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Studies on Manufacturing Wood Particle-Polypropylene Fiber Composite Board*[1]

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ABSTRACT

For finding both ways of recycling the wood and plastic wastes and solving the problem of free formaldehyde gas emission through manufacturing wood particle-polypropylene fiber composite board without addition of formaldehyde-based thermosetting resin adhesive, control particleboards and nonwoven web composite boards from wood particle and polypropylene fiber formulation of 50 : 50, 60 : 40, and 70 : 30 were manufactured at density levels of 0.5, 0.6, 0.7, and 0.8 g/cm^3, and were tested both in the physical and mechanical properties according to ASTM D 1037-93.

In the physical properties, control particleboard had significantly higher moisture content than composite board. In composite board, moisture content decreased with the increase of target density only in the board with higher content of polypropylene fiber and also appeared to increase with the increase of wood particle content at a given target density. Control particleboard showed significantly greater water absorption than composite board and its water absorption decreased with the increase of target density. In composite board, water absorption decreased with the increase of target density at a given formulation but increased with the increase of wood particle content at a given target density. After 2 and 24 hours immersion, control particleboard was significantly higher in thickness swelling than composite board and its thickness swelling increased with the increase of target density. In composite board, thickness swelling did not vary significantly with the target density at a given formulation but its thickness swelling increased as wood particle content increased at a given target density.

Static bending MOR and MOE under dry and wet conditions increased with the increase of target density at a given formulation of wood particle and polypropylene fiber. Especially, the MOR and MOE under wet condition were considerably larger in composite board than in control particleboard. In general, composite board showed superior bending strength properties to control particleboard, And the composite board made from wood particle and polypropylene fiber formulation of 50 : 50 at target density of 0.8 g/cm^3 exhibited the greatest bending strength properties.

Though problems in uniform mixing and strong binding of wood particle with polypropylene fiber are unavoidable due to their extremely different shape and polarity, wood particle-polypropylene fiber composite boards with higher performance, as a potential substitute for the commercial particleboards, could be made just by controlling processing variables.

Keywords: wood particle, polypropylene fiber, nonwoven web composite board, physical and mechanical properties, substitute for particleboard, recycling

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1. INTRODUCTION

Manufacturing the composite panel using waste wood, wood-based product, and plastic out of the municipal and industrial solid waste produced daily in vast quantities has an important meaning both in the stabilized supply of raw materials and solution of solid waste problem. Also, recycling the waste wood and wood-based materials will provide a profit of cost reduction in the plastic composite industry and recycling the waste plastic materials will help improve performance of products in the wood industry.

In this aspect, great efforts are in the progress and some outstanding successes have been achieved in the area of wood-plastic composite panel. Based on the raw materials and manufacturing process, composites from recycled materials fall into four main categories as follows: 1) thermoformable wood-plastic composites; 2) dry-formed wood-fiber-based composites; 3) inorganic bonded wood composites; and 4) wood-biomass fiber composites (Youngquist 1992).

Manufacturing composites from recycled materials has been considered as an effective and realizable way of reducing the problem of industrial and municipal solid waste such as wood, wood-based product, and plastic produced daily in large quantities (Rowell *et al.* 1991; Wegner *et al.* 1992; Youngquist 1992).

Based on manufacturing process, composites from wood fiber and thermoplastic fiber are classified into two general types of melt-blended and nonwoven web. In the melt-blending technology, wood fibers are blended with the matrix of molten thermoplastic and then the mixtures are extruded as sheets. These extruded sheets are subsequently shaped into the final product by injection molding. The melt-blended composites are made with wood fiber content up to 50% and used for various applications such as construction materials, interior materials for automobile, flooring, *etc.*

In the nonwoven web technology, wood fibers and thermoplastic fibers are mixed by air at room temperature and fabricated into a mat or web and then shaped into a panel or molding product by hot pressing. The nonwoven web composites can be produced with wood fiber content of 90% or more. When compared with melt-blending technology, the manufacturing process is very simple and even the low-density composites can be made easily in the nonwoven web technology (English 1992; Krzysik *et al.* 1991). The nonwoven web technology as a new spotlighted method in manufacturing natural and synthetic fiber products will permit a wide applications such as furniture components with both flat and curved surfaces, automobiles and truck components, interior sections, floor, wall and roof systems for light-frame construction, and packages (Youngquist *et al.* 1992, 1993).

Youngquist *et al.* (1990, 1993) reported that their physical and mechanical properties varied with the panel density in the nonwoven web composites manufactured from wood fibers and polymers of polyester and polyethylene.

In the evaluation test on the effectiveness of a maleated polypropylene (MAPP) as a coupling agent in the wood fiber-polypropylene fiber composites with wood fiber content of 70% or 85%, Krzysik and Youngquist (1991) and Krzysik *et al.* (1991) noted that the MAPP being incorporated in the nonwoven web composite panels at a level of 1 or 3% enhanced mechanical properties and also led to small improvements in water resistance for composite panels with wood fiber content of 85%. They considered the effectiveness of MAPP to be the result of efficient incorporation at the wood and polypropylene interface, thus providing effective coupling of the polar wood component to the non-polar polymer matrix.

In nonwoven web composites, Youngquist *et al.* (1993) found that the physical and mechanical properties improved as panel density increased from 0.4 to 1.2 g/cm^3 and as formulation changed from 90% hemlock and 10% polyester to 90% hemlock and 10% polypropylene to 80% hemlock, 10% polyester, and 10% phenol resin.

In lignocellulosic particle-plastic composite boards, Peng and Hwang (1996) reported that flexural properties and screw-holding ability improved with the increase of fibrous particle content and their water absorption and thickness swelling were much lower than those of wood-based panels.

Hwang (1997) noted in the plastic-wood composite board made from waste polyethylene and wood particles pretreated with urea resin that modulus of rupture and maximum deflection of boards decreased but thickness swelling increased with the increase of wood particle content and with the decrease of resin content of wood particle. He also stated that thickness swelling of composite boards increased with the increase of wood content and with the decrease of resin content of wood particles and that particles with surfaces covered by polyethylene film had positive effect on the strength property and dimension stability of composite boards.

In composite boards manufactured from wood and plastic wastes by simply heating and compressing, Boeglin *et al.* (1997) suggested that the resistance to static bending was close to that of commercial particleboards and water absorption was greater but thickness swelling was lower than those of commercial particleboards. They explained this contradictory result of lower thickness swelling in spite of higher water absorption in the wood-thermoplastic composites was attributed to higher absorption but lower penetration in depth during immersion in water than in commercial particleboards.

This research aimed to find both ways of recycling the wood and plastic wastes and solving the problem of free formaldehyde gas emission through manufacturing wood particle-polypropylene fiber composite panel without addition of formaldehyde-based thermosetting resin adhesive. And feasibility of this composite panel as a substitute for the commercial particleboard was discussed based on the physical and mechanical properties.

2. MATERIALS and METHODS

2.1. Characteristics of wood particle and polypropylene fiber

Needle-type wood particles of radiata pine (*Pinus radiata*) for core layer of commercial three-layered particleboard were used in manufacturing both wood particle-polypropylene fiber composite boards and control particleboards. Wood particles were dried to moisture content of about 4% and then were screened to remove those that would pass through a screen with mesh number of 20 for the better mechanical interweaving with polypropylene fibers. Deep green coloured polypropylene fibers were 1±0.1 cm long and 3 denier with the melt flow index (MFI) of 25 g/10 min. and the moisture content of 1%. The prepared wood particles and polypropylene fibers were kept in plastic bags for preventing moisture uptake before starting use.

2.2. Adhesive for control particleboard

The urea-formaldehyde resin with a solids content of 52% was used as a thermosetting adhesive. And aqueous solution of ammonium chloride (NH_4Cl) in 20% concentration was added as hardener in urea-formaldehyde resin at the level of 1.3% on the basis of solids weight. As a water repellent, wax emulsion with a solids content of 44% was incorporated in the wood particles at the level of 0.7% based on the oven-dry weight.

2.3. Manufacturing control particleboard

Four single-layered control particleboards measuring 300 mm long, 230 mm wide, and 5 mm thick were manufactured at each target density level of 0.5, 0.6, 0.7, and 0.8 g/cm^3 (Table 1). The prepared adhesive was applied to wood particles in a glue mixer at the resin content of 10% on the basis of oven-dry weight. The hand-formed mat in forming frame was hot pressed at a temperature of 130°C for 5 minutes. During hot pressing, the pressures applied were 15 kgf/cm^2 for the control particleboard with target density of 0.5 to 0.7 g/cm^3 and 25 kgf/cm^2 for those with target density of 0.8 g/cm^3 (Figure 1).

2.4. Manufacturing composite board

Wood particle-polypropylene fiber composite boards measuring 300 mm long, 230 mm wide, and 5 mm thick were manufactured according to the experimental design (Figure 2 and Table 2).

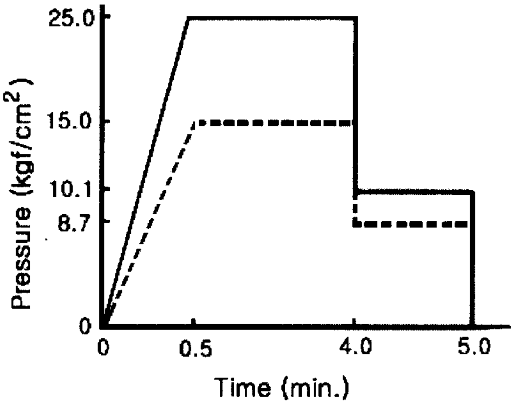

Fig. 1. Hot pressing schedule in manufacturing control particleboard. ——: target density of 0.8 g/cm^3; ----: target densities of 0.5 to 0.7 g/cm^3.

Four composite boards from wood particle and polypropylene fiber formulations of 50 : 50, 60 : 40, and 70 : 30, on the basis of oven-dry weight, with densities of 0.5, 0.6, 0.7, and 0.8 g/cm^3 were manufactured for comparison with control particleboards in physical and mechanical properties.

Wood particles and polypropylene fibers were roughly hand-mixed and then evenly mixed for 50 to 60 seconds in a specially designed air mixer by using turbulent air of 7 to 8 kgf/cm^2 which generated from an air compressor. The mixture was transferred and hand-formed into a mat in a forming frame, followed by hot pressing at a temperature of

Table 1. Experimental design in manufacturing control particleboard.

Target Density (g/cm^3)	Solids Content of Resin (%)	Resin Content[a] (%)	Mat Moisture Content (%)	Hot Pressing Condition		
				Temperature (℃)	Time (min.)	Pressure (kgf/cm^2)
0.5	52	10	14.5	130	5	15
0.6	52	10	14.5	130	5	15
0.7	52	10	14.5	130	5	15
0.8	52	10	14.5	130	5	25

[a] Solids basis on oven-dry particle weight.

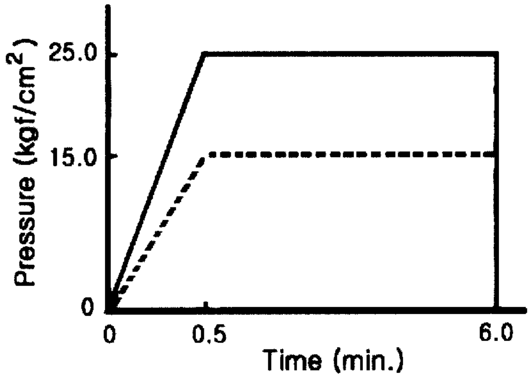

Fig. 2. Hot pressing schedule in manufacturing wood particle-polypropylene fiber composite board. —: target density of 0.8 g/cm^3; ----: target densities of 0.5 to 0.7 g/cm^3.

195°C for 6 minutes. During hot pressing, the pressure applied was 15 kgf/cm^2, except for 25 kgf/cm^2 in the composite board with target density of 0.8 g/cm^3 at the wood particle and polypropylene fiber formulation of 70 : 30.

Unloaded composite board after hot pressing was cooled in a cold press at room temperature for 3 minutes to prevent the springback in thickness direction. During cold pressing, the pressure applied was 0.7 kgf/cm^2, except for 7 kgf/cm^2 in the composite board with target density of 0.7 and 0.8 g/cm^3 at the wood particle and polypropylene fiber formulation of 70 : 30.

2.5. Testing properties of control particleboard and composite board

For testing the physical and mechanical properties, all the specimens from composite board and control particleboard 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) measurements under wet condition, the specimens were immersed in water for 24 hours at room temperature according to ASTM D 1037-93 (1995). The

Table 2. Experimental design in manufacturing wood particle-polypropylene fiber composite board.

Process Variable		Manufacturing Condition				
		Hot Pressing			Cooling	
Formulation (WP:PPF)[a]	Target Density (g/cm^3)	Temperature (°C)	Time (min.)	Pressure (kgf/cm^2)	Time (min.)	Pressure (kgf/cm^2)
50 : 50	0.5	195	6	15	3	0.7
60 : 40		195	6	15	3	0.7
70 : 30		195	6	15	3	0.7
50 : 50	0.6	195	6	15	3	0.7
60 : 40		195	6	15	3	0.7
70 : 30		195	6	15	3	0.7
50 : 50	0.7	195	6	15	3	0.7
60 : 40		195	6	15	3	0.7
70 : 30		195	6	15	3	7
50 : 50	0.8	195	6	15	3	0.7
60 : 40		195	6	15	3	0.7
70 : 30		195	6	25	3	7

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

measurements of physical and mechanical properties were statistically analyzed using a Statistical Analysis System (SAS) program.

3. RESULTS and DISCUSSION

3.1 Physical properties

3.1.1 Density

Results on the actual densities of wood particle-polypropylene fiber composite board and control particleboard by formulation and target density are presented in Table 3.

Actual density of composite board or control fiberboard was not significantly different from the target density established, and thus it was possible to manufacture the composite board and control fiberboard into the required density level by manufacturing condition established in this experiment.

Table 3. Actual density of wood particle-polypropylene fiber composite board and control particleboard.

Formulation (WP : PPF)[a]	Target Density (g/cm^3)	Board Density[b] (g/cm^3)
50 : 50	0.5	**0.50**[c] (0.03)[d]
	0.6	**0.64** (0.03)
	0.7	**0.68** (0.04)
	0.8	**0.76** (0.02)
60 : 40	0.5	**0.48** (0.01)
	0.6	**0.58** (0.03)
	0.7	**0.70** (0.05)
	0.8	**0.72** (0.02)
70 : 30	0.5	**0.47** (0.04)
	0.6	**0.55** (0.01)
	0.7	**0.63** (0.04)
	0.8	**0.74** (0.04)
Control (100 : 0)	0.5	**0.51** (0.04)
	0.6	**0.57** (0.04)
	0.7	**0.63** (0.02)
	0.8	**0.75** (0.02)

[a] Based on oven-dry weight of wood particle (WP) and polypropylene fiber (PPF).
[b] Based on oven-dry weight and oven-dry volume.
[c] Each mean value from 4 replications.
[d] Each standard deviation from 4 replications.

3.1.2 Moisture content

Results on the moisture content of wood particle-polypropylene fiber composite board and control particleboard by formulation and target density are shown in Table 4.

From the results, the control particleboard appeared to have significantly higher moisture content than the composite board after manufacture. In composite board, moisture content of composite board showed the decreasing tendency with the increase of polypropylene fiber content.

Moisture content showed a tendency of decrease with the increase of target density at wood particle and polypropylene fiber formulation of 50 : 50 and 60 : 40. The variation of moisture content by target density, however, was not statistically different in the composite board made from wood particle and polypropylene fiber formulation of 70 : 30 and control particleboard. Thus, the decrease of moisture content with the increase of target density was identified only in the composite board with higher content of polypropylene fiber.

3.1.3 Water absorption

Results on the water absorption of wood particle-polypropylene fiber composite board and control particleboard are given in Figures 3 and 4.

Control particleboard appeared to have significantly higher water absorption than the composite board and its water absorption

Table 4. Moisture content of wood particle-polypropylene fiber composite board and control particleboard.

Formulation (WP : PPF)[a]	Target Density (g/cm^3)	Moisture Content (%)
50 : 50	0.5	**3.83**[b] (0.09)[c] A[d]
	0.6	**3.63** (0.10) B
	0.7	**3.52** (0.05) BC
	0.8	**3.45** (0.08) C
60 : 40	0.5	**4.50** (0.15) A
	0.6	**4.38** (0.03) AB
	0.7	**4.28** (0.13) AB
	0.8	**4.13** (0.15) B
70 : 30	0.5	**5.08** (0.17) A
	0.6	**5.11** (0.06) A
	0.7	**5.09** (0.06) A
	0.8	**4.90** (0.04) A
Control (100 : 0)	0.5	**7.88** (0.09) A
	0.6	**7.91** (0.03) A
	0.7	**8.03** (0.08) A
	0.8	**8.02** (0.09) A

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

[b] Each mean value from 4 replications.

[c] Each standard deviation from 4 replications.

[d] Same letters are not statistically different at a 0.05-significance level.

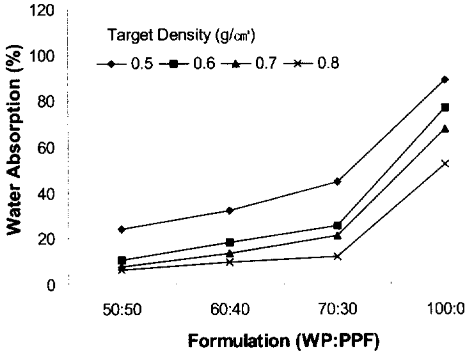

Fig. 3. Effect of formulation on water absorption of wood particle-polypropylene fiber composite board after 2-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

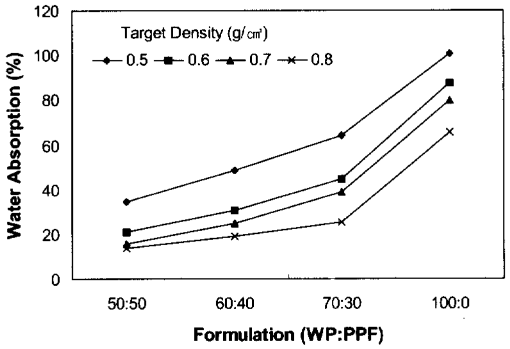

Fig. 4. Effect of formulation on water absorption of wood particle-polypropylene fiber composite board after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

decreased with the increase of target density after 2 and 24 hours immersion. In composite board, water absorption decreased with the increase of target density at a given formulation but increased with the increase of wood particle content at a given target density.

After 2 and 24 hours immersion in water, control particleboard exhibited significantly higher thickness swelling than composite board and its thickness swelling increased with the increase of target density. In composite board, however, thickness swelling did not vary significantly with the target density, which is in agreement with Yoon (1996), Krzysik *et al.* (1991) and Krzysik and Youngquist (1991). But thickness swelling of composite panel increased as wood particle content increased at a given target density.

3.1.4 Thickness swelling

Results on the thickness swelling of wood particle-polypropylene fiber composite board and control particleboard are given in Figure

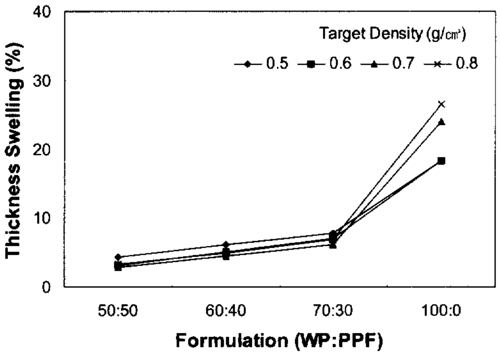

Fig. 5. Effect of formulation on thickness swelling of wood particle-polypropylene fiber composite board after 2-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

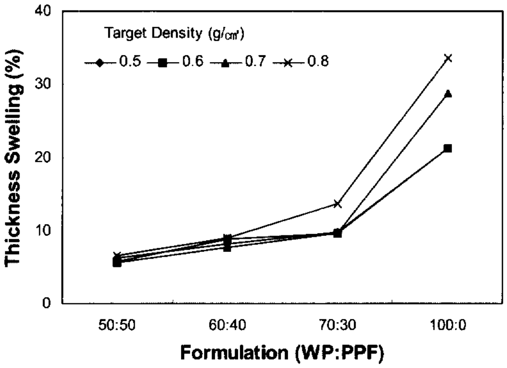

Fig. 6. Effect of formulation on thickness swelling of wood particle-polypropylene fiber composite board after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

5 and 6.

The present result of no significant variation of thickness swelling with the target density in the composite board seemed to be attributed to the limited water uptake by the encapsulated wood particles with molten polypropylene fibers during hot pressing.

Contrary to the result in this experiment, Youngquist *et al.* (1992), Gatchell *et al.* (1966), and Hallingan and Schniewind (1972) reported that thickness swelling increased with the increase of the density of composite panel. Youngquist *et al.* (1992) thought the greater thickness swelling in high-density composite panel to be the result of excessive built-up internal stresses caused by more wood material and more compaction, thus resulting in higher springback when exposed to very wet conditions such as soaking or boiling.

After 24-hour immersion in this study, on the other hand, water absorption decreased but thickness swelling increased significantly with the increase of target density from 0.7 to 0.8 g/cm^3 in the composite board with wood particle and polypropylene fiber formulation of 70 : 30. This contradictory result was thought to be attributed to the stronger built-up internal stresses caused by higher compression of mat in thickness direction during hot pressing, thus resulting in larger irreversible swelling of springback through occurrence of moisture plasticization when exposed to very wet condition of immersion in water (Lee 2000).

In this study, water absorption and thickness swelling increased with the increase of wood particle content at a given target density and most of the composite boards, except for composite board with target density of 0.8 g/cm^3 and wood particle and polypropylene fiber formulation of 70 : 30, met the thickness swelling of 12%, the least requirement in KS F 3104 (1997).

3.2 Mechanical properties

3.2.1 Static bending modulus of rupture

Results on the modulus of rupture (MOR) of wood particle-polypropylene fiber composite board and control particleboard are shown in Figures 7 and 8.

Under the dry condition after conditioning at

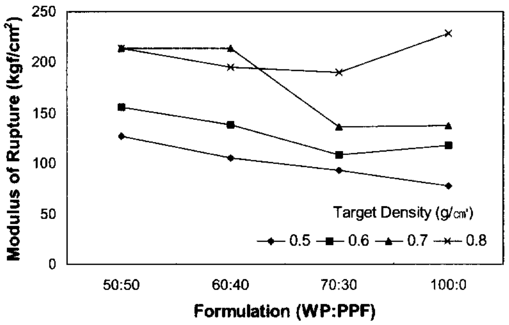

Fig. 7. Effect of formulation on modulus of rupture of wood particle-polypropylene fiber composite board under dry condition after conditioning at 65±1% RH and 20±3°C. WP = wood particle; PPF = polypropylene fiber.

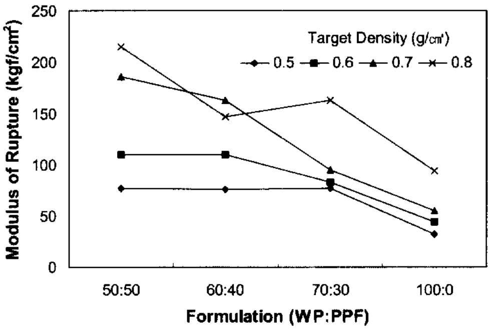

Fig. 8. Effect of formulation on modulus of rupture of wood particle-polypropylene fiber composite board under wet condition after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

65±1% RH and 20±3°C, MOR showed the increasing tendency with the increase of polypropylene fiber content at a given target density and with the increase of target density at a given formulation of wood particle and polypropylene fiber. This agrees with Yoon (1996) who reported that bending strength and tensile strength improved with the increase of thermoplastic fiber content. Geimer *et al.* (1993), however, reported that bending strength and tensile strength increased with the increase of wood fiber content and composite density and explained they were influenced more by the compression of wood fiber than by the content of wood fiber.

Under wet condition after 24 hours immersion in water, MOR of composite board appeared to be significantly higher than control particleboard and to show somewhat significant variation with the formulation at a given target density in composite board.

Especially, MOR under wet condition improved significantly as the target density increased from 0.7 to 0.8 g/cm^3 in the composite board made from wood particle-polypropylene fiber formulation of 70 : 30. This was thought to be resulted from enhanced encapsulation and binding of wood particles with molten polypropylene fibers by higher pressure applied during hot and cold pressing. Similar result was identified by Boeglin *et al.* (1997) who reported that MOR of the boards cooled in press were superior to that of the boards cooled without pressure.

On the other hand, MOR under dry condition decreased with the increase of target density from 0.7 to 0.8 g/cm^3 in the composite board made from wood particle and polypropylene fiber formulation of 60 : 40. This result was considered to be resulted from insufficient encapsulation and binding of wood particles with molten polypropylene fibers by the shortage of pressure applied during hot and cold pressing.

In this study, composite boards made from wood particle and polypropylene fiber formulations of 50 : 50 and 60 : 40 at target densities of 0.7 and 0.8 g/cm^3 and those made from wood particle and polypropylene fiber formulation of 70 : 30 at target density of 0.8 g/cm^3 satisfied the requirement of MOR value, 184 kgf/cm^2, under dry condition in unprocessed particleboard of 18.0 type in KS F 3104

(1997). And the composite boards made from wood particle and polypropylene fiber formulations of 50 : 50 and 60 : 40 at target densities of 0.6, 0.7, and 0.8 g/cm^3 and those made from wood particle and polypropylene fiber formulation of 70 : 30 at target densities of 0.7 and 0.8 g/cm^3 satisfied the requirement of MOR value, 92 kgf/cm^2, under wet condition in unprocessed particleboard of 18.0 type in KS F 3104 (1997).

3.2.2 Static bending modulus of elasticity

Results on the modulus of elasticity (MOE) of wood particle-polypropylene fiber composite board and control particleboard are shown in Figures 9 and 10.

Under the dry condition after conditioning at 65±1% RH and 20±3°C, MOE showed the increasing tendency with the increase of target density at a given formulation of wood particle and polypropylene fiber. This is in agreement with Geimer *et al.* (1993) who reported MOE improvement with the increase of target density. MOE under dry condition, however, did not vary significantly with the formulation of wood particle and polypropylene fiber at a given target density.

Under wet condition after 24 hours immersion in water, MOE of composite board appeared to be significantly higher than that of control particleboard and improved as target density increased at a given formulation. As the wood particle content increased, MOE under wet condition exhibited the decreasing tendency.

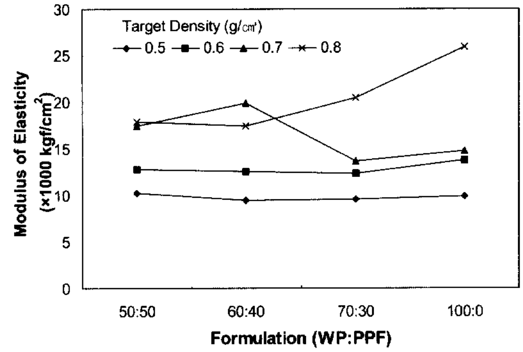

Fig. 9. Effect of formulation on modulus of elasticity of wood particle-polypropylene fiber composite board under dry condition after conditioning at 65±1% RH and 20±3°C. WP = wood particle; PPF = polypropylene fiber.

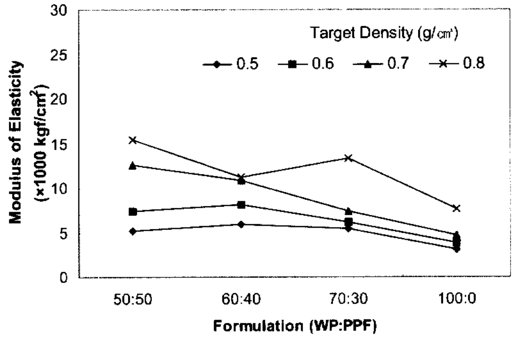

Fig. 10. Effect of formulation on modulus of elasticity of wood particle-polypropylene fiber composite board under wet condition after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

4. CONCLUSIONS

Control particleboards and nonwoven web composite boards with wood particle and polypropylene fiber formulation of 50 : 50, 60 : 40, and 70 : 30 were manufactured at target density levels of 0.5, 0.6, 0.7, and 0.8 g/cm^3, and their physical and mechanical properties were tested according to ASTM D 1037-93. The results obtained in this study were summarized as follows:

1. Control particleboard showed significantly higher moisture content than composite board. In composite board, the decrease of moisture content with the increase of target density was identified in the board with

higher content of polypropylene fiber and moisture content appeared to increase with the increase of wood particle content at a given target density.

2. Control particleboard were significantly higher in water absorption than composite board and its water absorption decreased with the increase of target density. In composite board, water absorption decreased with the increase of target density at a given formulation but increased with the increase of wood particle content at a given target density.
3. Control particleboard were significantly higher in thickness swelling than composite board and its thickness swelling increased with the increase of target density after 2 and 24 hours immersion. In composite board, thickness swelling did not vary significantly with the target density at a given formulation but its thickness swelling increased as wood particle content increased at a given target density.
4. Static bending MOR and MOE under dry and wet conditions increased with the increase of target density at a given formulation of wood particle and polypropylene fiber. Especially, the MOR and MOE under wet condition were considerably higher in composite board than in control particleboard.
5. Composite board generally showed superior performance in bending strength properties to control particleboard, and that made from wood particle and polypropylene fiber formulation of 50 : 50 at target density of 0.8 g/cm^3 exhibited the greatest bending strength properties.
6. Though problems in uniform mixing and strong binding of wood particle with polypropylene fiber are unavoidable due to their extremely different shape and polarity, wood particle-polypropylene fiber composite board with higher performance could be made as a potential substitute for the particleboard by adapting processing variables.

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