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# Studies on Thickness Swelling Mechanism of Wood Particle-Polypropylene Fiber Composite by Scanning Electron Microscopy*[1]

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## ABSTRACT

This study was carried out through scanning electron microscopy to elucidate the mechanism of thickness swelling in wood particle-polypropylene composite which is a typical way of using wood and plastic materials. For this purpose, control particleboards and nonwoven web composites from wood particle and polypropylene fiber formulations of 100:0, 70:30, 60:40, and 50:50 were manufactured at target density levels of 0.5, 0.6, 0.7, and 0.8 g/cm$^3$. Their water absorption and thickness swelling were tested according to ASTMD 1037-93 (1995). To elucidate thickness swelling mechanism of composite 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.

From the scanning electron microscopy, thickness swelling of composite was thought to be caused by the complicated factors of degree of built-up internal stresses by mat compression and/or amount of wood particles encapsulated with molten polypropylene fibers during hot pressing. In the composites with wood particle contents of 50 to 60% at target densities of 0.5 to 0.8 g/cm$^3$ and with wood particle content of 70% at target densities of 0.5 to 0.7 g/cm$^3$, thickness swellings seemed to be largely dependent upon the restricted water uptake by encapsulated wood particles with molten polypropylene fibers. Thickness swelling in the composite with wood particle content of 70% at target density of 0.8 g/cm$^3$, however, was thought to be principally dependent upon the increased springback phenomenon by built-up internal stresses of compressed mat.

*Keywords*: wood particle, polypropylene fiber, nonwoven web composite, water absorption, thickness swelling, scanning electron microscopy

## 1. INTRODUCTION

The principal drive for troublesome problems like pollution of environment and depletion of resources in this age of mass production and consumption is attributed to urbanization and industrialization following rising population and economic activities. Manufacturing composite

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using waste wood, wood-based product, and plastic out of the municipal and industrial solid wastes 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. The wood-plastic composite can be used for storage bins, furniture components, automobiles and truck parts, and packages and filters (Youngquist *et al.* 1992, 1993; Chinese Academy of Forestry 1997a, 1997b, 1998).

In the use of wood-based materials, dimensional stability is an important property and is often accompanied by permanent strength loss and sometimes product failure (Lee and Wu 2002). Thus, dimensional stability has attracted special attention as one of the most important properties to be studied.

Krzysik and Youngquist (1991) and Krzysik *et al.* (1991), 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%, noted that the MAPP being incorporated in the nonwoven web composites at a level of 1 or 3% led to small improvements in water resistance for composites with wood fiber content of 85%.

Youngquist *et al.* (1992) reported that thickness swelling increased with the increase of the density of air-formed wood fiber-polymer fiber composite. In lignocellulosic particle-plastic composites, Peng and Hwang (1996) reported that their water absorption and thickness swelling were much lower than those of wood-based panels.

Hwang (1997) found in the plastic-wood composite made from waste polyethylene and wood particles pretreated with urea resin that thickness swelling increased with the increase of wood particle content and with the decrease of resin content of wood particle, and noted that particles with surfaces covered by polyethylene film had positive effect on the dimension stability of composites.

In the composite manufactured from wood and plastic wastes by simply heating and compressing, Boeglin *et al.* (1997) reported that water absorption was greater but thickness swelling was lower than those of commercial particleboards and 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 the commercial particleboards.

Eom and Yoon (1997), in the study on thickness swelling mechanism of nonwoven web composite made with wood fiber and polypropylene fiber through a scanning electron microscopy, explained that the great internal stresses developed in the highly compressed or densified mat during hot pressing induced the excessive flow of molten polypropylene fibers and caused the polypropylene fibers in fluid form to encapsulate wood fibers and/or to build water barrier through filling up voids between wood fibers, thus resulting in the small thickness swelling in the high-density panel.

Eom *et al.* (2000) reported in the wood particle-polypropylene fiber composite that thickness swelling showed decreasing tendency with the increase of target density from 0.6 to 0.8 $g/cm^3$ but rather increasing trend with the increase of target density from 0.8 to 0.9 $g/cm^3$. They also explained that thickness swelling in the composite with target density up to 0.8 $g/cm^3$ was more dependent upon the restricted water uptake caused by the amount of encapsulated wood particles with molten polypropylene fibers but that in the composite with target density of 0.9 g/cm$^3$ was more dependent upon the springback caused by the strong built-up internal stresses from excessive mat compression, respectively.

This study was carried out to elucidate the mechanism of thickness swelling by formulation and density level of wood particle-polypropylene fiber composite through scanning electron microscopy.

# 2. MATERIALS and METHODS

## 2.1. Materials

### 2.1.1. Wood particle

Needle-type wood particles of radiata pine (*Pinus radiata*) for core layer of commercial three-layered particleboard (Table 1), obtained from Dongwha Enterprise Co., Ltd., Incheon, Korea, were used in manufacturing both control particleboards and wood particle-polypropylene fiber composites. 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. Finally, the screened wood particles were kept in plastic bags for preventing moisture uptake before start using.

### 2.1.2. Polypropylene fiber

Deep green coloured polypropylene fibers, obtained from Kolon Merak Co., Ltd., Kimchon, Korea, were 1±0.1 cm long, 3 denier with the melt flow index (MFI) of 25 g/10 min., and moisture content of 1%. The fibers were kept in plastic bags for preventing moisture uptake before starting use.

## 2.2. Methods

### 2.2.1. Manufacturing control particleboard

Four single-layered control particleboards measuring 300 mm long, 230 mm wide, and 5 mm thick were manufactured at target density levels of 0.5, 0.6, 0.7, and 0.8 g/cm$^3$ (Table 1).

The urea-formaldehyde resin with solids content of 52%, obtained from Dongwha Enterprise Co., Ltd., Inchon, Korea, 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 solid weight. As a water repellent, wax emulsion with solids content of 44% was incorporated in the wood particles at the level of 0.7% based on the oven-dry weight.

The prepared adhesive was applied to wood

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] Solid basis on oven-dry particle weight

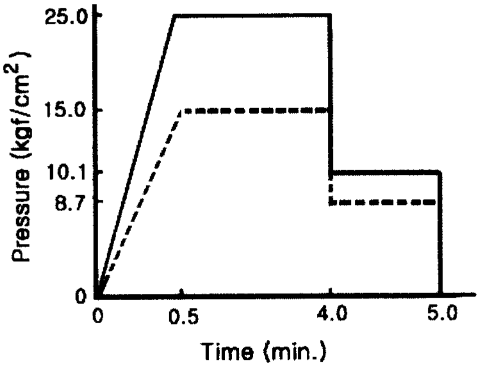



Fig. 1. Hot pressing schedule in manufacturing control particleboard. —: target density of 0.8 g/cm$^3$; ---: target densities of 0.5 to 0.7 g/cm$^3$.

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 pressure applied was 15 kgf/cm$^2$ in the control particleboard with target densities of 0.5 to 0.7 g/cm$^3$ and 25 kgf/cm$^2$ in that with target density of 0.8 g/cm$^3$ (Fig. 1).

### 2.2.2. Manufacturing composite

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

Four composites from wood particle and polypropylene fiber formulations of 50:50, 60:40, and 70:30, on the basis of oven-dry weight, were manufactured at the target density levels of 0.5, 0.6, 0.7, and 0.8 g/cm$^3$.

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

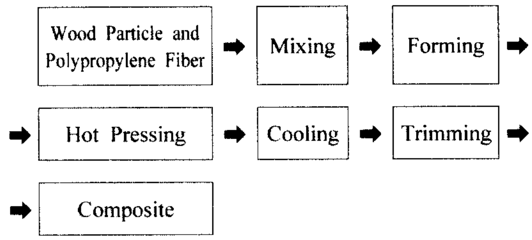



Fig. 2. Manufacturing process of wood particle-polypropylene fiber composite.

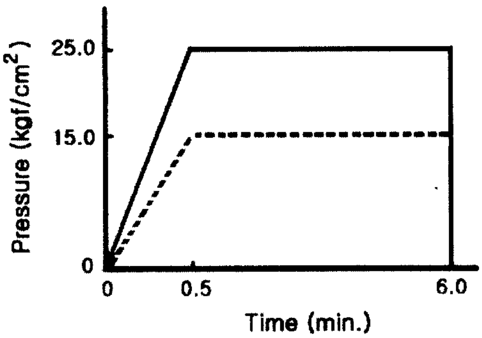



Fig. 3. Hot pressing schedule in manufacturing wood particle-polypropylene fiber composite. —: target density of 0.8 g/cm$^3$; ---: target densities of 0.5 to 0.7 g/cm$^3$.

mat in a forming frame, followed by hot pressing at a temperature of 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 with target density of 0.8 g/cm$^3$ at the wood particle and polypropylene fiber formulation of 70:30 (Fig. 3).

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

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

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

#### 2.2.3. Testing water absorption and thickness swelling

Test specimens measuring 50 × 50 mm for water absorption and thickness swelling were cut from control particleboard and composite. For testing water absorption and thickness swelling, the dry specimens from composite and control particleboard were conditioned at 65 ± 1% RH and 20 ± 3°C and the wet specimens were prepared after immersion in water for 24 hours at room temperature in conformance with ASTM D 1037-93 (1995).

#### 2.2.4. Scanning electron microscopy

Through the scanning electron microscopy, the common edges between dry and wet specimens of wood particle-polypropylene fiber composites were examined in thickness direction for detecting the change of internal structure such as the shape, distribution, and binding pattern of wood particles and molten polypropylene fibers. For the unbiased comparison of their internal structures, one additional dry specimen was prepared in the adjoining position of the test specimen for 24-hour water absorption and thickness swelling, and the specimen after immersion in water for 24 hours was reused after air drying as wet specimen.

The common edges for observation were sputter-coated with a 50 nm layer of gold using a JEOL JFC 1100E ion sputtering device and were viewed with a JEOL JSM 5410LV scanning electron microscopy (SEM) at an accelerating voltage of 15 kV.

## 3. RESULTS and DISCUSSION

### 3.1. Water absorption and thickness swelling

Control particleboard appeared to be significantly higher in water absorption (Figs. 4 and 5) than the wood particle-polypropylene fiber composite and its water absorption decreased with the increase of target density. In the composite, 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. Similar trends in water absorption were identified in the control fiberboard and wood fiber-polypropylene fiber composite by Kim and Eom (2001).

Thickness swelling (Figs. 6 and 7) of control particleboard appeared significantly higher than that of composite like the result in the fiber-board and wood fiber-polypropylene fiber composite by Kim and Eom (2001). With the increase of target density, thickness swelling showed increasing tendency in the control particleboard but did not vary significantly in the composite. Contrary to the result in this experiment, however, Youngquist *et al.* (1992), Gatchell *et al.* (1966), and Hallingan and Schniewind (1972) reported that thickness swelling increased with the increase of composite density. At a given target density, on the other hand, thickness swelling of composite increased as wood particle content increased, like the reports by Yoon (1996), Krzysik *et al.* (1991), Krzysik and Youngquist (1991), Hwang (1997), and Kim and Eom (2001).

Despite decrease of water absorption, however, thickness swelling increased significantly with the increase of target density from 0.7 to 0.8 g/cm$^3$ in the control particleboard and composite with wood particle and polypropylene fiber formulation of 70:30 (Figs. 5 and 7).

## 3.2. Microscopic interpretation on the mechanism of thickness swelling

To elucidate mechanism on thickness swelling of composite through the observation of morphological change of internal structures, the specimens before and after thickness swelling

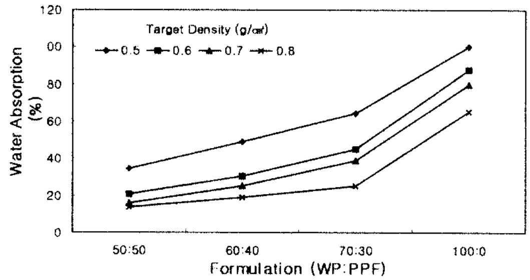



Fig. 4. Effect of formulation on water absorption of wood particle-polypropylene fiber composite after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

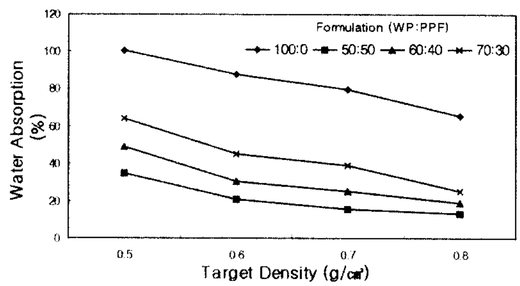



Fig. 5. Effect of target density on water absorption of wood particle-polypropylene fiber composite after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

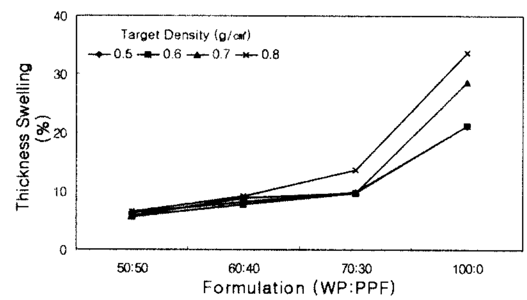



Fig. 6. Effect of formulation on thickness swelling of wood particle-polypropylene fiber composite after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

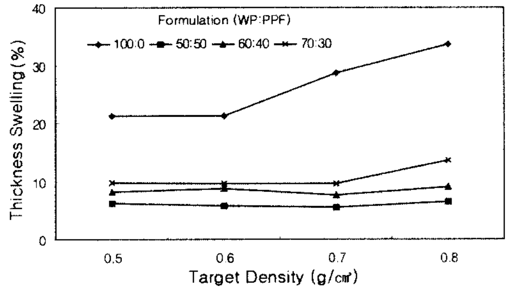
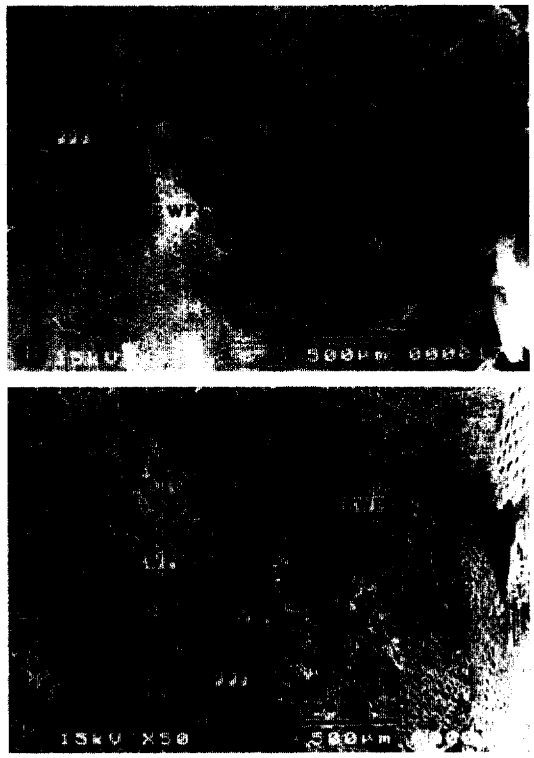



Fig. 7. Effect of target density on thickness swelling of wood particle-polypropylene fiber composite after 24-hour immersion in water at room temperature. WP = wood particle; PPF = polypropylene fiber.

test by 24-hour immersion in water were used in scanning electron microscopy.

Before immersion in water, internal structure of composite had larger amount of voids when the target density was lower at a given formulation and the internal structure became compact through the decrease of void volume with the increase of target density in composite (Figs. 8 and 9). After immersion in water for 24 hours, the composite made from wood particle-polypropylene fiber formulation of 50:50 at the target density of 0.7 g/cm$^3$ showed numerous interfacial dislocations between wood particle and molten polypropylene fiber (Figs. 10 and 11). As wood particle content and target density increased, more numerous voids and interfacial dislocations were observed in the composite (Figs. 11~13), resulting in higher thickness swelling (Figs. 6 and 7). This interfacial dislocation was thought to happen by the greater stresses caused by the swelling of compressed wood particles than the bond strength between polar wood particles and non-polar molten polypropylene fibers.

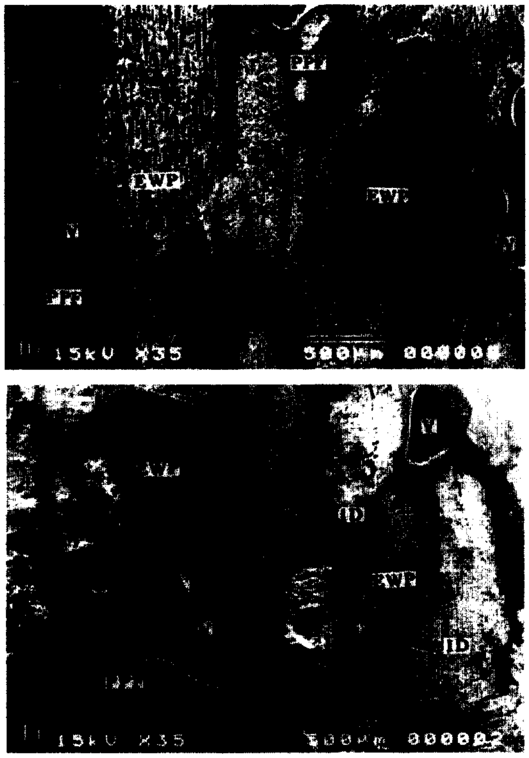
No significant variation of thickness swelling with the target density in the composite obtained in this study (Fig. 7), which was thought to be the result of limited water uptake by the



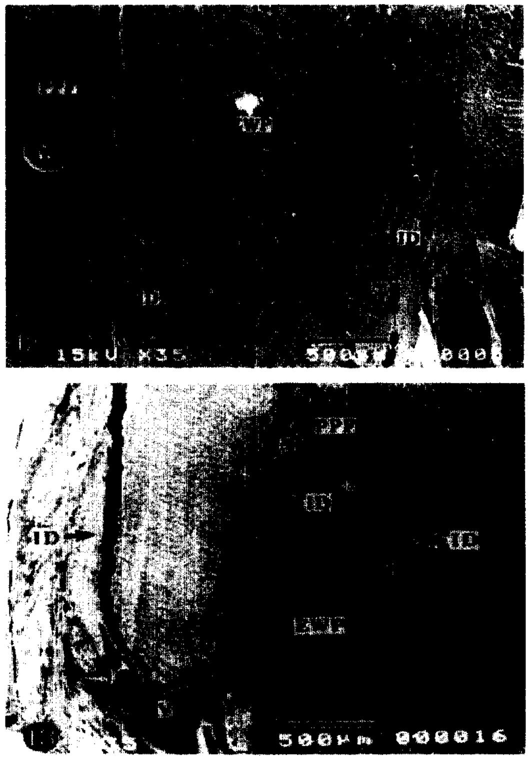

Figs. 8 and 9. Scanning electron micrographs showing internal structure of composite at wood particle and polypropylene fiber formulation of 70:30 under dry condition after conditioning at 65±1% RH and 20±3°C. 8: target density of 0.5 g/cm$^3$; 9: target density of 0.7 g/cm$^3$. PPF = molten polypropylene fiber; V = void; EWP = wood particle encapsulated by molten polypropylene fiber. Scale bars = 500 μm.

encapsulated wood particles with molten polypropylene fibers during hot pressing (Figs. 8 and 9). This is in agreement with Hwang (1997) that particles with surfaces covered by polyethylene film had positive effect on the dimension stability of composites.

After 24-hour immersion, 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




Figs. 10 and 11. Scanning electron micrographs showing internal structure of composite with target density of 0.7 g/cm$^3$ and wood particle and polypropylene fiber formulation of 50:50. -10: under dry condition after conditioning at 65±1% RH and 20 ±3°C; -11: under wet condition after immersion in water for 24 hours. PPF = molten polypropylene fiber; EWP = wood particle encapsulated by molten polypropylene fiber; V = void; ID = interfacial dislocation between wood particle and molten polypropylene fiber. Scale bars = 500 μm.




Figs. 12 and 13. Scanning electron micrographs showing internal structure of composite with target density of 0.8 g/cm$^3$ under wet condition after immersion in water for 24 hours. -12: wood particle and polypropylene fiber formulation of 60:40; -13: wood particle and polypropylene fiber formulation of 70:30. V = void; EWP = wood particle encapsulated by molten polypropylene fiber; PPF = molten polypropylene fiber; ID = interfacial dislocation between wood particle and molten polypropylene fiber. Scale bars = 500 μm.

composite with wood particle to polypropylene fiber formulation of 70:30 (Figs. 5 and 7). This contradictory result seemed to be attributed to the stronger built-up internal stresses caused by the higher compression of mat in thickness direction during hot pressing, resulting in larger irreversible swelling of springback and more numerous voids by interfacial dislocation (Figs. 11 ~ 13) through occurrence of moisture plasticization when exposed to very wet condition such as immersion in water. Youngquist *et al.* (1992) and Eom *et al.* (2000) also explained that the greater thickness swelling in high-density composite 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.

Thus, thickness swelling in the composite was considered to occur by the complicated factors of the degree of built-up internal stresses by mat compression and/or amount of wood particle encapsulated with molten polypropylene fiber during hot pressing. In the composites from wood particle and polypropylene fiber formulations of 50:50 to 60:40 at target densities of 0.5 to 0.8 g/cm$^3$ and from wood particle and polypropylene fiber formulation of 70:30 at target densities of 0.5 to 0.7 g/cm$^3$, thickness swellings seemed to be more dependent upon the restricted water uptake by encapsulated wood particles with molten polypropylene fibers. Thickness swelling in the composite from wood particle and polypropylene fiber formulation of 70:30 at target density of 0.8 g/cm$^3$, however, was thought to be more dependent upon the increased springback phenomenon by built-up internal stresses of compressed mat.

Krzysik and Youngquist (1991) and Kim and Eom (2002) reported that the reduced water absorption in the composite with higher polypropylene fiber content was attributed to the limited water uptake by the wood fibers which encapsulated with molten polypropylene fibers during hot pressing. And Youngquist *et al.* (1990, 1992) and Kim and Eom (2002) noted that greater thickness swelling, despite less water absorption, in high-density composite was 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.

# 4. CONCLUSIONS

Control particleboards and nonwoven web composites from wood particle and polypropylene fiber formulations of 100:0, 70:30, 60:40, and 50:50 were manufactured at target density levels of 0.5, 0.6, 0.7, and 0.8 g/cm$^3$. Their water absorption and thickness swelling were tested and the mechanism of thickness swelling by formulation and density level of nonwoven web composites was discussed. The results obtained in this study were as follows:

1) Control particleboard showed significantly higher water absorption than composite and its water absorption decreased with the increase of target density. In composite, 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.

2) Control particleboard were significantly higher in thickness swelling than composite and its thickness swelling increased with the increase of target density. In the composite, 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.

3) From the scanning electron microscopy, thickness swelling in the composite was thought to be caused by the complicated factors of the degree of built-up internal stresses by mat compression and/or amount of wood particle encapsulated with molten polypropylene fiber during hot pressing. In the composites with wood particle contents of 50 to 60% at target densities of 0.5 to 0.8 g/cm$^3$ and with wood particle content of 70% at target densities of 0.5 to 0.7 g/cm$^3$, thickness swelling seemed to be largely dependent upon the restricted water uptake by encapsulated wood particles with

molten polypropylene fibers. Thickness swelling in the composite with wood particle content of 70% at target density of 0.8 g/cm$^3$, however, was thought to be principally dependent upon the increased springback phenomenon by built-up internal stresses of compressed mat.

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