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Physical and Mechanical Properties of Wood Fiber-Polypropylene Fiber Composite Panel*1

Jee Woong Kim*2 and Young Geun Eom*3

ABSTRACT

This study was to find a way of reusing wood and plastic wastes, which considered as a troublesome problem to be solved in this age of mass production and consumption, in manufacturing wood fiber-polypropylene fiber composite panel. And the feasibility of this composite panel as a substitute for existing headliner base panel of automobile was also discussed, especially based on physical and mechanical performance.

Nonwoven web composite panels were made from wood fiber and polypropylene fiber formulations of 50 : 50, 60 : 40, and 70 : 30, based on oven-dry weight, with densities of 0.4, 0.5, 0.6, and 0.7 g/cm^3. At the same density levels, control fiberboards were also manufactured for performance comparison with the composite panels. Their physical and mechanical properties were tested according to ASTM D 1037-93. To elucidate thickness swelling mechanism of composite panel through the observation of morphological change of internal structures, the specimens before and after thickness swelling test by 24-hour immersion in water were used in scanning electron microscopy.

Test results in this study showed that nonwoven web composite panel from wood fibers and polypropylene fibers had superior physical and mechanical properties to control fiberboard.

In the physical properties of composite panel, dimensional stability improved as the content of polypropylene fiber increased, and the formulation of wood fiber and polypropylene fiber was considered to be a significant factor in the physical properties. Water absorption decreased but thickness swelling slightly increased with the increase of panel density.

In the mechanical properties of composite panel, the bending modulus of rupture (MOR) and modulus of elasticity (MOE) appeared to improve with the increase of panel density under all the tested conditions of dry, heated, and wet. The formulation of wood fiber and polypropylene fiber was considered not to be a significant factor in the mechanical properties. All the bending MOR values under the dry, heated, and wet conditions met the requirements in the existing headliner base panel of resin felt.

Keywords: wood fiber, polypropylene fiber, nonwoven web composite panel, physical and mechanical properties, headliner base panel

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*1 Received on May 7, 2001, accepted on July 23, 2001
*2 Wood Business Part, Samick Musical Instruments Co., Ltd., Inchon 404-250, Korea
*3 Department of Forest Products, College of Forest Science, Kookmin University, Seoul 136-702, Korea

1. INTRODUCTION

In the wood industry, a practical way of approaching to solve the problems of rising price and limited supply of wood as well as the concern on environmental disruption may lie in the appropriate recycling of waste wood, wood-based product, and plastic out of the municipal and industrial solid waste produced daily in vast quantities. As a way of recycling these wastes, studies on the manufacture and performance improvement of wood fiber-thermoplastic fiber composites have been extensively conducted (Rowell *et al.* 1991, 1993; Wenger *et al.* 1992; Youngquist 1992a).

Youngquist *et al.* (1990) reported in the wood fiber-plastic fiber composite by air-formed dry-process technology that panels made with yellow cypress fibers had higher strength properties and dimensional stability than those made with hemlock fibers, and decreasing the ratio of wood fiber to polypropylene fiber from 90 : 10 to 70 : 30 resulted in the enhanced mechanical and physical properties.

Youngquist *et al.* (1992b, 1993) found that water absorption decreased but thickness swelling increased as panel density increased in the air-formed wood fiber-polymer fiber composites and explained that this result was due to the enlarged springback with the increase of panel density.

Yoon (1996) described that physical and mechanical properties improved as the panel density increased, and bending and tensile properties slightly increased but thickness swelling decreased as the content of synthetic fiber increased in the wood fiber-thermoplastic fiber composite.

At present, hardboard and resin felt are commonly used for headliner base panel in automobiles. But the hardboard for this application has two disadvantages of the heavy weight by panel density of 1.0 g/cm^3 or higher and free formaldehyde emission from urea resin incorporated. And resin felt can be manufactured from jute, cotton, and synthetic fiber at low density level but has the problem of deteriorating the working environment through generation of lots of fine dust during cutting process.

Wood fiber-polypropylene fiber composite panel with low density level down to 0.4 g/cm^3 can be made quite easily through nonwoven web technology (Youngquist 1993). This nonwoven web composite panel has also the advantages of avoiding the emission of free formaldehyde and decreasing the generation of fine dust in working place.

Therefore, this study was designed to discuss the feasibility of wood fiber-polypropylene fiber composite panel as a substitute for existing headliner base panel of automobile, especially based on physical and mechanical performance. For this purpose, nonwoven web composite panels were manufactured from wood fiber and polypropylene fiber in conformance with standard requirements of resin felt used for headliner base panel in the aspects of density, panel thickness, and resin content (Hyundai Motor Company Commercial Vehicle R & D Center 1985). For the simplification of manufacturing process, only two variables, formulation of wood fiber and polypropylene fiber and density of composite panel, were employed and neither coupling agent nor bond reinforcing agent was taken into consideration in experimental design.

2. MATERIALS and METHODS

2.1 Wood fiber and polypropylene fiber for composite panel

The medium density fiberboard (MDF)-grade wood fibers of radiata pine (*Pinus radiata*) were conditioned to the moisture content of 10%. 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%. These fibers were kept in plastic bags before starting use.

2.2 Wood fiber and adhesive for control fiberboard

The MDF-grade wood fibers composed of radiata pine (*Pinus radiata*) and Scots pine (*Pinus sylvestris*) were 10% in moisture content. The urea-formaldehyde resin used had a solids content of 52%. The other additives included the 20% water solution of ammonium chloride (NH_4Cl) as a hardener and the wax emulsion with a solids content of 44% as a water repellent.

2.3 Manufacture of composite panel

Wood fiber-polypropylene fiber composite panels measuring 300 mm long, 230 mm wide, and 3 mm thick were manufactured according to the experimental design (Table 1). Four panels from wood fiber and polypropylene fiber formulations of 50 : 50, 60 : 40, and 70 : 30, on the basis of oven-dry weight, with densities of 0.4, 0.5, 0.6, and 0.7 g/cm^3 were produced for this experiment.

Wood fibers and polypropylene fibers were first evenly mixed in a specially designed air mixer by using turbulent air which generated from an air compressor. The fiber mixture was transferred and hand-formed into a mat or web in the forming frame, followed by prepressing and hot pressing at a temperature of 195°C for 4 minutes. The unloaded composite panel after hot pressing was cooled in a cold press at room temperature to prevent the springback in

Table 1. Experimental design in manufacturing wood fiber-polypropylene fiber composite panel.

Process Variable		Manufacturing Condition				
			Hot Pressing			
Formulation (WF : PPF)[a]	Target Density (g/cm^3)	Mat Moisture Content (%)	Temperature (°C)	Time (min.)	Pressure (kgf/cm^2)	Cooling Time (min.)
50 : 50	0.4	5.0	195	4	2	2
	0.5	5.0	195	4	4	2
	0.6	5.0	195	4	8	2
	0.7	5.0	195	4	15	2
60 : 40	0.4	6.0	195	4	2	2
	0.5	6.0	195	4	4	2
	0.6	6.0	195	4	8	2
	0.7	6.0	195	4	15	2
70 : 30	0.4	7.0	195	4	2	2
	0.5	7.0	195	4	4	2
	0.6	7.0	195	4	8	2
	0.7	7.0	195	4	15	2
Control (100 : 0)	0.4	22.4	140	4	2	0
	0.5	22.4	140	4	4	0
	0.6	22.4	140	4	8	0
	0.7	22.4	140	4	15	0

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

thickness direction (Table 1).

2.4 Manufacture of control fiberboard

The size, density level, and replication of the control fiberboards were set equal to those of wood fiber-polypropylene fiber composite panels (Table 1).

Aqueous solution of 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. And the water repellent of wax emulsion with 44% solids content was incorporated in the wood fibers at the level of 0.7% based on the oven-dry weight. The prepared adhesive was applied to wood fibers in a blender at the resin content of 12.2% on the basis of oven-dry weight. The hand-formed mat in forming frame was hot pressed at a temperature of 140°C for 4 minutes.

2.5 Testing properties of composite panel and control fiberboard

For testing density, moisture content, water absorption, and thickness swelling, all the specimens from composite panel and control fiberboard were conditioned at 65±1% RH and 20±3°C in conformance with ASTM D 1037-93 (1995). For the bending modulus of rupture (MOR) and modulus of elasticity (MOE) measurements, dry specimens were prepared by conditioning at 65±1% RH and 20±3°C and wet specimens were prepared after immersion in water for 24 hours at room temperature according to ASTM D 1037-93 (1995). Also, the bending MOR and MOE tests were performed using the specimens heated in the drying oven at 80°C for 3 hours in conformance with the specification of MS 341-11 (Hyundai Motor Company Commercial Vehicle R&D Center 1985). The measurements of physical and mechanical properties were statistically analyzed using a Statistical Analysis System (SAS) program.

3. RESULTS and DISCUSSION

3.1 Physical properties

Results on the difference of physical properties between wood fiber-polypropylene fiber composite panel and control fiberboard by density are presented in Table 2.

The actual density of composite panel or control fiberboard did not differ from the target density established, and thus it was possible to manufacture the composite panel and control fiberboard to the required density level using manufacturing condition established in this experiment (Table 1). The composite panel, however, showed lower moisture content by about 3% than the control fiberboard.

These test results generally indicated that composite panels were lower in water absorption and thickness swelling than control fiberboards, and thus incorporating the polypropylene fibers with wood fibers proved to be an effective way of improving dimensional stability.

3.1.1 Density and moisture content

Density and moisture content of wood fiber-polypropylene fiber composite panel are shown in Table 3.

Composite panel was manufactured almost identically to the target density established. The moisture content of composite panel appeared to increase with the increase of wood fiber content at a given panel density. At a given formulation, however, the moisture content of composite panel hardly varied with the panel density.

Table 2. Comparative physical properties between wood fiber-polypropylene fiber composite panel and control fiberboard.

Target Density (g/cm^3)	Panel Type	Panel Density[a] (g/cm^3)	Moisture Content (%)	Water Absorption (%)		Thickness Swelling (%)	
				2 hours	24 hours	2 hours	24 hours
0.4	Composite	0.40[b] A[d]	3.8[b] B[d]	24.6[b] B[d]	53.9[b] B[d]	3.7[b] B[d]	5.3[b] B[d]
	Control	0.39[c] A[d]	6.8[c] A[d]	268.4[c] A[d]	373.5[c] A[d]	85.6[c] A[d]	97.8[c] A[d]
0.5	Composite	0.50 A	3.7 B	18.7 B	43.7 B	4.0 B	6.0 B
	Control	0.49 A	6.5 A	119.3 A	210.0 A	68.9 A	91.6 A
0.6	Composite	0.60 A	3.6 B	13.2 B	34.7 B	3.7 B	6.8 B
	Control	0.58 A	6.4 A	101.8 A	184.9 A	69.4 A	99.2 A
0.7	Composite	0.70 A	3.6 B	9.9 B	28.9 B	3.8 B	7.8 B
	Control	0.71 A	6.7 A	125.9 A	163.4 A	69.4 A	86.8 A

[a] Based on oven-dry weight and air-dry volume.
[b] Each mean value from 24 replications.
[c] Each mean value from 8 replications.
[d] Means with the same letter are not significantly different at the 5 percent level.

Table 3. Density and moisture content of wood fiber-polypropylene fiber composite panel.

Target Density (g/cm^3)	Formulation (WF : PPF)[a]	Panel Density[b] (g/cm^3)	Moisture Content (%)
0.4	50 : 50	0.42[c] (0.03)[d]	3.1[c] (0.23)[d]
	60 : 40	0.38 (0.03)	3.9 (0.21)
	70 : 30	0.39 (0.04)	4.4 (0.22)
0.5	50 : 50	0.50 (0.06)	3.0 (0.12)
	60 : 40	0.51 (0.04)	3.9 (0.15)
	70 : 30	0.49 (0.03)	4.4 (0.28)
0.6	50 : 50	0.63 (0.05)	2.9 (0.17)
	60 : 40	0.59 (0.06)	3.8 (0.13)
	70 : 30	0.57 (0.06)	4.1 (0.47)
0.7	50 : 50	0.70 (0.04)	3.0 (0.12)
	60 : 40	0.69 (0.06)	3.6 (0.14)
	70 : 30	0.70 (0.04)	4.0 (0.09)

[a] Based on oven-dry weight of wood fiber (WF) and polypropylene fiber (PPF).
[b] Based on oven-dry weight and air-dry volume.
[c] Each mean value from 8 replications.
[d] Each standard deviation from 8 replications.

3.1.2 Water absorption

Figure 1 exhibits the water absorption of wood fiber-polypropylene fiber composite panel by formulation and density.

In this experiment, the water absorption after 2 and 24 hours immersion appeared to decrease with the increase of panel density at a given formulation and with the increase of polypropylene fiber content at a given density. This result is in agreement with Youngquist *et al.* (1992b), Yoon (1996), and Eom and Yoon (1997) who reported water absorption after 24 hours immersion to be lowered with the increase of composite panel density, and also with Eom and Yoon (1996) who found water absorption to be reduced with the increase of polypropylene fiber content in the wood fiber-polypropylene fiber composite panel with low density of 0.6 g/cm^3. And Krzysik and Youngquist (1991) explained that the reduced water absorption with the increase of polypro-

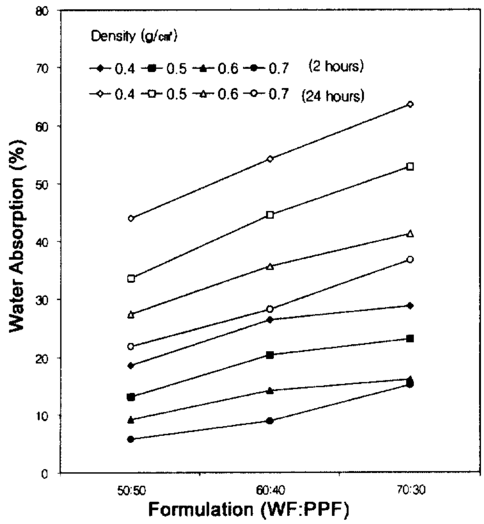

Fig. 1. Effects of formulation and density on water absorption of wood fiber-polypropylene fiber composite panel after immersion in water for 2 and 24 hours at room temperature. WF = wood fiber; PPF = polypropylene fiber.

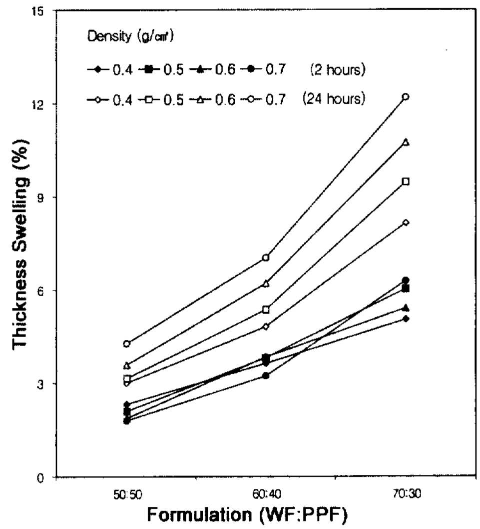

Fig. 2. Effects of formulation and density on thickness swelling of wood fiber-polypropylene fiber composite panel after immersion in water for 2 and 24 hours at room temperature. WF = wood fiber; PPF = polypropylene fiber.

pylene fiber content was attributed to the limited water uptake by the wood fibers which encapsulated with molten polypropylene fibers during hot pressing.

3.1.3 Thickness swelling

Thickness swelling of wood fiber-polypropylene fiber composite panel by formulation and density are presented in Figure 2.

Thickness swelling of composite panel after 2 hours immersion in water did not vary with the panel density at a given formulation but increased with the decrease of polypropylene fiber content at a given panel density. After 24 hours immersion in water, thickness swelling of composite panel greatly increased with the increase of wood fiber content at a given panel density but slightly increased with the increase of panel density at a given formulation. Especially in the 24-hour immersion test, thickness swelling appeared to increase steeply with the increases in both panel density and wood fiber content but not to be significantly varied with the panel density in the composite panel made with wood fiber content of 50%. The reduction of thickness swelling with the increase of polypropylene fiber content was thought to be attributed to the role of molten polypropylene fibers which encapsulate the wood fibers and fill up the voids between wood fibers, thus limiting water access to wood fibers and uptake by wood fibers.

Like the result in this experiment, Youngquist *et al.* (1990, 1992b) reported that thickness swelling of the composite panel decreased as the content of polypropylene fiber increased from 10 to 50% but increased as the panel density increased. They thought greater thickness swelling, despite less water absorption, in high-density composite panel to be the result of excessive built-up internal stresses caused by more wood material and more compaction, in turn resulting in higher springback when exposed to very wet conditions such as soaking or boiling.

Contrary to the result in this experiment, Yoon (1996) and Shin (1997) noted that thickness swelling decreased as the composite panel density increased. And Eom and Yoon (1997) stated in the nonwoven web composite that thickness swelling increased as panel density increased from 0.6 to 0.8 g/cm^3 but decreased as panel density increased from 0.8 to 1.2 g/cm^3. They considered the decrease of thickness swelling in the high-density panel to be resulted from more encapsulated wood fibers and more filled-up voids between wood fibers by the enforced flow of molten polypropylene fibers, thus leading to limited water uptake by wood fibers.

3.2 Mechanical properties

Results on the difference of mechanical properties between wood fiber-polypropylene fiber composite panel and control fiberboard by density are presented in Table 4.

Bending MOR appeared to be considerably greater in the composite panel than in the control fiberboard. Like bending MOR, the composite panel was superior to the control fiberboard in bending MOE under the dry, heated, and wet conditions.

3.2.1 Static bending modulus of rupture(MOR)

Figures 3 to 5 show the bending MOR of wood fiber-polypropylene fiber composite panel by formulation and density under the dry, heated, and wet conditions.

Irrespective of dry, heated, and wet conditions, bending MOR of composite panel generally improved with the increase of panel density at a given formulation but did not vary significantly with the formulation at a given panel density. Particularly, bending MOR at low-density panels of 0.4 and 0.5 g/cm^3 was not significantly different between formulations.

Table 4. Comparative mechanical properties, MOR and MOE, between wood fiber-polypropylene fiber composite panel and control fiberboard.

Target Density (g/cm^3)	Panel Type	Dry (kgf/cm^2)		Heated (kgf/cm^2)		Wet (kgf/cm^2)	
		MOR	MOE	MOR	MOE	MOR	MOE
0.4	Composite	104[a] A[c]	6512[a] A[c]	121[a] A[c]	6172[a] A[c]	48[a] A[c]	2074[a] A[c]
	Control	31[b] B[c]	1262[b] B[c]	30[b] B[c]	1332[b] B[c]	11[b] B[c]	0[b] B[c]
0.5	Composite	146 A	9232 A	182 A	9100 A	69 A	3161 A
	Control	63 B	2718 B	62 B	3239 B	21 B	461 B
0.6	Composite	230 A	13722 A	250 A	12463 A	118 A	5434 A
	Control	100 B	4849 B	99 B	4555 B	35 B	843 B
0.7	Composite	324 A	18998 A	341 A	16049 A	172 A	7993 A
	Control	184 B	11932 B	149 B	8723 B	69 B	2673 B

[a] Each mean value of specimen from 12 replications.
[b] Each mean value of specimen from 4 replications.
[c] Means with the same letter are not significantly different at the 5 percent level.

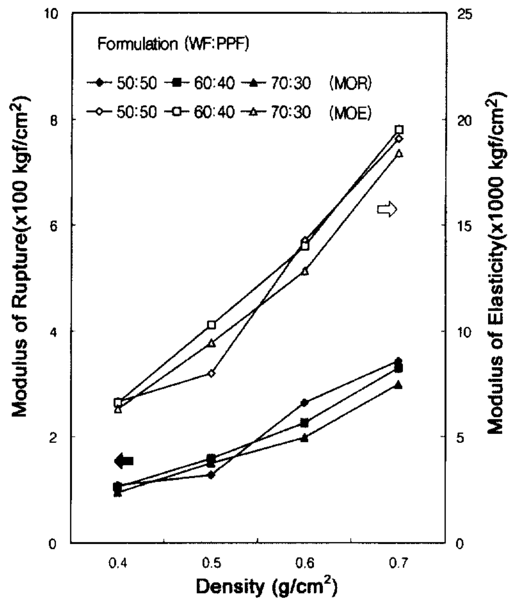

Fig. 3. Effects of density and formulation on MOR and MOE of wood fiber-polypropylene fiber composite panel under dry condition after conditioning at 65±1% RH and 20±3°C. WF = wood fiber; PPF = polypropylene fiber.

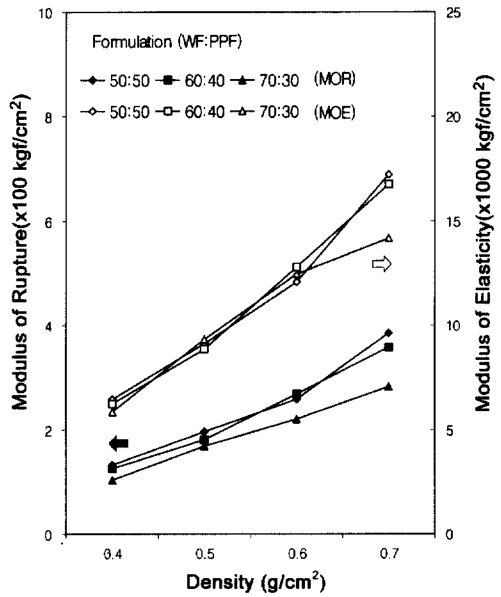

Fig. 4. Effects of density and formulation on MOR and MOE of wood fiber-polypropylene fiber composite panel under heated condition after 3-hour heating at 80°C. WF = wood fiber; PPF = polypropylene fiber.

Panel density, therefore, appeared to have a greater effect on bending MOR than the wood fiber and polypropylene fiber formulation. This agrees with Geimer *et al.* (1993) and Yoon (1996) who reported that MOR in the composite panel increased with the increase of panel density. Youngquist *et al.* (1990), however, described that increasing the content of polypropylene fiber from 10 to 30% and from 30 to 50% resulted in the respective improvement of MOR by 35 and 58% in the composite panel.

In regression analysis between moisture content and bending MOR in the composite panel (Figure 6), bending MOR was in the strong negative correlation with moisture content. Bending MOR of the composite panel decreased as the moisture content increased up to 40% but remained almost constant beyond moisture content of 40%, and this trend was more conspicuous in the high-density composite panel.

The minimum requirements of bending MOR in the material specification of MS 341-11 for the headliner base panel of resin felt (Hyundai Motor Company Commercial Vehicle R&D Center 1985) are 60 kgf/cm^2 under the dry condition, 50 kgf/cm^2 under the heated condition, and 30 kgf/cm^2 under the wet condition. In present study, bending MOR values of the composite panel met the requirements of MS 341-11 under all the test conditions.

3.2.2 Static bending modulus of elasticity(MOE)

Bending MOE of wood fiber-polypropylene fiber composite panel by formulation and density under the dry, heated, and wet conditions are presented in Figures 3 to 5.

Under the wet condition, the composite panel

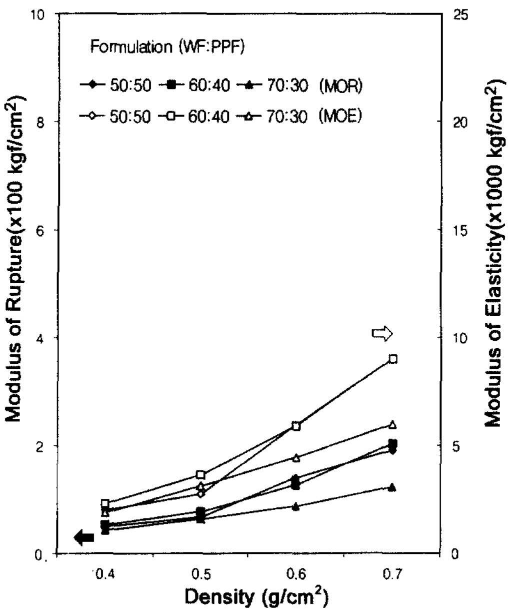

Fig. 5. Effects of density and formulation on MOR and MOE of wood fiber-polypropylene fiber composite panel under wet condition after immersion in water for 24 hours at room temperature. WF = wood fiber; PPF = polypropylene fiber.

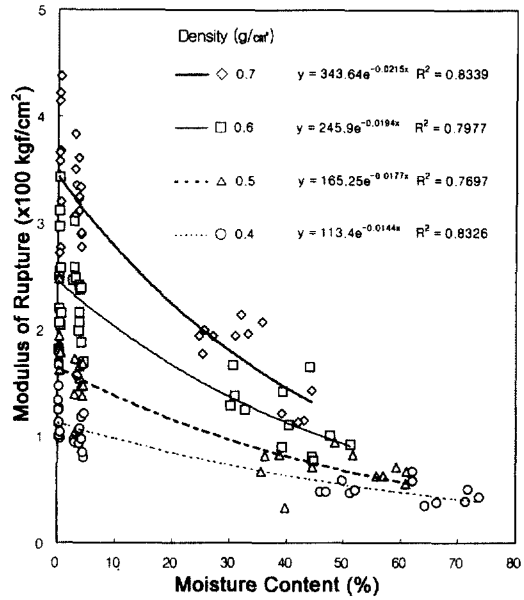

Fig. 6. Regression analysis between moisture content and MOR in wood fiber-polypropylene fiber composite panel by density.

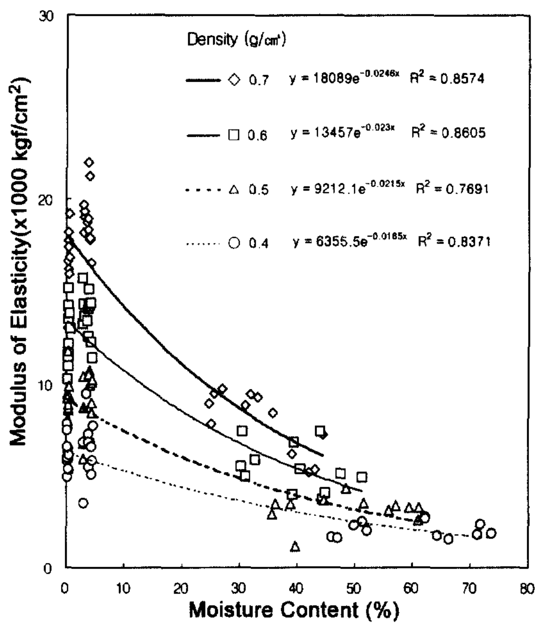

Fig. 7. Regression analysis between moisture content and MOE of wood fiber-polypropylene fiber composite panel by density.

with polypropylene fiber content of 30% exhibited lower bending MOE than that with polypropylene fiber content of 40 and 50% at the panel density of 0.7 g/cm^3. Irrespective of dry, heated, and wet conditions, however, bending MOE of the composite panel generally improved with the increase of panel density at a given formulation but did not vary significantly with the formulation at a given panel density. This agrees with Geimer *et al.* (1993) who reported that MOE in the composite panel clearly increased with the increase of panel density and was influenced more by the compression of wood fiber than by the content of wood fiber.

In regression analysis between moisture content and bending MOE in the composite panel (Figure 7), bending MOE was in the strong negative correlation with moisture content. Like the tendency in bending MOR, bending MOE of the composite panel decreased as the moisture content increased and this trend was more conspicuous in the high-density composite panel.

4. CONCLUSIONS

Nonwoven web composite panels were made from wood fiber and polypropylene fiber formulations of 50 : 50, 60 : 40, and 70 : 30, based on oven-dry weight, at density levels of 0.4, 0.5, 0.6, and 0.7 g/cm^3. Their physical and mechanical properties were tested. And the feasibility of this composite panel as a substitute for existing headliner base panel of automobile was discussed, especially based on physical and mechanical performance. The results obtained in this study were as follows:

1. Nonwoven web composite panel made from wood fibers and polypropylene fibers had superior physical and mechanical properties to control fiberboard.
2. In the physical properties of composite panel, dimensional stability improved as the content of polypropylene fiber increased, and the formulation of wood fiber and polypropylene fiber was considered to be a significant factor in the physical properties. Water absorption decreased but thickness swelling slightly increased with the increase of panel density.
3. In the mechanical properties of composite panel, the bending MOR and MOE appeared to improve with the increase of panel density under all the tested conditions of dry, heated, and wet. The formulation of wood fiber and polypropylene fiber was considered not to be a significant factor in the mechanical properties. All the bending MOR values under the dry, heated, and wet conditions met the requirements in the existing headliner base panel of resin felt.

The composite panel with enhanced physical and mechanical properties compared with control fiberboard could be manufactured just by controlling the wood fiber and polypropylene fiber formulation and panel density. And wood fiber-polypropylene fiber composite panel met the requirements for the headliner base panel of resin felt and thus proved to be a potential substitute for the existing product.

Further studies on fire resistance and hardness of wood fiber-polypropylene fiber composite panel for interior materials of automobiles are required. Also, development and performance improvement of composite panel from municipal and industrial wood and plastic wastes must be followed in both aspects of converting recovered resources into end-use applications and solving waste problem.

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