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A Comparative Study on the Effects of Material Blending Method on the Physico-Mechanical Properties of WPCs Made from MDF Dust

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ABSTRACT: The present study was carried out to investigate the effect of material-blending method and filler content on the physical and mechanical properties of medium density fiberboard (MDF) dust/PP composites. In the sample tests preparation, 40, 50, and 60 wt % of MDF dust were used as lignocellulosic material. Test samples were made to measure the influence of material-blending method and MDF dust content on water absorption (WA), thickness swelling (TS), modulus of elasticity (MOE), modulus of rupture (MOR), tensile strength, tensile modulus, and withdrawal strengths of fasteners. The mechanical properties of the test panels significantly decreased with increasing MDF dust contents due to the reduction of interface bond between the fiber and polymer matrix. The WA and TS values also increased by increasing the amount of MDF dust. So with the increase in the MDF dust content, there are more water residence (high hydroxyl groups (—OH) of cellulose and hemicelluloses) sites, thus more water is absorbed, so it can reduce mechanical strength. Furthermore, the results indicated that the physical and mechanical properties of samples made with melt-blend method were more acceptable than those of dry-blend method. Field emission scanning electron microscopy micrographs also showed that the polymer and the filler phase mixed better in the melt-blend method. On the basis of the findings of this research, it appears evident that certain amount of MDF dust material with suitable material-blending method can be used in manufacturing of wood–plastic composites for providing good physical and mechanical properties. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40513.

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INTRODUCTION

Wood–plastic composites (WPCs) have been introduced successfully to the academic sectors due to considerable processing advantages and improvement in certain physical and mechanical properties during the previous decades.[1] Materials now known as WPCs first appeared in the 1960s.[2] For making WPCs, the lignocellulosic fibers may be obtained from wood species[1,3–7] or agro-based fibers.[8–10] Currently, most WPC is for use in exterior building component and building panels, including decking, roofline products, windowsills, flooring material for trucks, standard containers, playground equipment, fencing, industrial flooring, landscape timbers, and railing.[4,11–13] The presence of wood in a plastic matrix can result in a stiffer and lower-cost material than if plastic alone were used.[14] According to different the manufacturing techniques, the dominant technologies to produce WPCs are extrusion to obtain unlimited profiles and injection molding leading to three-dimensional forms, so the width of WPCs with this manufacturing method is limited to a nearly 1.2–1.8 m.[1] Another possibility is producing WPCs on a flat-press.[15] Generally, the hot pressing method is an inexpensive way for producing of these materials, especially in laboratory scale, as compared with extrusion. Hot pressing can also be used to produce boards of large dimension, different densities, consumption of a high amount of lignocellulosic materials, in large volume. Lignocellulosic waste materials with different dimensions can also be used in hot pressing.[16,17] In this method, polymer and lignocellulosic fiber may be mixed in two ways: melt-blending and dry-blending.

WPC producers are forced to seek other nonwood sources to supply the increasing raw material requirement and protect timber resources.[18] On the other hand, using wood industry wastes in the construction of WPCs not only reduces production costs but also eliminates the problem of accumulating and discarding wood industry waste. Large amounts of waste are created each year in the wood products industry (63 million tons in the United States in 2002).[19] Using them in production can

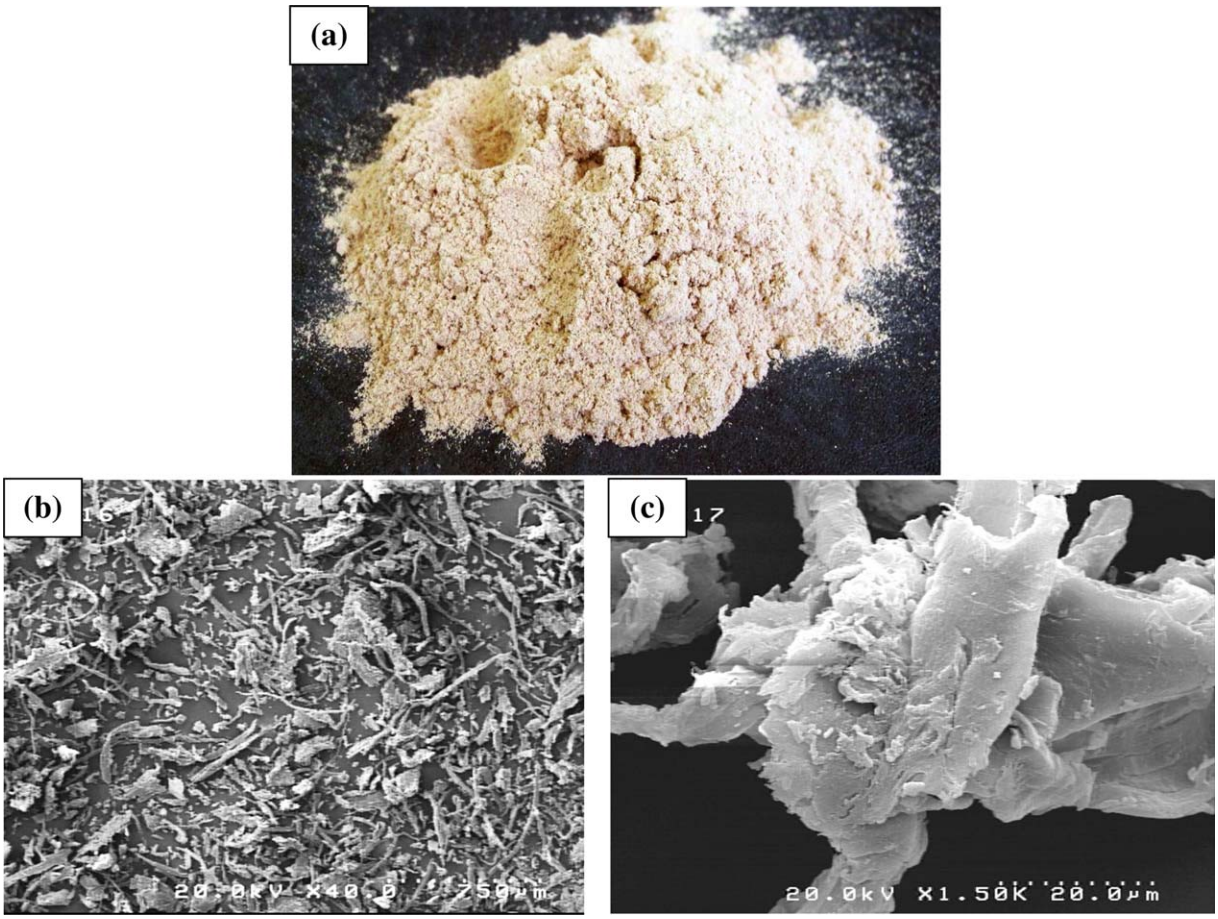

Figure 1. Image of MDF dust (a) and FE-SEM micrograph of MDF dust from sanded surface of medium density fiberboard boards (b and c). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

decrease the final cost of products.[20] For example, Iran's Arian Sina factory, which produces medium-density fiberboard (MDF), produces 30 ton of sand fines daily. In general, the level of mechanical and physical quality of WPCs is a function of formulation variables such as raw material characteristics and processing methods. It should be noted that the previous investigations on the effect of production process on the final product performance have been mainly limited to comparison between extrusion and injection molding. The performance of WPC can be optimized by the processing method.[16,17] For instance, the rate of moisture absorption can be minimized by variation in extrusion process.[21] In general, the product made in injection molding have possess significantly better properties including better orientation of materials,[22] in some cases higher mechanical properties,[23,24] more suitable surface quality,[25] with lower water absorption (WA) and thickness swelling (TS) as compared with the extrusion process.[17,26] Moreover, further scientific studies[27–29] have been reported using the dry-blend method for combining the wood, polymer, and additive components.

Most of publications focus on type and formulation of mixture as well as filler type, while only little is known on the effect of blending method in hot press processes and the use of wood industries' waste as lignocellulosic material. Hence, the ultimate goals of the present study were to explore the potential of MDF dust as filler for producing WPCs and investigate the effect of blending process in hot pressing method on the performance of final product of WPC.

MATERIALS AND METHODS

Materials

The source of this study's lignocellulose material was dust from sanding the surface of medium density fiberboard (MDF) boards manufactured at the Arian Sina factory in Sari, Iran. MDF is made from lignocellulosic fibers derived from defibrated wood chip. It is typically composed of softwood and hardwood. The material is often bound together with a urea-formaldehyde resin. According to Figure 1, MDF dust particles of less than 750 µm in length were shown, also very few small particles were observed. The particles were sifted with a vibrating screen and particles that pass through 40-mesh (for the separation of oversize particles) were used. Polypropylene (PP) with trade name V30S was supplied by Arak Petrochemical Co. (Iran). The PP was in the form of pellets with a melt flow index (MFI) of 18 g/10 min (190°C/2.16 kg) and a density of 0.918 g/cm^3. PP pellets that pass through 40-mesh were used. Maleic anhydride grafted polypropylene (MAPP), in the form of powder (grade PPG-101) with a density of 0.91 g/cm^3, a MFI of 64 g/10 min

Table I. Composites Formulation with Different Blending Methods (Percent by Weight)

Blending method	Codes	MDF dust content (%)	PP content (%)	MAPP content (%)
Dry-blend	TD1	40	56	4
	TD2	50	46	4
	TD3	60	36	4
Melt-blend	TM1	40	56	4
	TM2	50	46	4
	TM3	60	36	4

(230°C/2.16 kg), was purchased from Kimia Javid Sepahan, Iran. The use of coupling agent such as MAPP as a compatibilizer enhances the dimensional stability of the PP and MDF dust via improving adhesion between PP and filler.

Sample Preparation

The WPC test panels were produced in 6 formulations with nominal density of 1 g/cm^3 and dimensions of 30 × 20 × 1 cm^3 (Table I). WPC panels were produced in a two-material blending method:

Melt-Blend Method. The required MDF dust (oven-dried) and PP for each mixture were blended by a counter-rotation twin-screw extruder (Model WPC-4815, Bornapars Mehr, Iran) and then powdered with a laboratory grinder. The obtained granules were then placed in hot press at 190°C for 15 min and finally cooled to room temperature under pressure. The pressure for heating was used at 30 bar.[9]

Dry-Blend Method. Composite panels were produced in a two-stage. In the first stage, MDF dust was dried in an oven at 105 ± 5°C for 24 h. In the second stage, MDF dust, MAPP and PP pellets were premixed mechanically at various formulations and then placed in hot press at 190°C with specific press pressure of 30 bar for 15 min.[9]

Mechanical Testing

Flexural strength, also known as modulus of rupture (MOR) a mechanical parameter for brittle material, is defined as a material's ability to resist deformation under load. The flexural strength represents the highest stress experienced within the material at its moment of rupture. Also, the flexural modulus or bending modulus is the ratio of stress to strain in flexural deformation, or the tendency for a material to bend. ASTM D 790 also describes determination of the modulus of elasticity (MOE), or flexural modulus, which is the ratio of stress to corresponding strain at the proportional limit. Samples for flexural testing (flexural modulus and strength), tensile testing (tensile modulus and strength), and withdrawal strength of fasteners (screw and nail) were prepared according to the technical specifications CEN/TS15534:2007.[30] The samples were cut to 20 × 2 × 1 cm^3 (length × width × thickness) and 5 × 5 × 1 cm^3 specimens for the bending/tensile tests and the withdrawal strength of fasteners, respectively. For the nail withdrawal tests, the round wire nails with length of 50 mm and diameter of 2.8 mm were used. The threaded length and diameter of screw were 50 and 4.3 mm, respectively. A power drill was used to drive the screws into specimens. Screw (coarse threads drywall) and nail used in this study are shown in Figure 2. Withdrawal strength of fasteners was calculated using the following equation:

$$\text{Withdrawal strength of fasteners } (\text{N/mm}) = \frac{P_{\max}}{L} \qquad (1)$$

where $P_{\max}$ is ultimate load required to pull out a screw and nail from the specimen, and L is the depth of the penetrated part of the screw, and nail (mm) in specimen.

Also, three-point flexural testing was carried out by an Instron Universal Testing Machine (model 4486), with loading speed of 5 mm/min. For each case (mechanical properties), six replicates samples were tested and the average values were reported. In addition, the experimental conditions for tensile testing were

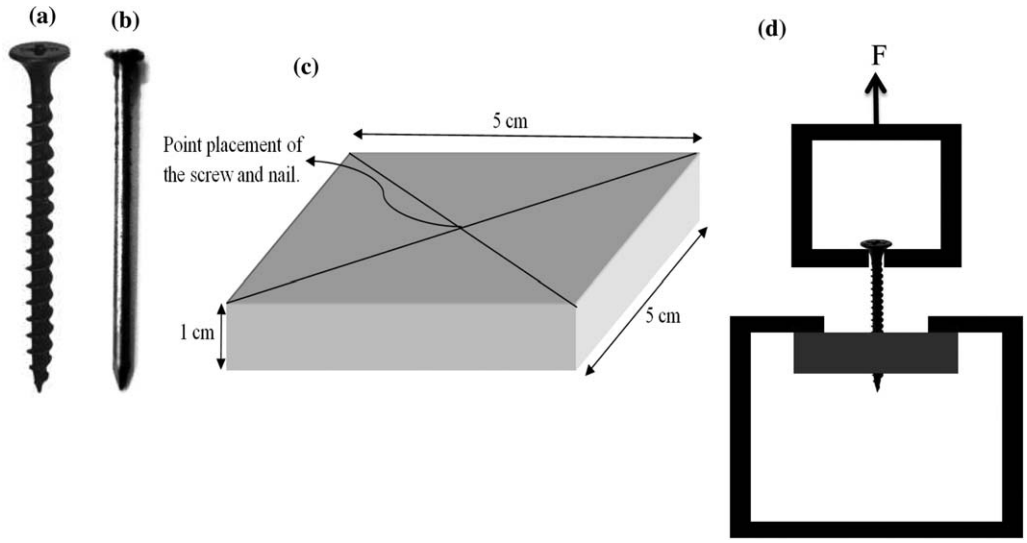

Figure 2. Screw (a) and nail (b) used in this study with schematic pictures of samples (c) and test set up of specimens (d).

performed at ambient conditions with a temperature of 25 ± 2°C and a relative humidity of ~50%.

Physical Testing

Physical properties, namely TS and WA were tested in accordance with ASTM D 570.[31] The samples were cut to 5 × 5 × 1 cm^3 for the TS and WA. Before testing, samples were weighed and dimensions were measured. The specimens were entirely immersed in distilled water at 25°C for 2 and 24 h. The weights of the specimens were recorded before and after soaking. Six replications of each sample type were tested. WA was calculated by the following equation:

$$\text{Water absorption}\,(\%) = 100(W_W - W_C)/W_C \quad (2)$$

where W_W represents the wet weight of specimen, W_C is the conditioned weight of specimen before water immersion. The values of the TS in percentage were calculated using the following equation:

$$\text{Thickness swelling}\,(\%) = 100(T_W - T_C)/T_C \quad (3)$$

where, T_W is the thickness of the sample at time t and T_C is the initial thickness of the sample.

Field Emission Scanning Electron Microscopy

The samples were initially placed in liquid nitrogen. The fracture surfaces of the samples were investigated using a field emission scanning electron microscope (FE-SEM) (model S-4160, Hitachi, Japan) with accelerating voltage of 20 kV. All specimens were sputter-coated with gold prior to examination to enhance the conductivity.

Statistical Analysis

SPSS programming version 18 (SPSS 18) was used for all statistical analysis. An analysis of variance, ANOVA, was conducted ($P \leq 0.01\%$ and $P \leq 0.05\%$) to evaluate the effects of the MDF dust content on the mechanical and physical properties of the WPC samples. When the ANOVA indicated a significant difference among factors and levels, a comparison of the means was done, employing Duncan's multiple range test (DMRT), to identify the groups that were significantly different from other groups at 99% and 95% confidence levels. *t*-test was also used for comparing blending methods.

RESULTS AND DISCUSSIONS

Mechanical Properties

The results of the mechanical tests, along with statistical analysis, are shown Table II for all the fabricated composites. Statistical analysis showed that the mechanical properties in terms of MOR, tensile strength, tensile modulus, and withdrawal strength of fasteners (screw and nail) of the boards were significantly influenced by the MDF dust contents (Table II). There was no significant difference in the MOE of the composites with different levels of MDF dust. Table III shows the statistical results of *t*-tests for mechanical tests between melt-blend and dry-blend samples. The *t*-test results revealed significant differences between tensile strength and tensile modulus of the composites made with the different methods.

The highest strength was observed in samples containing 40 wt % of MDF dust and it was decreased by increasing the amount of MDF dust (Table II). This indicates weak interaction between the MDF dust and polymer matrix. In fact, due to the high

Table II. The Mechanical Properties for All the Fabricated Composites and the Test Results of ANOVA and Duncan's Mean Separation Tests

Properties	MDF dust content (%)	Material blending method: Dry-blending[a]		Material blending method: Melt-blending[a]	
MOR (MPa)	40	25.94^{A}		26.35^{A}	
		(2.45)		(2.85)	
	50	24.37^{B}		25.9^{AB}	
		(1.91)	**	(2.54)	*
	60	17.18^{B}		22.22^{B}	
		(1.43)		(1.18)	
MOE (MPa)	40	2433^{A}	ns	2567^{A}	ns
		(233.12)		(272.41)	
	50	2278.5^{AB}		2357.83^{B}	
		(193.3)		(264.6)	
	60	2098^{B}		2204.17^{B}	
		(198.3)		(133.63)	
Tensile strength (MPa)	40	21.34^{A}		26.87^{A}	
		(1.42)		(0.78)	
	50	18.56^{B}	**	23.34^{B}	**
		(0.81)		(1)	
	60	12.58^{C}		14.96^{C}	
		(0.86)		(0.78)	
Tensile modulus (MPa)	40	3343.67^{A}		3724.33^{A}	
		(378.45)		(86.13)	
	50	2555.5^{B}	**	3005.33^{B}	**
		(302.8)		(320.98)	
	60	1939.33^{C}		2460.17^{C}	
		(171.44)		(347.23)	
Screw withdrawal strength (N/mm)	40	181.68^{A}		191.73^{A}	
		(8.41)		(10.86)	
	50	139.93^{A}	**	150.43^{A}	**
		(36.31)		(18.46)	
	60	126.77^{B}		138.05^{B}	
		(18.15)		(21.46)	
Nail withdrawal strength (N/mm)	40	38.03^{A}		40.965^{A}	
		(5.4)		(2.64)	
	50	32.08^{AB}	*	34.77^{B}	**
		(6.76)		(4.28)	
	60	24.43^{B}		26.51^{C}	
		(8.54)		(2.7)	

ns: no significant.
The numerical value in the parenthesis is standard deviation.
Different letters indicate significantly different groups ($P \leq 0.01$).
[a] Means of six tests.
*Significant difference at the 5% level ($P \leq 0.05\%$).
**Significant difference at the 1% level ($P \leq 0.01\%$).

Table III. Results of t-Test Analysis for Mechanical and Physical Properties Between Melt-Blend and Dry-Blend Methods

Properties	F	*t*	Significant
MOR	3.649	1.833	0.075^{ns}
MOE	0.049	1.112	0.274^{ns}
Tensile Strength	2.927	2.759	0.009**
Tensile Modulus	0.216	2.165	0.030*
Screw withdrawal strength	0.983	1.029	0.311^{ns}
Nail withdrawal strength	0.813	0.981	0.334^{ns}
Water absorption (2 h)	10.104	−4.319	0.000**
Water absorption (24 h)	0.093	−2.247	0.031*
Thickness swelling (2 h)	22.878	−6.341	0.000**
Thickness swelling (24 h)	15.131	−9.689	0.000**

t is the calculated value for comparing two independent variable in *t*-test. *F* is the calculated value belongs for homogeneity of variances test between groups.
ns: no significant.
*Significant difference at the 5% level ($P \leq 0.05\%$).
**Significant difference at the 1% level ($P \leq 0.01\%$).

percentage of MDF dust (60 wt %), the PP amount is not sufficient to adequately impregnate the filler. For this reason, the MOE decreased with increasing MDF dust. Various parameters impress the mechanical properties of WPC panels including the fiber-matrix adhesion, stress transfer at the interface, production methods, and mixing temperatures. In addition, as can be seen in Table II, MOE, MOR, tensile strength, tensile modulus, and withdrawal strengths of fasteners in samples made with the melt-blending method are higher than those made with the dry-blending method. Sanadi et al.[32] have reported similar results indicating a reduction in MOE with the increase in fiber content from 60 to 85%. A decrease in flexural strength by increasing in wood flour content, corresponds with findings by Chaharmahali et al.[29]

The observed increase in the mechanical properties of samples produced by melt-blending can be attributed to the improved interfacial bonding between the MDF dust and the polymer matrix. Besides, the observed effect could arise from a higher compacting level in melt-blending. Furthermore, a different dispersion level of the MDF dust could also affect the mechanical properties. Fuentes Talavera et al.[33] attributed the general weakening of the WPC composites when increasing the filler content to the poor bonding between organic filler and polymer.

In both of the blending methods, increasing MDF dust loading decreases the withdrawal strength of the composites (Table II). This is in accordance with the results published by Chaharmahali et al.[29] and Madhoushi et al.,[9] who studied the properties of wood plastic composites. Suitable withdrawal strength of fasteners results were obtained with melt-blending method because of more homogeneous structure of composites. Different levels of MDF dust and blending method seems to be the key factor in achieving better mechanical properties when blended with PP. The observed effect can relate to a higher compacting level in melt-blending and improved interfacial adhesion between the matrix and fibers.[10]

Table IV. The Physical Properties for All the Fabricated Composites and the Test Results of ANOVA and Duncan's Mean Separation Tests

		Blending method			
Properties	MDF dust content (%)	Dry-blending[a]		Melt-blending[a]	
WA 2 h (%)	40	2.027^{A}	**	0.84^{A}	**
		(0.64)		(0.2)	
	50	5.13^{B}		1.56^{A}	
		(0.72)		(0.23)	
	60	8.65^{C}		3.5^{B}	
		(0.74)		(0.6)	
WA 24 h (%)	40	4.67^{A}	**	3.05^{A}	**
		(0.84)		(1.1)	
	50	9.24^{B}		5.62^{B}	
		(1.23)		(1.2)	
	60	11.94^{C}		10.03^{C}	
		(0.94)		(1.13)	
TS 2 h (%)	40	0.36^{A}	ns	0.6^{A}	ns
		(0.17)		(0.2)	
	50	0.40^{A}		0. 61^{A}	
		(0.18)		(0. 3)	
	60	0.67^{A}		0.7^{A}	
		(0.37)		(0.2)	
TS 24 h (%)	40	0.80^{A}	ns	1.4^{A}	ns
		(0.10)		(0.4)	
	50	0.97^{A}		1.5^{A}	
		(0.15)		(0.9)	
	60	1.39^{B}		1.7^{A}	
		(0.51)		(0.5)	

ns: no significant.
The numerical value in the parenthesis is standard deviation.
Different letters indicate significantly different groups ($P \leq 0.01$).
[a] Means of six tests.
*Significant difference at the 5% level ($P \leq 0.05\%$).
**Significant difference at the 1% level ($P \leq 0.01\%$).

Physical Properties

The results of the physical tests, along with ANOVA and Duncan's mean separation are given in Table IV for TS and WA of the WPC samples after 2 and 24 h water-immersion times. Statistical analysis showed that the physical properties in terms of WA (both after 2 and 24 h water immersion) of the boards were significantly influenced by the MDF dust contents. Also, the *t*-test results revealed significant differences between physical properties of the composites made with the different methods (Table III).

WA and TS in both blending methods increases as the percentage of MDF dust in the composites increases. The hydrophilic nature of wood (high free-OH) is responsible for more water penetration into WPC composites.[34–37] Besides, huge number of porous tubular structures presented in fiber accelerates the water infiltration rate by the so-called capillary effect. Ayrilmis et al.[15] attributed the wettability of the WPC samples decreased with increasing polymer matrix content. Generally, water

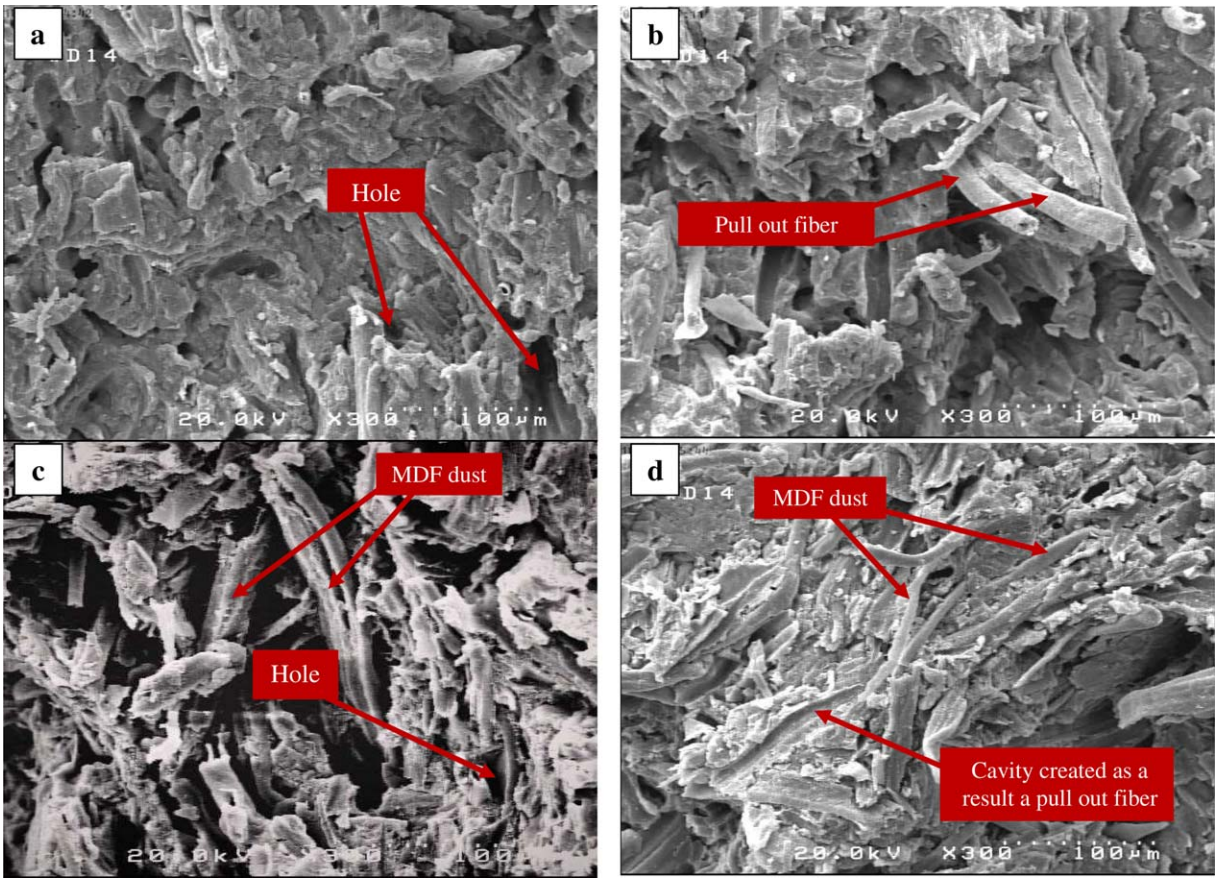

Figure 3. FE-SEM micrographs from fracture surface of MDF dust/PP composites made with melt-blending [a: (40 wt %), b: (60 wt %)] and dry-blend [c: (40 wt %), d: (60 wt %)] method. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

penetration into WPCs depends on their porosity, amount of lignocellulosic fibers, and their availability for incoming water.[38] For this reason, in the WPC panels produced by the dry-blend method, fibers were more accessible for WA.

FE-SEM Study

Microstructure of the fracture surface of test specimens was examined using FE-SEM. Improvement in physical and mechanical properties of MDF dust/PP composites made with melt-blending method can be attributed to the type of production process. Since MDF dust has very fine particle size, appropriate mixing, and covering the polymer during the process is required. It was found that integrating and mixing of MDF dust with polymer matrix is restricted by adding the MDF dust amount. The more uniform distribution evident in the sample produced by the melt-blend method suggests that the MDF dust was better mixed [Figures 3(a,b)]. There are some voids where the fibers have been pulled-out. The presence of these voids means that the interfacial bonding between the fiber and the matrix polymer is weak [Figure 3(c)].

FE-SEM images taken from failure surface of composites containing 40 and 60 wt %, has been shown in Figures 3(a–d), respectively. The figures reveals that the fibers surfaces have been better blended with the polymer matrix in composite containing 40 wt % MDF dust when compared with composite containing 60 wt % MDF dust. The presence of these uncovered fibers confirms that the interfacial bonding between the filler and the matrix polymer is poor and weak [Figures 3(b,d)]. It is also possible to observe the lignocellulosic material being weakly bonded to the matrix and thus pulled out from the matrix during fracture.[20] In addition, the value of decrease was higher in the composites made with the dry-blending method, which may be related to the shape of polymer (the pellets) used in the dry-blending process. Using polymer (PP) in pellets form, small dimensions of the MDF dust and the dry-blend process may be the reasons for the unsuitable blending.

CONCLUSIONS

This study was conducted to investigate the effect of filler content and material-blending method on physico–mechanical properties of MDF dust/PP composites. For this purpose, MDF dusts were used as lignocellulosic material and WPC panels then were produced in a two-material blending method. Statistical analysis showed that there is a significant difference in the physical and mechanical properties of composites at the 99% confidence level. The mechanical properties (including flexural properties, tensile properties, and fastener withdrawal strength) of the composites made with the melt-blending method are slightly higher than those made by dry-blending method at the same ratio of PP to MDF dust. It was also confirmed with SEM micrographs. Also, with increased the MDF dust content,

significant increasing in WA occurred, but these variations were not considerable for TS. Generally, WA and TS increased when increasing the amount of MDF dust. The FE-SEM images shows that no clear gap between MDF dust and PP matrix in samples produced by melt-blend method, indicating the suitable interface bonding. In fact, the mixing of MDF dust and polymer matrix has been much better in melt-blend method rather than another method. Finally, it was concluded that utilization of wood industrial wastes (such as MDF dust) for fabrication of WPC composites is favorable alternative to compensate the shortage of raw material for WPC industry.

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