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Effect of Wood Particle Size on Physical and Mechanical Composites by Nonwoven Web Process*1

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ABSTRACT

This study was carried out to discuss the feasibility of wood and plastic wastes as the raw materials for wood particle-plastic composites. For this purpose, composites were manufactured from coarse and fine wood particles and polypropylene fibers by nonwoven web process. And the effect of wood particle size on the performance of the composites were analyzed according to ASTM D 1037-93.

In the physical properties of composites, water absorption decreased with the increase of target density and polypropylene fiber content. And the composites with fine wood particles appeared to have slightly lower water absorption than those with coarse wood particles. Thickness swelling did not vary significantly with the increase of target density but increased with the increase of wood particle content. And the composites with fine wood particles were significantly lower in thickness swelling than those with coarse wood particles. In the mechanical properties of composites, dry and wet MOR showed the increasing tendency with the increase of polypropylene fiber content and target density. Dry and wet MOE showed the increasing tendency with the increase of target density but only wet MOE exhibited the increasing tendency with the increase of polypropylene fiber content. Composites with fine wood particles appeared to be generally higher in wet MOR and MOE than those with coarse wood particles.

In conclusion, composites with fine wood particles showed generally higher performance than those with coarse ones. Also, composites were significantly superior to control particleboards in the performance, especially in water absorption and thickness swelling.

Keywords : wood particle size, polypropylene fiber, nonwoven web process, composites, physical and mechanical properties

1. INTRODUCTION

In general, wood and plastic wastes have been the subject of studies in the composite industry with the intention of solving wastes problem as well as furnishing raw materials. Nonwoven web system can be made with up to 95 weight percent wood fibers and yield better mechanical properties than melt-blended products (Krzysik *et al.*, 1991; Wegner *et al.*, 1992; Yoon and Lee 1997).

But wood particles have rarely been discussed

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Fig. 1. Comparison of fine (right) and coarse (left) wood particles.

as the raw material in manufacturing composites with plastic wastes through the melt-blending technology, differently from wood fibers or flours. In case of wood particle-polypropylene fiber composites, some problems in uniform mixing and strong binding of wood particle with polypropylene fiber were unavoidable due to their extremely different shape and polarity but composites with higher performance could be made as a potential substitute for the existing particleboard by adapting processing variables. And performance of thermoplastic composites made of wood particle was reported to be superior to that of commercial particleboards (Lee 2000). In nonwoven web composites, thus, extensive studies are needed for more efficient use of wood particles.

This paper reports the results of an investigation to determine the effects of wood particle size on the physical and mechanical properties of nonwoven web composites.

2. MATERIALS and METHODS

2.1. Wood Particles and Polypropylene Fibers

Wood particles of acicular type for core layer of commercial three-layered particleboards, obtained from Dongwha Enterprise Co., Ltd., Incheon, Korea, were used in manufacturing both wood particle-polypropylene fiber composites and control particleboards.

These wood particles consisting of slabs of sosna (*Pinus sylvestris*), municipal and construction wastes, and secondary mill residues were sized into coarse and fine particles by screens of 5, 8.2, and 20 mesh. Coarse wood particles referred to the elements caught between 5 and 8.2 mesh screen, and fine wood particles referred to those passing through 20 mesh screen (Fig. 1). After screening, these wood particles were dried to moisture content of about 4.2% to 3.8%.

Deep green coloured polypropylene fibers, obtained from Kolon Merak Co., Ltd., Kimchon, Korea, were 1 ± 0.1 cm long and 3 denier with the melting temperature of $170 \sim 175^{\circ}C$, melt flow index (MFI) of 25 g/10 min. and 1% in moisture content.

2.2. Manufacturing Composites and Control Boards

Wood particle-polypropylene fiber composites and control particleboards measuring 300 mm long, 230 mm wide, and 5 mm thick were manufactured according to a completely randomized experimental design (Table 1).

Four composites by wood particle size, wood particle and polypropylene fiber formulation, and target density were manufactured for comparison with control particleboards in the physical and mechanical properties. Wood particles and polypropylene fibers were first roughly mixed by hand and then evenly mixed for 50 to 60 sec in a specially designed air mixer using turbulent air of 7 to 8 kg/cm^3 in pressure. These mixtures were transferred and formed manually into mats in the forming frame, followed by hot pressing (Table 1).

Four single-layered control particleboards measuring 300 mm long, 230 mm wide, and 5

Table 1. Experimental design in manufacturing wood particle-polypropylene fiber composites

Processing Variable			Manufacturing Condition				
			Hot pressing			Cooling	
Particle Size	Formulation (WP:PPF)[a]	Target Density (g/cm^3)	Temp. (^oC)	Time (min.)	Pressure (kgf/cm^2)	Time (min.)	Pressure (kgf/cm^2)
Coarse Particle	50:50	0.5	195	6	3.0	3	0.12
	60:40		195	6	4.5	3	0.30
	70:30		195	6	7.5	3	0.30
	50:50	0.6	195	6	6.0	3	0.12
	60:40		195	6	7.5	3	0.30
	70:30		195	6	12.0	3	0.30
	50:50	0.7	195	6	12.0	3	0.12
	60:40		195	6	15.0	3	0.30
	70:30		195	6	22.5	3	0.30
	50:50	0.8	195	6	22.5	3	0.12
	60:40		195	6	22.5	3	0.30
	70:30		195	6	30.0	3	0.30
Fine Particle	50:50	0.5	195	6	3.0	3	0.12
	60:40		195	6	4.5	3	0.30
	70:30		195	6	7.5	3	0.30
	50:50	0.6	195	6	6.0	3	0.12
	60:40		195	6	7.5	3	0.30
	70:30		195	6	12.0	3	0.30
	50:50	0.7	195	6	12.0	3	0.12
	60:40		195	6	15.0	3	0.30
	70:30		195	6	22.5	3	0.30
	50:50	0.8	195	6	22.5	3	0.12
	60:40		195	6	22.5	3	0.30
	70:30		195	6	30.0	3	0.30

[a]Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).

mm thick were manufactured by particle size and target density for comparison with composites in physical and mechanical properties. Manufacturing variables of control particleboards are shown in Table 2.

In order to manufacture control particleboards, the urea-formaldehyde resin with solids content of 60% was used. And ammonium chloride (NH_4Cl) in powder form was added as a hardener at 1% level based on solids weight of resin. As a water repellent, wax emulsion with solids content of 55% was incorporated in the resin at the level of 0.4% based on the oven-dry weight of wood particles.

2.3. Testing Properties of Composites and Control Particleboards

Two test specimens measuring 50×250 mm for dry and wet bending properties and two test specimens measuring 50×50 mm for density, moisture content, water absorption, and thickness

Table 2. Experimental design in manufacturing control particleboards

Particle Size	Target Density (g/cm^2)	Solids Content of Resin (%)	Resin Content[a] (%)	Mat Moisture Content (%)	Hot Pressing Condition		
					Temperature (°C)	Time (min.)	Pressure (kgf/cm^2)
Coarse Particle	0.5	60	10	10.7	150	5	7.5
	0.6	60	10	10.7	150	5	12.0
	0.7	60	10	10.7	150	5	22.5
	0.8	60	10	10.7	150	5	30.0
Fine Particle	0.5	60	10	10.7	150	5	7.5
	0.6	60	10	10.7	150	5	12.0
	0.7	60	10	10.7	150	5	22.5
	0.8	60	10	10.7	150	5	30.0

[a]Based on oven-dry weight of resin and wood particle.

swelling were cut from each composite and control particleboard. Two additional test specimens for density, moisture content, water absorption, and thickness swelling were also prepared from the specimen after dry bending test.

For testing the physical and mechanical properties under dry condition, all the specimens from composites and control particleboards were conditioned at a relative humidity (RH) of 65±1% and a temperature of 20±3°C in conformance with ASTM D 1037-93 (1995). For the bending modulus of rupture (MOR) and modulus of elasticity (MOE) under wet condition, the specimens were immersed in water for 24 h at a room temperature according to ASTM D 1037-93 (1995).

The measurements of physical and mechanical properties were statistically analyzed using a Statistical Analysis System (SAS) program. In this study, the analysis of variance (ANOVA) was conducted through the use of a completely randomized design (CDR) for the test differences in the density, moisture content, water absorption, thickness swelling, MOR, MOE to investigate the effects of formulation, target density, and wood particle size on the physical and mechanical properties. The significances of treated means were tested at a 95% significance level, and then compared by Tukey's and T-test methods.

3. RESULTS and DISCUSSION

3.1. Moisture Content

The control particleboards appeared to be significantly higher in moisture content than the composites. In the composites, moisture content increased with the increase of wood particle content irrespective of wood particle size (Table 3 and Fig. 2). Moisture content of composites showed slightly decreasing tendency with the increase of target density, but showed no significant difference by target density. Moisture content, however, appeared to increase with the increase of wood particle content, like the reports by Lee (2000) and Kim (2000).

Generally, the composites with fine wood particles was higher in moisture content than those with coarse ones irrespective of target density and formulation. This might be due to the formation of more barriers against release of water vapor from wood particles by the molten polypropylene fibers during hot pressing.

Table 3. Moisture content of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Moisture Content (%)	
		Coarse Particle	Fine Particle
0.5	50:50	4.85[b] (0.39)[c] C, a[d]	5.19[b] (0.21)[c] D, a[d]
	60:40	5.55 (0.36) B, a	6.00 (0.38) C, a
	70:30	5.81 (0.28) B, a	7.10 (0.31) B, b
	Control (100:0)	9.37 (0.06) A, a	9.41 (0.10) A, a
0.6	50:50	3.60 (0.22) D, a	5.30 (0.24) D, b
	60:40	4.41 (0.22) C, a	5.96 (0.39) C, b
	70:30	5.60 (0.29) B, a	7.05 (0.36) B, b
	Control (100:0)	9.32 (0.08) A, a	9.75 (0.06) A, b
0.7	50:50	4.66 (0.11) D, a	5.16 (0.15) D, b
	60:40	5.32 (0.23) C, a	5.94 (0.09) C, b
	70:30	6.55 (0.19) B, a	6.77 (0.14) B, a
	Control (100:0)	9.14 (0.10) A, a	9.43 (0.05) A, b
0.8	50:50	4.40 (0.13) D, a	4.24 (0.15) D, a
	60:40	5.57 (0.14) C, a	5.43 (0.11) C, a
	70:30	6.34 (0.15) B, a	6.81 (0.03) B, b
	Control (100:0)	9.19 (0.09) A, a	9.51 (0.06) A, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Each mean from 8 replications.
[c] Each standard deviation from 8 replications.
[d] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

The control particleboards made of fine wood particles were generally higher in moisture content than those made of coarse ones. This might to be attributed to the relatively smaller spread rate by larger surface area in fine particles than in coarse ones even at the same resin content. Kelly (1977) reported that larger particles could be satisfactorily bonded at lower resin content because of drastically reduced surface area in the larger particles.

3.2. Water Absorption

Average water absorption of wood particle-polypropylene fiber composites and control particleboards by formulation, target density, and particle size are given in Fig. 3 and Table 4 & 5. Control particleboards were higher in water

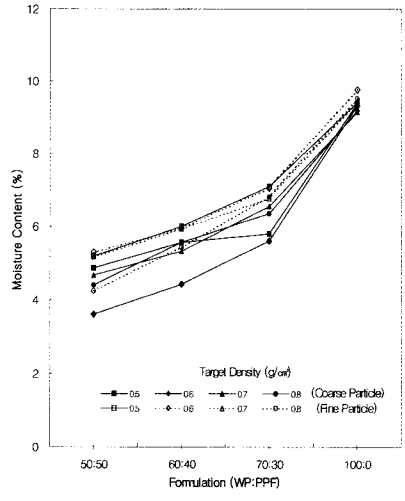

Fig. 2. Moisture content of coarse and fine wood particle-polypropylene fiber composites by formulation. WP = wood particle; PPF = polypropylene fiber.

Table 4. Water absorption of coarse and fine wood particle-polypropylene composites by formulation at a given target density after 2-h immersion in water

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Water Absorption (%)	
		Coarse Particle	Fine Particle
0.5	50:50	28.64[b] (2.05)[c] C, a[d]	25.04[b] (3.61)[c] BC, b[d]
	60:40	35.19 (2.38) B, a	22.64 (5.22) C, b
	70:30	49.45 (3.81) A, a	34.77 (7.38) A, b
	Control (100:0)	49.75 (2.67) A, a	28.49 (3.01) B, b
0.6	50:50	17.73 (2.55) D, a	14.86 (1.90) C, a
	60:40	26.92 (2.30) C, a	19.78 (3.48) B, b
	70:30	31.90 (4.75) B, a	30.85 (3.17) A, a
	Control (100:0)	47.86 (5.91) A, a	30.18 (1.74) A, b
0.7	50:50	11.85 (1.34) C, a	7.86 (1.43) D, b
	60:40	12.33 (1.73) C, a	11.85 (1.38) C, a
	70:30	21.46 (2.90) B, a	17.86 (1.44) B, b
	Control (100:0)	32.88 (1.64) A, a	21.43 (1.39) A, b
0.8	50:50	7.12 (0.63) D, a	3.39 (0.40) D, b
	60:40	9.66 (1.30) C, a	5.30 (0.83) C, b
	70:30	15.36 (2.14) B, a	12.87 (1.60) B, b
	Control (100:0)	26.78 (0.89) A, a	18.62 (0.90) A, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Each mean from 8 replications.
[c] Each standard deviation from 8 replications.
[d] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

absorption than the composites and their water absorption decreased with the increase of target density, like the report by Vital and Wilson (1980).

In the composites, water absorption decreased with the increase of target density but increased with the increase of wood particle content. This is in agreement with the reports by Yoon (1996), Krzysik and Youngquist (1991), Youngquist *et al.* (1993), Lee (1998), Lee (2000), and Kim (2000). Also, Geimer *et al.* (1993) noted that water absorption decreased significantly at polypropylene content of above 40%, like the result in this study.

After 2 h immersion, the composites with fine wood particles were slightly lower in water absorption than those with coarse wood particles irrespective of target density and formulation. This might be attributed to the more numerous and uniformly distributed water barrier by molten polypropylene fibers in the composites with fine wood particles than in those with coarse wood particles.

The control particleboards with fine wood particles were significantly lower in water absorption than those with coarse wood particles. This was thought to be caused by less and slow penetration of liquid water due to smaller and shorter voids between wood particles in the control particleboards with fine wood particles than in those with coarse wood particles. Like the result in the present study, Duncan (1974) reported that water absorption decreased with the decrease of particle size in particleboards.

Table 5. Water absorption of coarse and fine wood particle- polypropylene composites by formulation at a given target density after 24-h immersion in water.

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Water Absorption (%)	
		Coarse Particle	Fine Particle
0.5	50:50	43.26[b] (2.48)[c] D, a[d]	34.04[b] (7.61)[c] C, a[d]
	60:40	51.20 (4.07) C, a	47.88 (4.76) B, a
	70:30	66.14 (3.91) B, a	71.37 (4.23) A, b
	Control (100:0)	85.60 (1.99) A, a	76.02 (2.40) A, b
0.6	50:50	30.08 (4.05) D, a	29.18 (2.13) D, a
	60:40	39.97 (2.17) C, a	38.47 (4.77) C, a
	70:30	47.58 (3.90) B, a	54.32 (1.62) B, b
	Control (100:0)	75.91 (5.28) A, a	67.97 (3.46) A, b
0.7	50:50	19.36 (2.31) C, a	12.79 (3.12) D, a
	60:40	21.93 (2.25) C, a	24.13 (2.44) C, b
	70:30	38.70 (3.00) B, a	39.14 (4.42) B, a
	Control (100:0)	61.96 (2.46) A, a	53.22 (1.23) A, b
0.8	50:50	12.45 (0.99) D, a	7.27 (0.88) D, b
	60:40	16.42 (1.86) C, a	12.53 (2.34) C, b
	70:30	30.04 (4.20) B, a	9.12 (2.51) B, a
	Control (100:0)	58.53 (3.21) A, a	48.46 (1.90) A, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Each mean from 8 replications.
[c] Each standard deviation from 8 replications.
[d] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

Kelly (1977) reported that an increase of board density generally resulted in a decrease in water absorption, with only a few exception. Lehmann (1970, 1974), however, mentioned that density alone was not significant factor in determining water absorption and thickness swelling. Although some authors have found either an increase or no change in dimensional stability with increasing particleboard density, Vital *et al.* (1974) noted that the higher compaction ratio always resulted in the lower water absorption than the lower compaction ratio.

3.3. Thickness Swelling

Average thickness swelling of wood particle-polypropylene fiber composites and control particleboards by formulation, target density, and particle size are given in Fig. 4 and Table 6 & 7.

In thickness swelling of composites after 2-h immersion in water, the effect of formulation appeared to be significantly higher than that of target density. And thickness swelling decreased with the increase of polypropylene fiber content but did not change with the variation of target density.

Lee (2000) explained that thickness swelling in composites did not vary with the increase of target density due to the limited water uptake by the encapsulated wood particles with molten polypropylene fibers during hot pressing. Krzysik *et al.* (1991) reported that the composites underwent not only reversible swelling but also irreversible swelling in thickness direction by the release of residual compressive stresses imparted

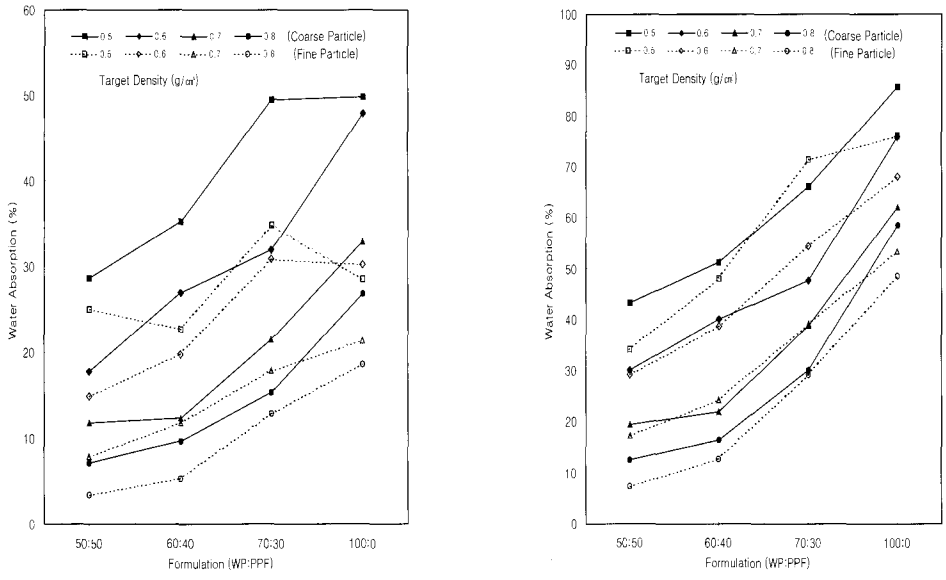

Fig. 3. Effect of formulation on water absorption of coarse and fine wood particle-polypropylene composites after 2-h (left) and 24-h (right) immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

Table 6. Thickness swelling of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density after 2-h immersion in water

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Thickness Swelling (%)	
		Coarse Particle	Fine Particle
0.5	50:50	4.86[b] (1.17)[c] C, a[d]	1.61[b] (0.57)[c] C, b[d]
	60:40	4.85 (0.86) C, a	2.19 (0.46) C, b
	70:30	8.75 (1.24) B, a	4.79 (0.49) B, b
	Control (100:0)	18.17 (2.77) A, a	8.09 (1.02) A, b
0.6	50:50	4.09 (1.60) C, a	0.77 (0.37) D, b
	60:40	5.45 (0.83) C, a	1.69 (0.49) C, b
	70:30	11.03 (2.54) B, a	4.86 (1.01) B, b
	Control (100:0)	20.44 (2.07) A, a	11.18 (0.79) A, b
0.7	50:50	2.88 (0.95) D, a	1.33 (0.68) C, b
	60:40	5.32 (0.90) C, a	1.57 (0.71) C, b
	70:30	9.34 (1.45) B, a	4.77 (0.75) B, b
	Control (100:0)	21.32 (1.69) A, a	11.33 (0.60) A, b
0.8	50:50	2.14 (1.52) D, a	1.41 (0.81) C, a
	60:40	5.15 (2.07) C, a	2.03 (0.51) C, b
	70:30	9.78 (1.39) B, a	5.77 (1.01) B, b
	Control (100:0)	21.61 (2.04) A, a	12.15 (1.14) A, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Each mean from 8 replications.
[c] Each standard deviation from 8 replications.
[d] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

Table 7. Thickness swelling of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density after 24-h immersion in water

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Thickness Swelling (%)	
		Coarse Particle	Fine Particle
0.5	50:50	7.87[b] (1.16)[c] C, a[d]	2.69[b] (0.73)[c] D, b[d]
	60:40	8.88 (1.98) C, a	5.20 (0.50) C, b
	70:30	12.70 (1.56) B, a	8.87 (0.51) B, b
	Control (100:0)	23.27 (2.92) A, a	14.07 (1.05) A, b
0.6	50:50	7.41 (0.99) C, a	2.80 (0.42) D, b
	60:40	9.18 (1.98) C, a	5.79 (0.81) C, b
	70:30	16.58 (2.50) B, a	8.68 (0.42) B, b
	Control (100:0)	26.43 (2.57) A, a	17.44 (1.31) A, b
0.7	50:50	6.62 (0.59) D, a	3.72 (0.55) D, b
	60:40	9.66 (1.04) C, a	4.64 (0.98) C, b
	70:30	12.21 (3.00) B, a	8.09 (0.44) B, b
	Control (100:0)	31.59 (2.50) A, a	19.95 (0.77) A, b
0.8	50:50	5.73 (1.94) C, a	2.33 (0.54) D, b
	60:40	7.92 (2.10) C, a	3.67 (0.64) C, b
	70:30	13.87 (1.78) B, a	9.40 (0.55) B, b
	Control (100:0)	35.78 (3.70) A, a	23.85 (0.62) A, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Each mean from 8 replications.
[c] Each standard deviation from 8 replications.
[d] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

to the compressed products during hot pressing and could be a great problem in composites made from high percentages of wood fibers. Geimer *et al.* (1993) described that thickness swelling decreased significantly at polypropylene content levels above 40%, like the result in this experiment.

After 2 and 24 h immersion in water, the composites with fine wood particles appeared to exhibit significantly lower thickness swelling than those with coarse wood particles irrespective of target density and formulation. This result was considered to be caused by the decreased water uptake and springback, the irrecoverable thickness swelling, by smaller voids and lower swelling stresses in the composites with fine wood particles than in those with coarse wood particles.

4. MECHANICAL PROPERTIES

4.1. Modulus of Rupture (MOR)

Average modulus of rupture (MOR) of wood particle-polypropylene fiber composites and control particleboards by formulation, target density, and particle size are given in Fig. 5 and Table 8 & 9.

In the effect of processing variables, dry MOR showed the increasing tendency with the increase of polypropylene fiber content and with the increase of target density. This agrees with Yoon (1996) and Lee (2000) who reported that bending strength increased with the increase of wood fiber content and composite density. Geimer *et al.* (1993), however, described that bending and tensile strengths increased with the

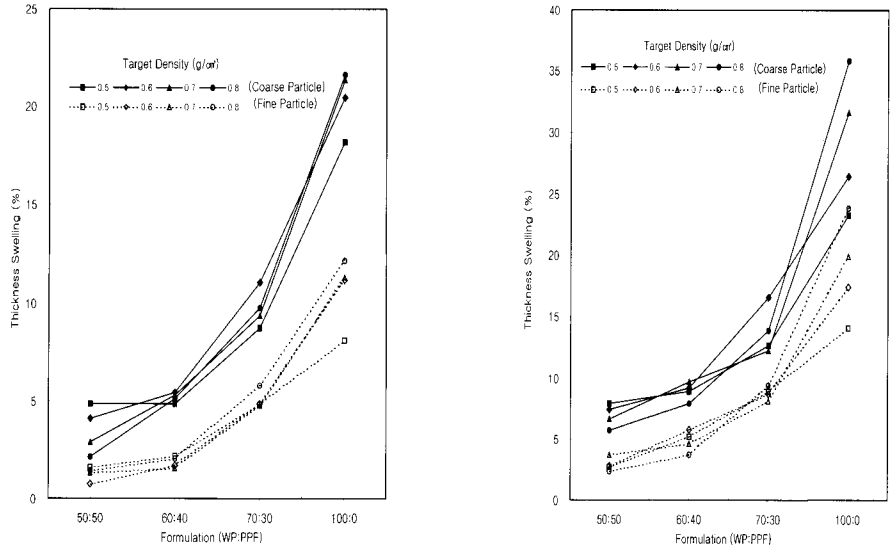

Fig. 4. Effect of formulation on thickness swelling of coarse and fine wood particle-polypropylene fiber composites after 2-h (left) and 24-h (right) immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

Table 8. Dry modulus of rupture (MOR)[b] of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Modulus of Rupture (kgf/cm^2)	
		Coarse Particle	Fine Particle
0.5	50:50	89.0[c] (4.8)[d] A, a[e]	127.8[c] (7.8)[d] A, b[e]
	60:40	79.3 (9.9) A, a	90.4 (6.9) B, b
	70:30	81.7 (10.6) A, a	83.1 (5.8) B, a
	Control (100:0)	45.2 (6.4) B, a	35.7 (11.2) C, a
0.6	50:50	135.1 (10.9) A, a	124.7 (5.0) B, a
	60:40	140.5 (14.5) A, a	154.1 (3.7) A, a
	70:30	119.4 (17.9) A, a	99.3 (5.5) C, a
	Control (100:0)	63.0 (8.0) B, a	81.8 (14.2) D, a
0.7	50:50	229.6 (25.0) A, a	210.4 (15.2) A, a
	60:40	202.5 (8.9) B, a	181.7 (13.6) B, a
	70:30	148.2 (9.8) C, a	129.6 (13.7) C, a
	Control (100:0)	116.5 (11.8) D, a	120.6 (6.9) C, a
0.8	50:50	228.1 (14.9) A, a	324.9 (26.5) A, b
	60:40	223.9 (18.0) A, a	227.9 (42.0) A, a
	70:30	168.9 (20.3) B, a	166.7 (13.5) C, a
	Control (100:0)	150.3 (21.4) B, a	153.5 (10.2) C, a

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] MOR after conditioning at 65±1% RH and 20±3℃.
[c] Each mean from 4 replications.
[d] Each standard deviation from 8 replications.
[e] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

Table 9. Wet modulus of rupture (MOR)[b] of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Modulus of Rupture (kgf/cm^2)	
		Coarse Particle	Fine Particle
0.5	50:50	62.6[c] (5.3)[d] A, a[e]	90.8[c] (4.0)[d] A, b[e]
	60:40	60.1 (3.8) A, a	86.4 (5.2) A, b
	70:30	48.6 (1.8) B, a	50.9 (6.3) B, a
	Control (100:0)	11.9 (1.4) C, a	19.0 (2.1) C, b
0.6	50:50	96.6 (5.3) A, a	144.0 (4.4) A, b
	60:40	80.1 (6.7) B, a	103.0 (4.5) B, b
	70:30	51.4 (2.5) C, a	57.7 (6.7) C, a
	Control (100:0)	19.4 (2.0) D, a	32.8 (4.2) D, b
0.7	50:50	159.7 (23.4) A, a	158.8 (7.9) A, a
	60:40	111.9 (12.0) B, a	122.8 (24.4) B, a
	70:30	75.8 (8.2) C, a	92.0 (10.1) C, a
	Control (100:0)	22.7 (1.6) D, a	52.1 (3.3) D, b
0.8	50:50	183.8 (15.0) A, a	256.8 (27.2) A, b
	60:40	177.6 (9.3) A, a	161.9 (27.8) B, a
	70:30	116.5 (9.7) B, a	120.8 (24.5) C, a
	Control (100:0)	36.0 (3.9) C, a	48.6 (3.2) D, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] MOR after 24-h immersion in water.
[c] Each mean from 4 replications.
[d] Each standard deviation from 8 replications.
[e] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

increase of wood material content and composite density and were influenced more by the compression of wood fiber than by the content of wood fiber.

Composites with fine wood particles appeared to be occasionally higher in dry MOR than those with coarse wood particles. This might be the result of uniformity of wood particle distribution in the composite mats because fine wood particles with higher aspect ratio and lower weight could be more easily and uniformly mixed with polypropylene fibers than coarse wood particles. Stark and Rowlands (2003) noted that composite with high aspect ratio was significantly higher in flexural strength than that with low aspect ratio and this aspect ratio had more effect on strength and stiffness than particle size in the composite. Osswald (1999) reported that stresses could be efficiently transferred from the matrix to the fiber without fiber or matrix fracture in the condition of good bonding between matrix and fiber, resulting in a stronger composite at a critical fiber length.

In the present study, dry MOR exhibited the largest difference between composites made of coarse and fine wood particles with the target density of 0.8 g/cm^3 and polypropylene fiber content of 50%. This result was thought to be caused by higher compaction in the composite mats with fine particles than in those with coarse particles at the same pressing pressure as Kelly (1977) concluded through literature review that MOR increased with the increase of compaction ratio.

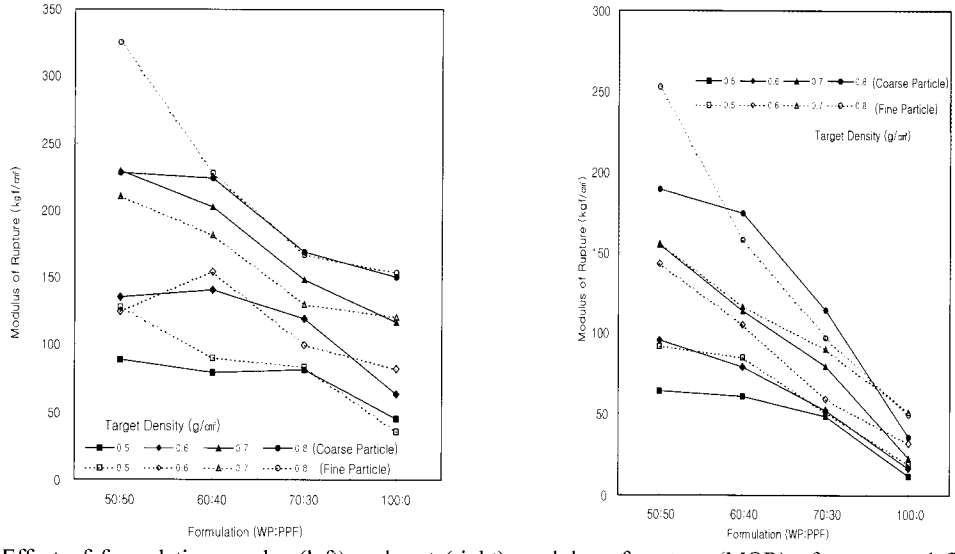

Fig. 5. Effect of formulation on dry (left) and wet (right) modulus of rupture (MOR) of coarse and fine wood particle-polypropylene fiber composites. WP = wood particle; PPF = polypropylene fiber.

In the effect of processing variables, wet MOR showed the increasing tendency with the increase of polypropylene fiber content and with the increase of target density. Composites with fine wood particles generally showed higher wet MOR than those with coarse wood particles, and this might be resulted from relatively smaller density reduction by significantly lower thickness swelling in the composites with fine wood particles after immersion in water.

The average dry MOR of control particleboards appeared to be lower than that of composites and increased with the increase of target density. Control particleboards made of fine wood particles were superior in wet MOR to those of coarse wood particles and this might be attributed to the decrease of density by higher thickness swelling in the control particleboards with coarse wood particles.

4.2. Modulus of Elasticity (MOE)

Average modulus of elasticity (MOE) of wood particle-polypropylene fiber composites and control particleboards by formulation, target density, and particle size are given in Fig. 6 and Table 10 & 11.

In the effect of processing variables, dry MOE showed the increasing tendency with the increase of target density and was more affected by target density than by formulation, like the reports by Kim (2000) and Lee (2000) who reported that bending stiffness increased with the increase of composite density. Geimer *et al.* (1993) noted that poor bonding between the hydrophilic wood and hydrophobic polypropylene allowed many separations, or voids, to occur at the interface but MOE clearly increased with the increase of panel density, despite the poor bonding between the wood and the polypropylene, because wood compaction and reduction of voids improved bending stiffness of the composite.

Composites with fine wood particle occasionally showed higher dry MOE than those with coarse ones but the effect of particle size on dry MOE was not generally identified. In the composites with wood flour and fiber, MOE showed

Table 10. Dry modulus of elasticity (MOE)[b] of coarse and fine wood particle-polypropylene fiber composites by formulation at a given target density

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Modulus of Elasticity (kgf/cm^2)	
		Coarse Particle	Fine Particle
0.5	50:50	6692[c] (238.4)[d] A, a[e]	9639[c] (1374.9)[d] A, b[e]
	60:40	6149 (985.4) A, a	7265 (387.5) B, a
	70:30	6911 (494.1) A, a	7670 (257.0) B, a
	Control (100:0)	4923 (426.7) B, a	4572 (1354.8) C, a
0.6	50:50	10331 (321.5) B, a	11363 (571.1) B, a
	60:40	10778 (588.5) B, a	14345 (696.0) A, b
	70:30	11934 (723.2) A, a	10909 (2227.5) B, a
	Control (100:0)	6601 (620.4) C, a	11027 (1706.0) B, b
0.7	50:50	16887 (2274.5) AB, a	16330 (636.2) AB, a
	60:40	17214 (2716.4) A, a	17727 (1537.5) A, a
	70:30	16662 (784.5) AB, a	11926 (1505.2) C, b
	Control (100:0)	13680 (1665.0) B, a	14770 (542.3) B, a
0.8	50:50	18957 (886.4) A, a	26351 (908.3) A, b
	60:40	21065 (1846.5) A, a	21294 (1656.8) B, a
	70:30	19217 (710.3) A, a	19969 (2489.3) B, a
	Control (100:0)	14301 (2072.3) B, a	18810 (1883.2) B, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] MOE after conditioning at 65±1% RH and 20±3℃.
[c] Each mean from 4 replications.
[d] Each standard deviation from 8 replications.
[e] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level. respectively.

the increasing tendency with the increase of aspect ratio (Stark and Rowlands 2003) and compaction ratio (Geimer *et al.* 1993). Although aspect and compaction ratios of fine wood particles were higher than those of coarse ones, in this experiment, the difference in MOE between composites with coarse and fine wood particles was not significant and this result might be attributed to the effect of length difference between coarse and fine particles.

In the effect of processing variables, wet MOE showed the increasing tendency with the increase of polypropylene fiber content and with the increase of target density. This wet MOE, like dry MOE, was thought to be more dependent on target density than on formulation. This might be due to better stress transfer from polypropylene to wood particle by the smaller void volume in the composites with higher density. The effect of particle size on wet MOE was clearly observed and this was thought to be resulted from better stress transfer by lower thickness swelling and less interfacial separation between wood particles and molten polypropylene fibers in the composites with fine wood particles than those with coarse ones. The control particleboards with higher density and fine wood particles were superior in dry MOE to those with lower density and coarse wood particles.

The effect of particle size on wet MOE was clearly identified, like the wet MOE of composites. In the particleboards, Vital *et al.* (1974) showed that a highly significant linear relation-

Table 11. Wet modulus of elasticity (MOE)[b] of coarse and fine wood particle-polypropylene fiber composite s by formulation at a given target density

Target Density (g/cm^3)	Formulation (WP:PPF)[a]	Modulus of Elasticity (kgf/cm^2)	
		Coarse Particle	Fine Particle
0.5	50:50	3733[c] (328.3)[d] A, a[e]	5879[c] (414.8)[d] A, b[e]
	60:40	3930 (102.6) A, a	5185 (660.0) A, b
	70:30	3712 (287.1) A, a	3004 (474.4) B, a
	Control (100:0)	790 (121.7) B, a	1834 (69.9) C, b
0.6	50:50	5416 (501.9) A, a	8779 (424.7) A, b
	60:40	5150 (267.6) A, a	7371 (281.0) B, b
	70:30	4308 (398.7) B, a	4618 (942.1) C, a
	Control (100:0)	1552 (218.5) C, a	2785 (445.0) D, b
0.7	50:50	8644 (1656.3) A, a	11630 (761.9) A, b
	60:40	8282 (1406.0) A, a	9283 (1435.5) B, a
	70:30	5879 (343.2) B, a	6425 (466.5) C, b
	Control (100:0)	1676 (188.1) C, a	5260 (622.0) C, b
0.8	50:50	10941 (929.7) A, a	16021 (1652.2) A, b
	60:40	10336 (848.1) A, a	11760 (1396.7) B, a
	70:30	7176 (1427.9) B, a	7187 (774.2) C, a
	Control (100:0)	2223 (222.0) C, a	4779 (764.8) D, b

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] MOE after 24-h immersion in water.
[c] Each mean from 4 replications.
[d] Each standard deviation from 8 replications.
[e] Means with the same big and small letters in the same column and row are not statistically different at a 0.05-significance level, respectively.

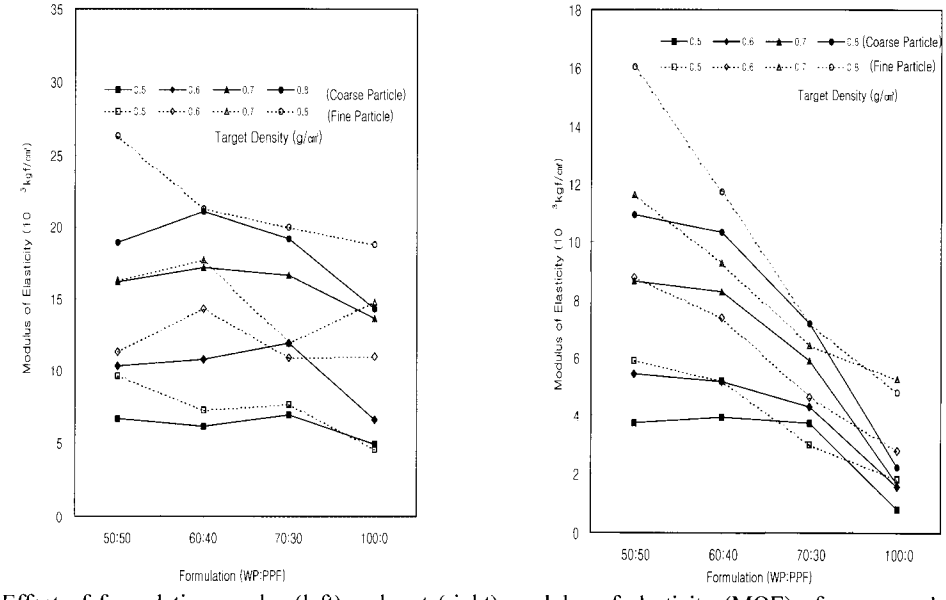

Fig. 6. Effect of formulation on dry (left) and wet (right) modulus of elasticity (MOE) of coarse and fine wood particle-polypropylene fiber composites. WP = wood particle; PPF = polypropylene fiber.

ship existed between MOE and panel density and compaction ratio. Kelly (1977) described that MOE generally increased with the increase of panel density, compaction ratio, and vertical density gradient. Lehmann (1974) reported that the MOE was strongly dependent on particle length, and thus longer particles produced particleboards with substantially higher MOE. Rackwitz (1963) found the optimum MOE to be obtained at particle aspect ratio range of 100 to 130, and MOE increased as the ratio increased up to this range but remained constant beyond this range.

5. CONCLUSIONS

1) Control particleboards had significantly higher moisture content than composites. In the composites, moisture content increased with the increase of wood particle content. Generally, the composites with fine wood particles appeared to be higher in moisture content than those with coarse ones.

2) Control particleboards showed higher water absorption than composites and their water absorption decreased with the increase of target density. In the composites, water absorption decreased with the increase of target density and polypropylene fiber content. And the composites with fine wood particles appeared to have slightly lower water absorption than those with coarse wood particles irrespective of target density and formulation.

3) Control particleboards were significantly higher in thickness swelling than composites and their thickness swelling increased with the increase of target density. In the composites, thickness swelling did not vary significantly with the increase of target density but increased with the increase of wood particle content. And the composites with fine wood particles were significantly lower in thickness swelling than those with coarse wood particles irrespective of target density and formulation.

4) Control particleboards were significantly lower in dry and wet MOR and MOE than composites and their MOR and MOE increased with the increase of target density. In the composites, dry and wet MOR and wet MOE showed the increasing tendency with the increase of polypropylene fiber content and with the increase of target density but dry MOE showed the increasing tendency with the increase of target density. Composites with fine wood particles appeared to be clearly higher in wet MOR and MOE but not in dry MOR and MOE than those with coarse wood particles.

5) In conclusion, composites with fine wood particles were generally superior in physical and mechanical properties to those with coarse ones. This may be attributed to more layered structure of encapsulated wood particles with molten polypropylene fibers and less void volume by more uniform mixing of fine wood particles with polypropylene fibers in air-turbulent mixer than coarse ones, resulting in significantly lower water absorption and thickness swelling.

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