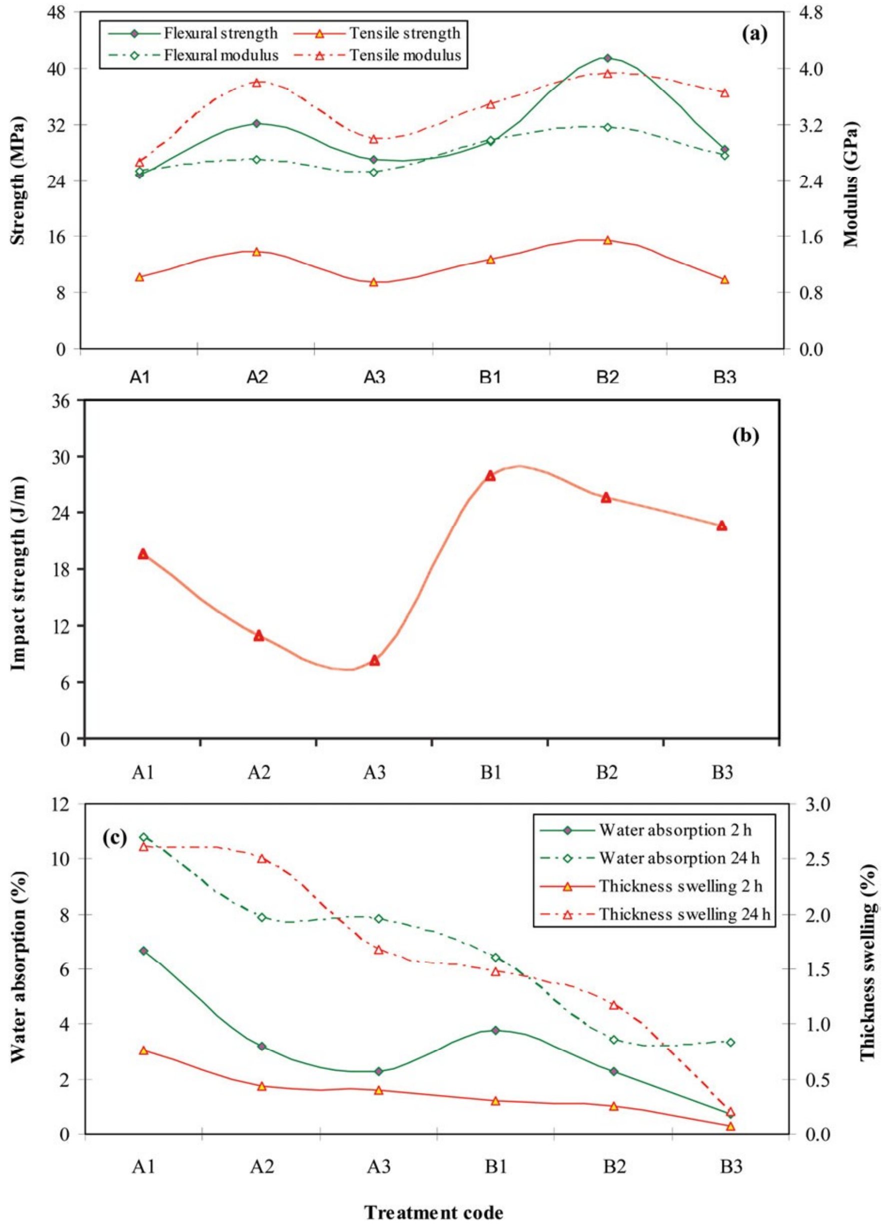

Figure 1. Mechanical and physical properties of WPCs made with canola stalk, paulownia and nanoclay. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Physical Properties

One of the most important properties to be evaluated for WPCs is water absorption, since it can affect the mechanical properties and also dimensional stability. According to the ANOVA tests, all variable factors exerted a significant influence ($P \leq 0.01\%$) on water absorption and thickness swelling for 2 and 24 h immersion as a single factor. In addition, the interaction between the main variables is significant with the 99% confidence based on the ANOVA analysis (Table III).

Water Absorption

Figure 1(c) shows the percentages of the water uptake for the WPCs at different filler loadings, which vary depending upon the lignocellulosic materials and nanoclay contents. In all cases, the water uptake was found to increase with the increase in the time of immersion. Water absorption occurred initially at a rapid rate and finally at a slower rate. At certain amount of fibrous material, the different water absorptions among the manufactured boards can be attributed to the role of paulownia and canola stalk. The water absorption values after 2 and 24 h for paulownia samples vary from 0.7 to 6.4%, and these values for canola stalk composites were 2.3–10.8%, respectively. The water absorption of the pure PP, however, was less than 1%, due to its hydrophobic nature. In general, polymers do slightly absorb moisture, indicating that moisture is absorbed by the cellulosic material in the composite.

Lignocellulosic materials contain cellulose, hemicellulose, lignin, and extractives in various amounts and chemical compositions. Cellulose is a natural biopolymer containing many hydroxyl groups, and these groups and their ability to form hydrogen bonds govern the physical properties of cellulose. In addition, noncellulosic carbohydrates or hemicelluloses have amorphous structure and hydrophilic characteristic, so water can be absorbed in hemicellulose. However, lignin is totally amorphous and hydrophobic; therefore water absorption can not occur in lignin. The extractives comprised of tannins, pectins, fats, waxes, gums, essential oils, and volatile materials, and thus these cannot absorb water, either. Additionally, large numbers of porous tubular structures present in fiber accelerate the penetration of water by the capillary action.[16] As can be seen from Table I, canola stalk has higher holocellulose (cellulose + hemicellulose) and lower lignin contents than paulownia, resulting in higher water absorption compared to paulownia. Many studies have supported the above observation.[19–22]

Figure 1(c) also clearly shows that the water absorption decreased sharply with increasing nanoclay loading in the composites—a trend that is true for both lignocellulosic fillers. It can be observed that the composites made with 5% nanoclay and paulownia exhibited the lowest water absorption as compared with those made without nanoclay and canola stalk (2.26 and 6.8% after 2 and 24 h water immersions, respectively). This is possible because the organically modified clay increases the tortuous path for water transport and, as a result, water diffusivity decreases.[23] Decrease in the available space for water absorption due to the occupation of void spaces in the fiber by the nanoclay can be another mechanism for the lower water uptake of nanocomposites.[24]

Thickness Swelling

Thickness swelling is an important property that represents the stability performance of the composites. The effect of fibrous materials and nanoclay on the thickness swelling of composites is presented in Figure 1(c). The thickness swelling of the composites increases with the water absorption and thus has a trend similar to that of the water absorption. The thickness swelling of the WPCs varied significantly with fiber type. Besides, thickness swelling decreases meaningfully with the incorporation of nanoclay. The thickness swelling values for paulownia samples vary from 0.1 to 1.5%, and these values are increased for canola stalk composites, varying from 0.4 to 2.6%. Composites, with canola stalk as filler, exhibited maximum thickness swelling. This could be possible due to the existence of a poor adhesion between the matrix and canola stalk, which is because of the presence of more gaps in the interfacial region and also more hydrophilic groups as hydroxyls that are available for hydrogen bonding with water. In addition, the presence of nanoclay leads to decreasing thickness swelling. Nanoclay increases the tortuous path for water transport and as a result water diffusivity decreases. The presence of nanoclay in the composite hinders the permeation of water through the composite.[25,26] Many studies have supported the above observation.[20–22]

Scanning Electron Microscopy

SEM micrographs taken from the fracture surface of specimens, broken during the tensile test, are shown in Figure 2. It clearly presents the partial implication of failure mode and interfacial adhesion. The presence of numerous cavities is clearly visible in Figure 2(a). This indicates that the strength of interfacial bonding between the fibers and the matrix is weak, and when stress is applied, it causes the fibers to be pulled out from the matrix easily, leaving behind gaping holes. Figure 2(b) shows the fracture surface of specimens prepared with 3% nanoclay. The coverage of the wood flour with the polymer and the relatively

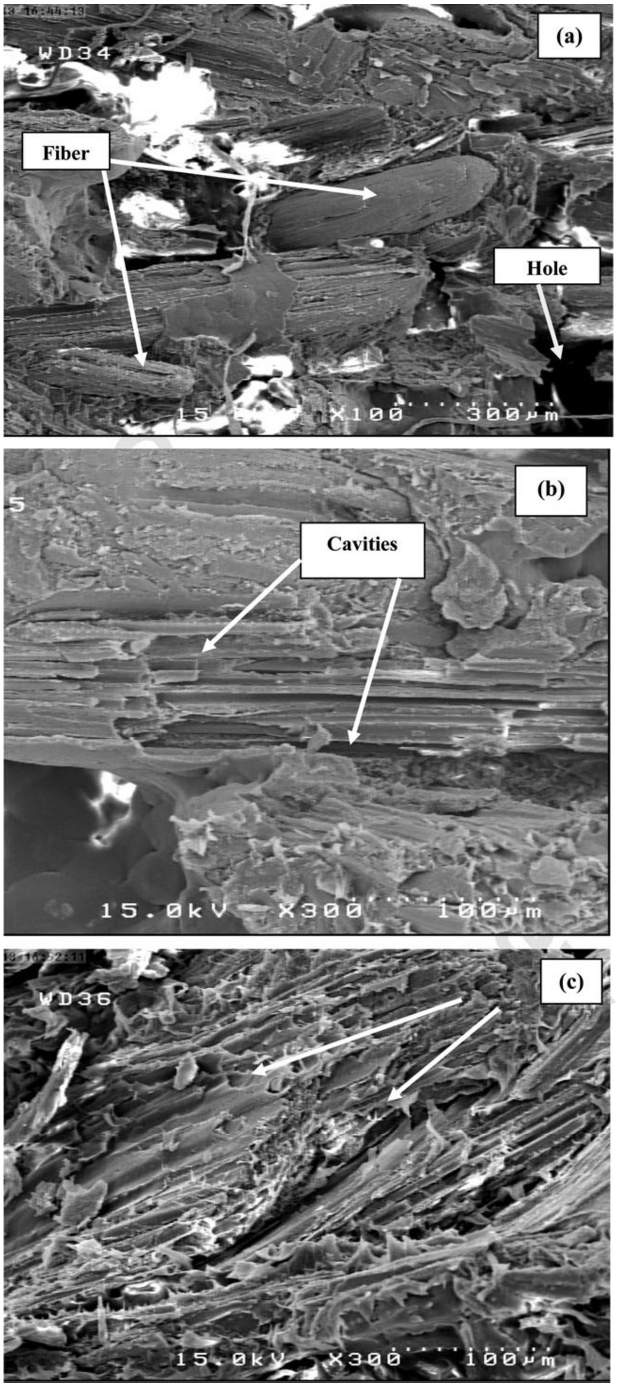

Figure 2. SEM micrographs of tensile fracture surfaces of WPCs types of B1 (a), B2 (b), and B3 (C).

Table IV. XRD Results of the OMMT and Some Selected Composites

Specimen	2θ (°)	d_{001} (nm)
OMMT	2.8	31.3
B2	2.4	37.3
B3	2.5	35.3

small number of holes related to debonding or fiber pull out indicate good adhesion between PP and lignocellulosic material and effectiveness of nanoclay in improvement of the interaction. The addition of nanoclay to the formulations altered the fracture modes. The roughness of a fracture surface is generally attributed to the fracture properties and critical strain energy release rates,[27] smooth featureless fracture surfaces are attributed to brittle nanocomposites and rougher fracture properties relate to tough nanocomposites.[28] SEM micrographs for specimens without nanoclay revealed fracture surfaces that were relatively smooth and featureless. The roughness of the fracture surfaces relatively increased with increasing nanoclay content up to 3 wt% [Figure 2(b)]. At high nanoclay loading (5 wt%), ineffectiveness of the nanoparticles in providing good interaction between PP and fibrous material is shown [Figure 2(c)].

X-Ray Diffraction

The XRD patterns of pure OMMT and WPCs with different percentages of nanoclay loading are shown in Table IV. The organically modified nanoclay showed its characteristic intense peak at $2\theta = 2.8°$ (this peak is absent in the sample B1). The composite specimens with 3 and 5 wt% nanoclay loading showed a peak shift to lower diffraction angle (2θ) than OMMT, indicating an increase in interlayer spacing of silicate layers and intercalation of polymer chains between clay layers (Figure 3). The reduced peak intensity is attributed to the low concentration of clay in the samples. Similar observations have been reported by Deka and Maji[24] and Khanjanzadeh et al.[25]

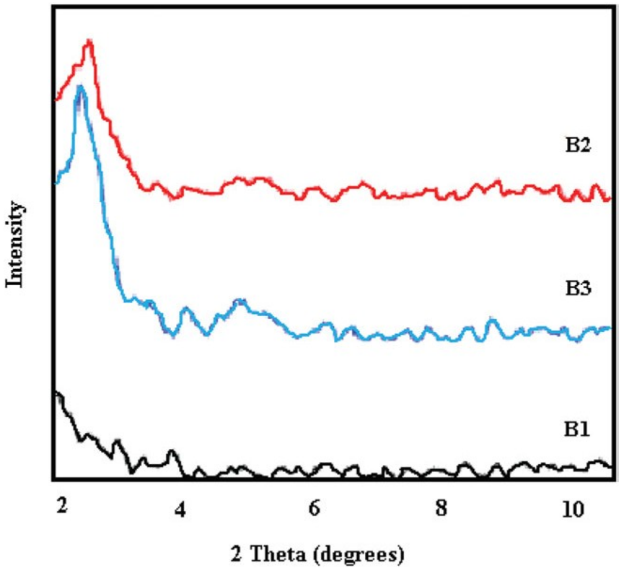

Figure 3. XRD patterns of different composites made with paulownia. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Transmission Electron Microscopy

Figure 4 shows the TEM micrographs of WPC with various percentage of nanoclay content. The dark line represents the intersection of silicate layers while the white background corresponds to PP matrix. When the loading level of nanoclay in the composite was 3 wt% [Figure 4(a)], nanoclay exhibited uniform dispersion of the clay layers within the polymer matrix compared with 5 wt% of nanoclay content [Figure 4(b)]. However, with the increase in the level of nanoclay loading to 5 wt% [Figure 4(b)], the size of nanoclay became larger or aggregated. Similar observation was reported by many authors.[24,29,30]

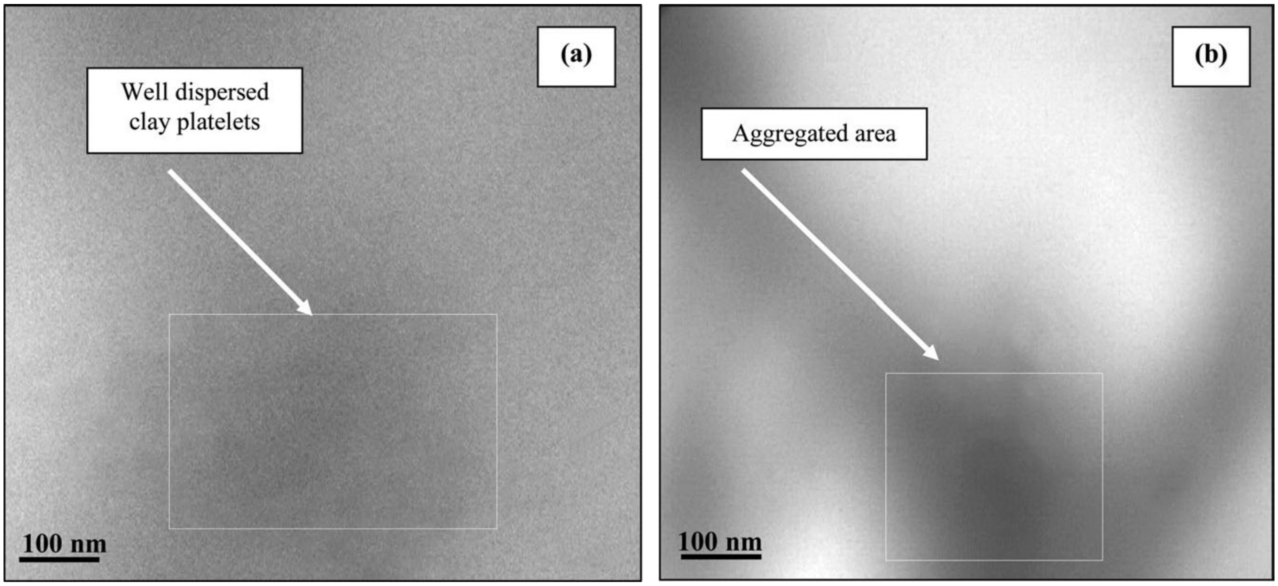

Figure 4. TEM micrographs of WPCs types of B2 (a) and B3 (b).

CONCLUSIONS

The present study has shown that lignocellulosic materials along with mineral filler (nanoclay) can be successfully utilized to make WPCs with acceptable physicomechanical properties. Except tensile modulus, statistical analysis showed significant differences in the physical and mechanical properties of composites at 95 and 99% confidence levels. All paulownia filled composites had superior mechanical properties compared to composites made with canola stalk, due to its higher aspect ratio. In addition, all the composites showed a high uptake of water, which is attributed to the high content of lignocellulosic materials present in the composites. Composites with canola stalk as filler, exhibited maximum water absorption. This may be due to a high amount of holocellulose and low lignin content present in the filler. Composites made with paulownia and 3 wt% nanoclay showed the maximum mechanical properties and the minimum water absorption and thickness swelling in all formulations. In general, the thickness swelling and water absorption of the composites significantly decreased as the nanoclay loading increased. Morphological findings of nanocomposites by XRD and TEM showed that samples containing 3 wt% of nanoclay had higher order of intercalation than those at 5 wt%, and SEM study also shows that interfacial adhesion between the fiber and the matrix is improved with the addition of nanoclay. In general, paulownia fiber showed superior physical and mechanical properties due to its chemical compositions and morphological characteristics. Besides, the use of small amount of nanoclay (3 wt%) has been an attractive approach for enhancing the mechanical and physical properties of the WPCs. However, a homogeneous dispersion of nanoparticles in a polymer matrix must be fully accomplished first to achieve those improvements.

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