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Mechanical and physical properties of aluminum powder/MDF dust/polypropylene composites

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HIGHLIGHTS

- Aluminum powders have significant effects on mechanical properties of the WPCs.
- The mechanical strengths of WPCs reduced by increasing MDF dust levels.
- With decreasing MDF dust ratio, the physical properties of WPCs improved.

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ABSTRACT

This research concerns the using metal powders and MDF production wastes as alternative sources to natural fibers in manufacturing wood–plastic composites (WPCs). The objective of this work was to investigate the influence of various levels of MDF dust and aluminum powder (AlP) on physical and mechanical characteristics of MDF dust/polypropylene composite. Polypropylene was used as a thermoplastic matrix, and maleic anhydride grafted polypropylene (MAPP) as a coupling agent. Hot pressing method was used to prepare samples with 1 g/cm^3 nominal density. The mechanical and physical properties were measured according to the technical specifications CEN/TS15534 and ASTM standard D 570, respectively. It was found that mechanical properties decreased and water absorption and thickness swelling increased with increasing amount of MDF dusts and AlP. Applying field emission scanning electron microscopy (FE-SEM), the aluminum powder and composite morphology was studied.

1. Introduction

Wood–plastic composites (WPCs) are relatively new materials which are gaining considerable attention during last years [1,2]. They appeared firstly as thermoplastic molding compounds in the 1960s and now they are known as an emerging group of renewable materials based on performance, process, and innovation in product design popular in the United States since the 1970s [3]. Thermoplastic composites play an important role in our society, as uses of such composites range from cookware to components of the space shuttle [4]. WPC is durable and low maintenance compared to wooden products (such as MDF and particle board), and hence according to thermoplastic character of WPC ideal for nonstructural applications [5]. 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 [5–9]. For making wood–plastic composites, the lignocellulosic fibers may be obtained from wood species [1,6,7,10–12] or agro-based fibers [13–15]. Polymer prices have rapidly increased because of increased consuming rate, the lack of oil and high demand in recent decades [16] and will lead to more growth in plastic price. Follow to relative increments in polymer prices in recent years; adding fibers and natural fillers in order to reduce costs in plastic industry has gained great attention [15]. In recent years, lignocellulosic fibers have gained considerable importance as biodegradable fillers for commercial thermoplastics. They have rapidly growing and developing now, and are replacing to inorganic or synthetic materials in different applications [17,18]. Moreover, a large amount of natural fibers as wood waste (such as sawdust) may be produced in various stages of wood/wood composites industrial (MDF and particleboard industry) processing. Utilization of these materials in manufacturing of WPC can lead to low production costs and eliminates the problem of accumulating and discarding wood industries waste [19–21]. Large amounts of wood waste are created annually as sawdust (which some parts are related to MDF and particleboard industries) worldwide. Regarding to Iran, in one new MDF factory, 30 ton of sand fines are daily produced. On the other hand, this cheap source of lignocellulosic materials can be used for production of wood–plastic composites with acceptable mechanical and physical properties [22]. Accordingly, application of low cost lignocellulosic material in manufacturing these types of compos-

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ites may affordable strategy production of these products. Consequently, utilization of MDF dusts may be used as an inexpensive and available material due to they are MDF plant wastes that usually are burnt in most cases, which new composites manufacturing are more economical than burning. On the other hand, aluminum is common practical material which many studies have been made about its reactivity [23]. Metal powder/polymer composites are an interesting category of materials which, due to their physical properties, may use in the particular application [24]. Metal powder/polymer composites that have both characteristics of metals and polymer simultaneously and also polymers have been studied in last two decades. They have a wide range of industrial applications due to their low density, high corrosion resistance, ease of production and low cost [25–27]. Structure and properties of metal powder/polymer composites are important to design new engineering materials with desired properties [25,27].

Aluminum is a relatively soft, ductile and lightweight metal with a density of 2.7 g/cm^3. Metals owing to their thermal conductive nature are frequently used in industries. Since wood products industry annually a huge value on resin curing under hot press, decrease press time is of high importance. Aluminum powders used in this study was underutilized by-product of a metallurgy plant. Including these studies, Kang et al. [28] investigated the properties of polypropylene/aluminum–multi-walled carbon nanotube (PP/Al–CNT) composites. They observed that tensile modulus increased by using more than 10 wt.% of aluminum particles, and tensile strength decreased in 30 wt.% and 50 wt.%. In another research in the field of metal reinforcements in polymer matrix 5%, 10%, and 15% volume of iron (Fe) powder and high density polyethylene (HDPE) were used in preparation of metal–polymer matrix which 5% (vol) Fe reduced izod impact strength and elongation of HDPE about 40% and 90% respectively and increased the modulus of elasticity of HDPE about 31% [27]. Withdrawal strengths of screw and nailed joints of WPC have been evaluated by Chaharmahali et al. [22]. They observed that withdrawal strengths of such joints are dependent on fiber content of WPCs containing waste fibers of MDF and particleboard. As filler content increased, withdrawal strength was lower than that of MDF panels. With filler content less than 60%, withdrawal strength of screwed joints on WPC panels was higher than the other boards.

Hence, the objective of this study is to investigate the possibility of using MDF dust and AlP in WPC production. Mechanical and physical properties of WPC with AlP were investigated. It should be noted that the authors could not yet find any published work regarding the effect of AlP on physical and mechanical properties of WPCs.

2. Materials and methods

2.1. Materials

MDF dust was obtained from MDF plant Arian Sina (Sari, Iran) as residue from sanding panel surfaces (Fig. 1b). The MDF dust was dried in an oven at 100 ± 5 °C for 24 h aiming consistent moisture content of 3% prior to blending with the polymer. Polypropylene (PP) with trade name of V30S was 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 was supplied by Arak Petrochemical Co. (Iran), in the form of pellets.

Maleic anhydride grafted polypropylene (MAPP), in the form of powder (grade PPG-101) with a density of 0.91 g/cm^3 and a MFI of 64 g/10 min, was obtained from Kimia Javid Sepahan Co., Iran. Aluminum powder (AlP), as a waste of aluminum cutting with nominal dimension of fewer than 250 μm (Fig. 1a) and purity of 99% was prepared from Poyan Shimi, Iran.

2.2. Preparation of composites

The 12 formulations for the wood–plastic composites are listed in Table 1. After weighing the required quantity of materials for each treatment, a dry-blending method was used for compounding the materials. WPC boards' dimensions were 30 × 20 × 1 cm^3, and 1 g/cm^3 was considered as nominal density of each them.

Following the materials blending process, the samples were hot-pressed at 190 °C, specific pressing pressure of 30 bar and pressing time of 15 min. The hot pressing process was completely according to Madhoushi et al's work [14].

2.3. Mechanical testing

Samples for bending strength, tensile strength, fasteners withdrawal strength, were prepared according to the technical specifications CEN/TS15534:2007 "Wood–plastics Composites (WPC) – Part 1: Test Methods for Characterization of WPC Materials and Products" [29]. The samples were cut to 17 cm × 2 cm × 1 cm (length × width × thickness) specimens for the bending and tensile tests and 5 cm × 5 cm × 1 cm for the withdrawal strength of fasteners. It should be noted that from one board six samples were cut for each test. The tests were performed using an Instron 4486 testing machine (model 4486).

2.4. Physical testing

Physical properties, namely thickness swelling (TS) and water absorption (WA) were tested in accordance with ASTM D 570. Before testing, the weight and dimensions, i.e. length, width and thickness of each specimen were measured. The specimens were entirely immersed in distilled water at 25 °C for 2 and 24 h. The weights of the specimens before and after soaking were recorded. Six replications of each sample type were tested. Water adsorption was calculated by the following equation:

$$\text{Water absorption } (\%) = 100\ (W_W - W_C)/W_C \quad (1)$$

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

$$\text{Thickness swelling } (\%) = 100\ (T_W - T_C)/T_C \quad (2)$$

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

2.5. Field emission scanning electron microscopy (FE-SEM)

The fracture surfaces of the samples were investigated using a field emission scanning electron microscopy (FE-SEM) (model S-4160, Hitachi, Japan). All specimens were sputter coated with gold prior to examination to enhance the conductivity.

2.6. Statistical analysis

The experimental design consisted of twelve treatments including MDF dust and AlP and their interactions. A factorial analysis, General Linear Model (GLM), was conducted ($p \leqslant 0.01$) to evaluate the effect of the MDF dust and AlP on the physical and mechanical properties of the WPC panels.

3. Results and discussion

3.1. Mechanical properties

Results for composite mechanical properties, along with statistical analysis, are given in Tables 2 and 3 and Figs. 2–4.

3.1.1. Bending properties

Average values of modulus of elasticity (MOE) and modulus of rupture (MOR) of aluminum powder/MDF dust/PP composite in different formulations are given in Fig. 2. Maximum value of MOE and MOR was obtained in treatment A1 and minimum value was observed in treatment C4 (Fig. 2). Statistical analysis showed that the mechanical properties in terms of MOR and MOE of the samples were significantly influenced by the MDF dust and AlP (Table 3). However, in wood–plastic composites with higher levels of fiber content, plastics are utilized as adhesives for bonding wood particles/fibers together [22]. When the MDF dust content increased from 40% to 60% no sufficient adhesive bonding was present to achieve higher modulus values and WPC samples were easily bent under load [22]. The possible reason proposed for this kind of behavior may be the weak interfacial adhesion between the matrix and MDF dust with the used AlP. Sanadi et al. [30] have reported similar results indicating a decrease of the modulus of elasticity with the increase in fiber content from 60% to 80%. This

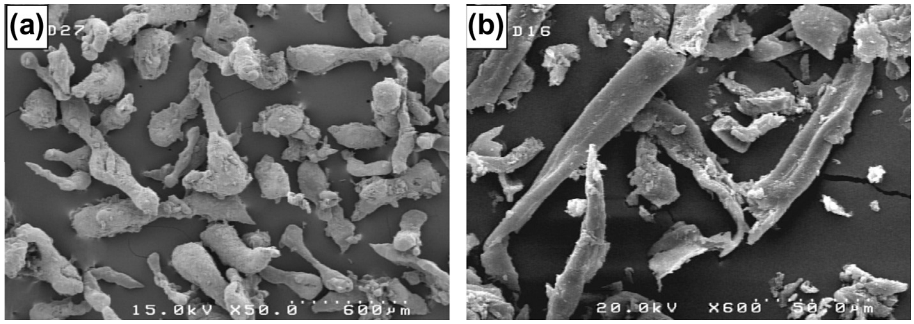

Fig. 1. FE-SEM image of AlP (a) and MDF dust (b).

Table 1
Aluminum powder/MDF dust/PP composite formulations and WPC density.

Treatment code		MDF dust (%)	PP (%)	AlP (%)	MAPP (%)	WPC density (g/cm^3)
A						
A1	40% MDF dust, 56% PP, 0% AlP, 4% MAPP	40	56	0	4	0.840
A2	40% MDF dust, 51% PP, 5% AlP, 4% MAPP	40	51	5	4	0.844
A3	40% MDF dust, 46% PP, 10% AlP, 4% MAPP	40	46	10	4	0.850
A4	40% MDF dust, 41% PP, 15% AlP, 4% MAPP	40	41	15	4	0.847
B						
B1	50% MDF dust, 46% PP, 0% AlP, 4% MAPP	50	46	0	4	0.830
B2	50% MDF dust, 41% PP, 5% AlP, 4% MAPP	50	41	5	4	0.800
B3	50% MDF dust, 36% PP, 10% AlP, 4% MAPP	50	36	10	4	0.840
B4	50% MDF dust, 31% PP, 15% AlP, 4% MAPP	50	31	15	4	0.832
C						
C1	60% MDF dust, 36% PP, 0% AlP, 4% MAPP	60	36	0	4	0.820
C2	60% MDF dust, 31% PP, 5% AlP, 4% MAPP	60	31	5	4	0.842
C3	60% MDF dust, 26% PP, 10% AlP, 4% MAPP	60	26	10	4	0.843
C4	60% MDF dust, 21% PP, 15% AlP, 4% MAPP	60	21	15	4	0.822

Table 2
Mean values and standard deviation of composites made with MDF dust and AlP.

Treatment code			Tensile		Withdrawal		WA		TS	
	MOE (MPa)	MOR (MPa)	Modulus (MPa)	Strength (MPa)	Screw (N/mm)	Nail (N/mm)	2 h (%)	24 h (%)	2 h (%)	24 h (%)
A1	2433 (333.12)	25.94 (3.45)	3343.67 (378.45)	21.35 (1.46)	181.68 (8.4)	38.03 (5.4)	2.027 (0.64)	4.67 (0.84)	0.36 (0.17)	0.80 (0.1)
A2	2343.83 (167.51)	24.69 (2.68)	3149.83 (150.54)	19.11 (1.46)	170.8 (9.57)	31.06 (3.73)	3.16 (0.63)	5.98 (1.48)	0.38 (0.21)	0.87 (0.31)
A3	2260.3 (332.04)	22.97 (4.2)	2829.33 (219.73)	18.36 (1.04)	158.05 (16.82)	30.14 (5.24)	4.74 (1.48)	6.46 (1.17)	0.43 (0.19)	0.93 (0.37)
A4	2014.16 (117.37)	21.76 (3.22)	2506.67 (288.03)	17.47 (0.67)	116.13 (7.08)	25.21 (6.33)	6.88 (1.21)	9.81 (1.21)	0.47 (0.08)	1.02 (0.22)
B1	2278.5 (193.29)	24.38 (1.91)	2555.5 (302.8)	18.57 (0.81)	139.93 (16.31)	32.08 (4.76)	5.13 (0.72)	9.24 (1.23)	0.40 (0.18)	0.97 (0.15)
B2	2198.83 (101.32)	23.97 (2.23)	2300.5 (295.73)	16.62 (0.88)	134.26 (4.24)	25.99 (2.52)	8.63 (1.15)	10.06 (2.007)	0.52 (0.31)	1.17 (0.52)
B3	2072 (51.03)	17.11 (2.16)	1933.5 (188.13)	14.63 (0.53)	118.55 (11.41)	25.09 (4.98)	9.51 (0.62)	12.58 (0.96)	0.55 (0.28)	1.19 (0.42)
B4	1522.9 (213.8)	14.84 (1.79)	1877.33 (113.08)	13.46 (1.31)	79.86 (7.46)	14.9 (2.05)	10.33 (1.67)	13.49 (1.14)	0.60 (0.09)	1.24 (0.29)
C1	2098 (198.28)	17.19 (1.42)	1939.33 (171.44)	12.59 (0.86)	126.76 (18.15)	24.43 (4.54)	8.65 (0.74)	11.94 (0.94)	0.67 (0.37)	1.39 (0.51)
C2	1894 (381.97)	16.9 (4.26)	1679.17 (92.83)	10.53 (0.63)	108.93 (20.6)	20.81 (4.95)	11.46 (1.27)	13.81 (1.38)	0.85 (0.26)	1.59 (0.13)
C3	1604.31 (281.5)	12.66 (2.25)	1471.83 (87.77)	9.74 (0.6)	72 (11.98)	13.91 (2.6)	11.99 (1.36)	15.46 (0.81)	0.92 (0.46	1.71 (0.5)
C4	1021.93 (138.21)	7.1 (2.22)	1364.5 (97.71)	9.2 (0.83)	45.98 (12.09)	8.01 (1.5)	12.712 (1.22)	17.82 (0.91)	0.90 (0.18)	1.80 (0.34)

The numerical value in the parenthesis is standard deviation (SD).

mechanical properties decrease as fiber content increase is in agreement with previous reports [1,22].

3.1.2. Tensile properties

Statistical analysis showed that the mechanical properties in terms of tensile strength and tensile modulus of the boards were significantly influenced by the AlP and MDF dust contents (Table 3). By adding AlP from 5% to 10% and 15%, tensile strength and tensile modulus decreased which these results can be seen in Fig. 3. Increment in MDF dust wt.% caused reduction in tensile modulus values, that 60 wt.% MDF dust have minimum values of strengths (Fig. 3). In fact, increasing fiber content decreases energy to break [31]. Minimum tensile modulus was found in 15 wt.% AlP with 60 wt.% MDF dust combination, which was 1364.5 MPa (Fig. 3 and Table 2). Maximum value of tensile modulus was obtained in control test sample (0% AlP) with 40 wt.% of MDF dust (3343.6 MPa). Average tensile strength of the samples ranged from 9.2 MPa to 21.35 MPa (Fig. 3 and Table 2).

3.1.3. Withdrawal strength of fasteners

The fastener withdrawal strengths are reduced by increasing MDF dust and AlP content, as observed for all samples. Nail and screw withdrawal strengths for aluminum powder/MDF dust/PP composite lie, respectively, in the range of 8.01–38.03 N/mm and 45.98–181.68 N/mm (Fig. 4 and Table 2). Generally, it found that the nail and screw withdrawal strength is reduced by increasing in MDF dust and AlP levels. This finding is also consistent with previous findings [22]. Regarding to control samples (without AlP),

Table 3
Analysis of variance on the effects of MDF dust and AlP contents and their interaction on some mechanical and physical properties.

Properties		Source of variations				
		A	*B*	*A* × *B*	Error	Total
	df	2	3	6	60	71
MOR	SS	1325.65	756.2	124.86	575.41	2782.14
	MS	662.82	252.06	20.81	9.59	
	F	69.1**	26.2**	2.17 ns		
	df	2	3	6	60	71
MOE	SS	4496299.42	5819595.18	796433.42	3975859.97	15088188.01
	MS	2248149.7	1939865.06	132738.9	66264.3	
	F	33.9**	29.2**	2.003^{ns}		
	df	2	3	6	60	71
Tensile strength	SS	895.4	172.18	8.16	56.97	1132.73
	MS	447.7	57.4	1.36	0.95	
	F	471.4**	60.4**	1.4^{ns}		
	df	2	3	6	60	71
Tensile modulus	SS	21891223.1	5193654.04	239508.3	2898651.1	30223036.65
	MS	10945611.5	1731218.01	39918.05	48310.85	
	F	226.5**	35.8**	0.82^{ns}		
Nail withdrawal strength	df	2	3	6	60	71
	SS	2466.85	2240.34	134.01	1491.7	1491.7
	MS	1233.43	746.78	22.335	24.862	
	F	49.6**	30.03**	0.89^{ns}		
	df	2	3	6	60	71
Screw withdrawal strength	SS	56198.22	49486.94	2306.45	19460.26	127451.89
	MS	28099.11	16495.64	384.410	324.338	
	F	86.6**	50.8**	1.18^{ns}		
	df	2	3	6	60	71
WA	SS	595.65	215.29	15.51	75.5	901.9
2 h	MS	297.827	71.766	2.586	1.258	
	F	236.68**	57.03**	2.05^{ns}		
	df	2	3	6	60	71
WA	SS	779.9	257.97	13.49	89.49	1140.86
24 h	MS	389.95	85.99	2.25	1.49	
	F	261.439**	57.651**	1.508^{ns}		
	df	2	3	6	60	71
TS	SS	2.55	0.417	0.082	4.05	7.108
2 h	MS	1.28	0.139	0.014	0.068	
	F	18.95**	2.05^{ns}	0.202^{ns}		
	df	2	3	6	60	71
TS	SS	6.327	0.883	0.096	7.588	14.894
24 h	MS	3.164	0.294	0.016	0.126	
	F	25.013**	2.327^{ns}	0.127^{ns}		

A = MDF dust; *B* = AlP; df = degree of freedom; MSs = mean of squares; SSs = sum of squares; F = F value; ns = not significant.
** Significant difference at the 99% level.

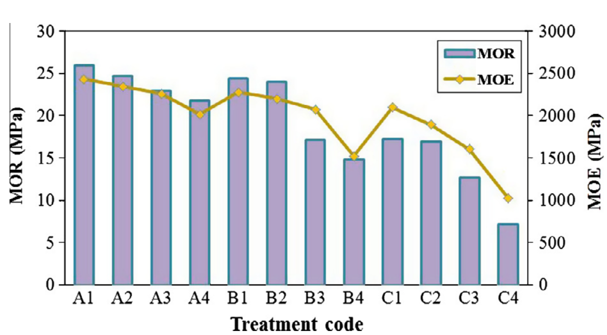

Fig. 2. Influence of MDF dust and aluminum powder content on MOE and MOR.

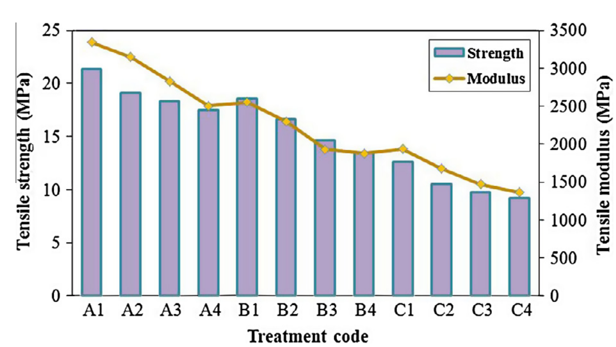

Fig. 3. Influence of MDF dust and aluminum powder content on tensile modulus and tensile strength.

finding is consistent with Madhoushi et al's [14] where at higher fiber to polymer ratios (>50%) the fastener withdrawal strengths declined.

3.2. Physical properties

The results of the physical properties, along with statistical analysis, are shown in Tables 2 and 3 and Figs. 5 and 6 for all the fabricated composites.

3.2.1. Water absorption tests

Results indicate that as the amount of AlP and MDF dust increases, the WA of the test samples increase significantly (Table 3, Fig. 5). WA value in control samples with 60% of MDF dust is higher, almost quadruple of control samples with 40% of MDF dust. WA increases substantially with increasing fiber content [31]. Adding in wt.% portion of AlP also causes enhanced WA value. Average WA of the samples ranged from 2.027% to 12.712% and 4.673% to 17.828% after 2 and 24 h immersion, respectively (Fig. 5 and Ta-

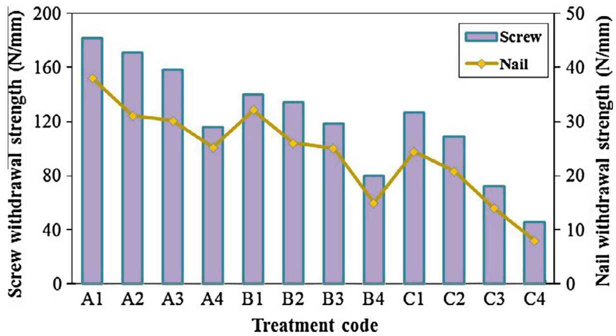

Fig. 4. Influence of MDF dust and aluminum powder content on screw and nail withdrawal strengths.

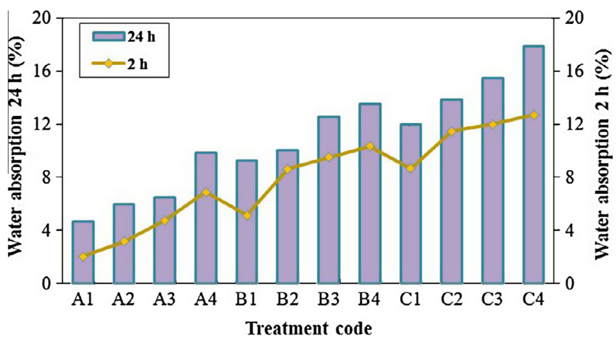

Fig. 5. Influence of MDF dust and aluminum powder content on WA after 2 h and WA after 24 h immersion.

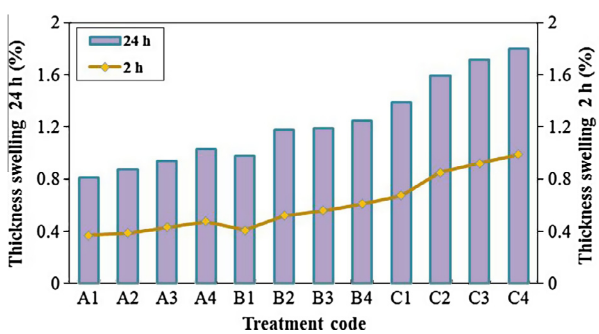

Fig. 6. Influence of MDF dust and aluminum powder content on TS after 2 h and TS after 24 h immersion.

ble 2). Generally thermoplastic polymers such as polypropylene due to their hydrophobic nature, do not absorb water indicating that moisture is solely absorbed by the hydrophilic wood component in the composite as well as voids and micro-gaps at the interface [32,34]. Generally, water absorption in WPCs depends on the porosity, amount of lignocellulosic fibers, and their availability for incoming moisture [32].

3.2.2. Thickness swelling tests

According to the results, TS (both after 2 and 24 h immersion) is significantly influenced by the amount of MDF dust (Table 3). Diameter swelling values of test samples also has been enhanced by increasing in consumed AlP amounts, which maximum value is belonged to 15 wt.% of AlP. Maximum and minimum swelling values are 1.8% and 0.8%, which are belonged to 24 h immersion in test samples of different treatments (Fig. 6 and Table 2). The hydrophilic nature of wood (high contents of hydroxyl groups in

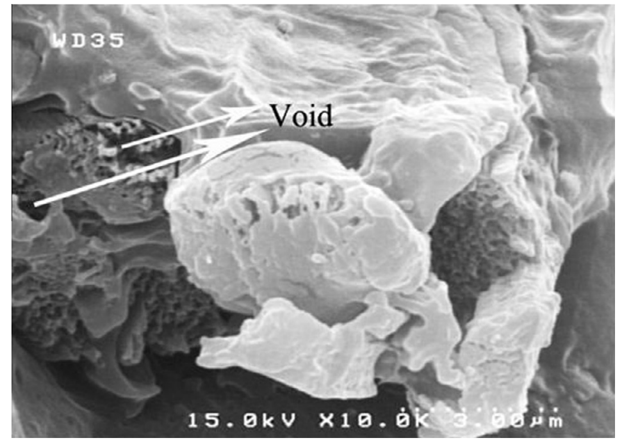

Fig. 7. FE-SEM image from aluminum powder/MDF dust/PP composite test sample.

cellulose and hemicelluloses) is responsible for water absorption [33–37].

3.3. FE-SEM study

Through FE-SEM study, the distribution and compatibility between the fiber and the matrix could be observed. Ultrastructure study shows that there are considerable differences between composites with and without AlP. Use of polymer in form of pellet and process type and also fine dimensions of MDF dust are causes for inappropriate mixing of the ingredients together. 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 (Figs. 7 and 8). Inappropriate mixing of MDF dust with polymer matrix has been shown in Fig. 8, which is due to applied production process for desired composite. Also, reductions in mechanical and physical properties may be attributed to weaken bonds between lignocellulosic and thermoplastic material due to decline in use of thermoplastic material quantity. These strength diminutions also can be given to use polymer form (pellets) and production process type (hot press). Nonmelted polymers as fine pellets was visible in failure surface of test samples that indicates MDF dusts has not been desirable compounded with thermoplastic materials.

FE-SEM observations showed that an empty space is created and bonding between filler and polymeric phase is reduced due to using AlP, lead to reduction in strengths (Fig. 9). From FE-SEM images also can be such considered that fine holes have been occurred in structure of aluminum powder/MDF dust/PP composite combination of desired composite ingredients when test samples were produced which are seen in different parts of test samples. Indeed, these fine holes were occurred where AlP were existed. This means that, no bonding was induced between AlP and polymeric phase, which lead to holes in test samples micro structure. Thus, it is considered that, these fine holes cause to weak points in aluminum powder/MDF dust/PP composite and stress concentration led to failure in test samples. Also, it can referred to existing fine aluminum holes which occurred in aluminum powder/MDF dust/PP composite as main reasons for increasing water absorption, where is for moisture accumulation typically (Fig. 9).

4. Conclusion

The objective of this work was to study the possibility to use MDF wastes and aluminum powder in the manufacturing of wood–plastic composite and to determine how aluminum pow-

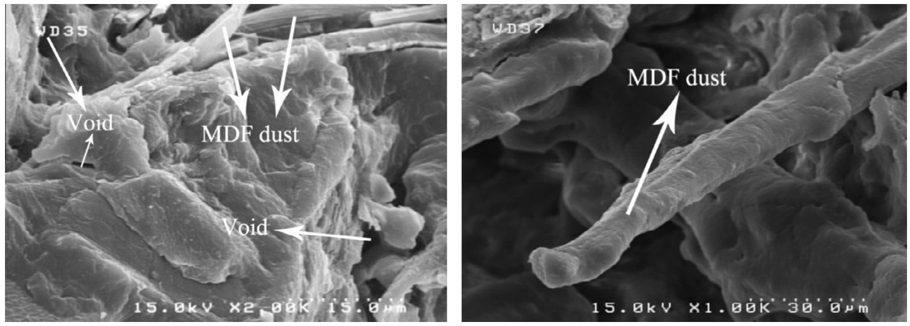

Fig. 8. FE-SEM images from MDF dusts/PP composite (control samples).

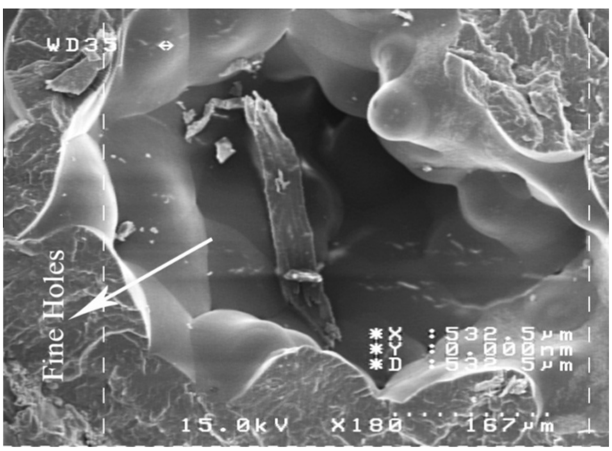

Fig. 9. FE-SEM image of aluminum powder/MDF dust/PP composite.

der and MDF dust content affect MOE, MOR, tensile modulus, tensile strength, nail and screw withdrawal strengths, WA and TS of WPC samples. For this purpose dust from sanding the surface of MDF boards and aluminum powder were used to produce composites. MOE, MOR, tensile modulus, tensile strength and nail and screw withdrawal strengths of all composites were reduced when increasing the content of MDF dust in aluminum powder/MDF dust/PP composite. It was found that mechanical strengths decreased and WA and TS increased when increasing the amount of MDF dust and AlP. Aluminum powder had the most incompatibility among the composites as revealed by FE-SEM study. Poor compatibility lowers the friction between the screw and the panels thus causing a lower withdrawal load. Also, there are two possible satisfactory reasons for using of MDF dust in manufacturing WPC panel. One is that the using wood industrial wastes for fabrication of WPC composite are favorable alternative to compensate the shortage of raw material for WPC industry. Another possible reason is the production of WPC is more admissible because it has more added worth and also it lead to employ (establishing of WPC production plants from MDF dusts next to MDF factories) and converting substances (MDF dust) which are hazardous for health individually, to safe materials (like as WPC panels).

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