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Compressive Shear and Bending Performance of Compressed Laminated Wood after Microwave Heating

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Abstract

To manufacture laminated wood with improved mechanical properties by providing uniform adhesiveness, the adhesive was applied and the plate adhesive was laminated on the wood surface. Then, after laminating the wood on the top part of the adhesivebond, it was heated and dried while the adhesive was stiffened using microwaves, and the test piece was manufactured by compressing it with the press machine for thirty minutes. The temperature and the water content were examined according to the heating time of the wood heated with the microwave, and testing was conducted on the shear strength and flexural strength of the wood. In addition, the microstructure of the adhesive bond between the wood was recorded to confirm the penetrabilityinto the wood structure for the adhesive. After the test was conducted, it was found that the test piece manufactured with wood that has its water content leveled with the microwave heating showed improved shear strength and bending strength compared to the standard test piece. With regard to adhesives, liquefied polyvinyl acetate resin and plate's PVB resin were found to have superior adhesive strength. Also, after filming the cellular microstructure, it was found that when the laminated wood is heated with microwaves, the infiltration of the adhesive into the inside of the wood becomes easy, which makes it effective for improving adhesiveness.

Keywords : microwave, laminated wood, adhesive film, shear strength, bending strength, adhesive strength

1. Introduction

1.1 Research background and objective

Recently reinforced concrete construction and steel framed structure are characterized for long-span floor and high-rise buildings. With the current trend toward 'green' construction, more and more wood structures are being constructed[1]. But despise thisincrease in the number of products developed and produced, there are few long-span floor and medium and large-scale structures made of wood compared to reinforced concrete or steel-framed reinforced structures. Wood is usually used for special purpose structures, including monumental buildings and museums. This is because of the fundamental difficulty in obtaining large-sized wood. For this reason, the research and development of related wood should be carried out to build more and more medium and large-scale eco-friendly wooden structures.

Large building structures made of wood as a structural member are constructed using composite wood classified as engineered wood[2]. Composite wood is made by bonding Larix leptolepis, which is more standardized in terms of size than general structural wood, giving greater freedom in terms of shape and length. Even better, a structural format can be expressed with composite wood, which is

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impossible with current wooden material. However, composite wood was developed in the mid-20thcentury and is still produced under the traditional production process, which means there are some restrictions in its production process and time. In addition, liquid-phenol resorcinol resin adhesive, which is known to have hazardous environmental effects, is used. Only K industry officially produces and sells the adhesive, and the material cost is at least 5 times higher than when dimensional conifer lumber is used. In addition, as the lumber is laminated by applying adhesive, adhesion is noteven, and a large amount of adhesive must be used to address this. Therefore, new wood materials with improved usability and economy should be developed to expand the base of medium- and large-scale wooden structures using lightweight wood.

This study aims to develop a composite wood material that has performance and economy equivalent to or better than existing materials by minimizing the production process in the drying and bonding phases, and administering an eco-friendly adhesive that will guarantee an even adhesion surface.

1.2 Research scope and specimen manufacturing process

The validity of the reduction in the manufacturing process and the bonding method was analyzed by reviewing the characteristics at the bonding area of the specimen manufactured by drying, bonding, and bonding material. The specimen manufacturing process is as follows. First, the previous studies [3,4] were reviewed to understand changes in temperature and moisture according to the microwave heating schedule. The lumbers bonded with the adhesive film made from poly vinyl acetate ethylene-vinyl acetate copolymer emersion, PVB and AL metal film were pressed by a compressor for a period of time to perform a comparative study with Plain (composite material bonded with resorcinol resin) in terms of shear strength atthe bond, and bendingstrength according to lamination. In addition, micro tissue was photographed to analyze the segregation between adhesive and wood.

2. Theoretical review

2.1 Composite wood

Since the 2000s and until recently, demand for composite wood has been on a gradual rise, and the number of companies that produce the related products has also increased. Composite wood is widely used as furniture material, interior material for general houses, finishing material, structural material for wooden houses, and stair material. Composite material is advantageous as an alternative to general structural materials to build beams for long span structures and large structures, but there are few companies that specialize in composite material production in Korea, and the increasing demand in Korea has been met by imported goods.

In Korea, K company first introduced composite materials after the 1990s, and a forestry science center under the Korea Forestry Research Institute started to produce laminated wood for structures in 1996. Since then, the use of composite materials structures has spread. But most of the domestic need has been fulfilled by foreign products, and the production companies are usually small, which has been a great obstacle to the widespread adoption of laminated wood for structures.

In general, the manufacturing process of composite materials is complex. The manufacturing process is as follows. First, wood is classified by bending strength and stress[5]. Second, the strongest material is laminated for the outermost

surface, and the material considered to have weak machine stress is placed near the neutral axis with low bending strength. Third, finger joint coupling is used to make the lumbers join together as one. Fourth, to check the quality at the coupling area, the adhesive squeezed around the finger joint is removed, and the surface Plaind using a Plain, and then bonded after applying phenol resorcinol formaldehyde type resin. The manufacturing condition and quality of the laminated wood for structure are indicated in Table 1[6].

Table 1. Manufacturing condition and quality of the laminated wood for structure

Tree species used	Manufacturing condition	Flexural strength(MPa)	Modulus of elasticity(MPa)
Larch	·resorcinol resin : Amount of application 300g/㎡ ·Compression pressure : Over 0.5MPa	50.60	10 016
P. rigida		37.70	7 779
Cedar		36.10	6 245

2.2 Water content leveling of wood heated by microwave and adhesion

The adhesive used for composite materials is expensive, and must be used in a relatively high volume. The volume applied is about 300g/m^2[7]. This is twice as much used as for plywood or laminated veneer lumber, and the production cost of composite materials for special use is increased even more. Based on this fact, we reached the conclusion that if a heating and drying schedule that can keep the water content level constant and show the optimal adhesion performance can be derived, it will contribute to reducing both the manufacturing process and production cost. On the other hand, it is found that the heterogeneous water content before heating became leveled in the wood heated by microwave due to the rapid rise of temperature, which is referred to as water content leveling[8].Considering that the heterogeneous water content may cause defective adhesion, heating and drying by microwave is very effective in terms of economy as it prevents the loss caused by unstable water content in wood due to over-drying in the drying phase.

3. Experiment

3.1 Test factors and process

The test factors are indicated in Table 2. In the test domestic larch was used. The temperature and water content were measured for the specimen over heating by microwave. Liquid and film type adhesive were used. The wood and adhesive were laminated by microwave and then pressed using a compressor.

The physical and mechanical properties of the specimen used in this study are indicated in Figure 1, and the test was done in the order shown in Figure 2. The average of 10 specimens was set as a representative value to conduct an analysis.

Table 2. Test factors

Microwave	Output	3kW	Heating time	4, 6, 8, 12, 15min	
Test piece	Tree species	Larch (Korean)	Size	450×180×30㎜	
Press	Compression	0.5MPa	Time	30min	
Adhesive material	Plain	·resorcinol		Amount of application	300g/㎡
	Liquid	·Polyvinyl acetate ·Vinyl acetate			25g /0.081㎡
	Plate	·PVB ·AL metal plate		Thickness	·0.76㎜ ·0.15㎜
Analysis ·Discussion	·Temperature and water content of the test piece after the microwave heating ·Wood shear test(KS F 2209) ·Wood bending strength test (KS F 2208) ·Wood adherend SEM analysis				

(a)Polyvinyl acetate (b)Vinyl acetate (c)PVB(Plate) (d)AL metal(Plate)

Figure 1. Using Adhesive materials

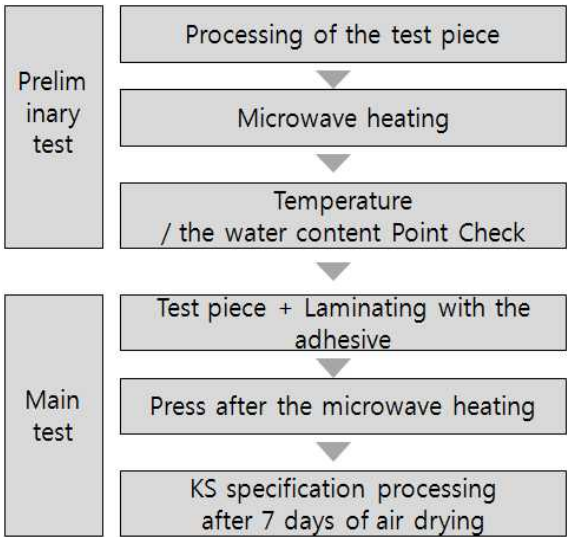


Figure 2. Study Flow

3.2 Microwave heating of wood

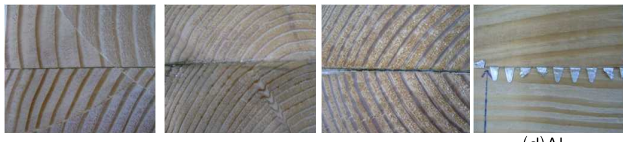
The power of the microwave heating/drying machine used in this study can be set to 6kW, but the power was set to 3kW considering water content before heating and the size of specimen. In addition, based on the water content distribution and surface temperature, one factor was selected, and the specimen was manufactured and then tested to identify mechanical properties.

3.3 The surface temperature and water content of heated wood

Several points were set in the specimen to measure temperature and water content at each section, and the specimen was heated by microwave. The water content and temperature at each section were measured and reported in the wood heated according to Table 2. An infrared thermometer was used to measure temperature, and an electric resistance moisture meter was used to measure water content. The drying machine and the measuring instrument are shown in Figure 3, and the sections after bonding are shown in Figure 4.

(a)Microwave heating /drying machine (b)Infrared thermometer (c)Function rate meter

Figure 3. drying machine and Function rate meter

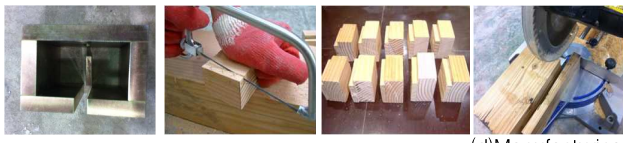


(a)plain (b)Vinyl acetate (c)PVB(Plate) (d)AL metal(Plate)

Figure 4. Sided Adhesive

3.4 Test of bending strength, shear bond and compression of heated wood

The specimen was compressed immediately after being heated by microwave, and stored in a condition that allowed it to air-dry for seven days after release. The specimen was processed and measured in compliance with KS[9,10]. Table 5 illustrates the shapes of test jig and specimen.



(a)Jig for testing shear (b)Manufacturing of the shear test piece (c)After the plain processing (d)Manufacturing of the bending strength test piece

Figure 5. Test piece's Bending strength for the press machine and adhesive shear

4. Test result and review

4.1 Surface temperature and moisture distribution of microwave heated wood

The wood specimen was divided into 10 sections, and then rapidly heated with microwaves. Table 3 indicates the changes in surface temperature and water content over heating time. Figures 6 and 7 illustrate the temperature change over time at each section.

Table 3. Wood temperature and water content distribution (average)/classification immediately after microwave heating

Division	Before heating	4min	6min	8min	12min	15min
Temperature (℃)	18	60	72	78	87	98
Water content (%)	9.4	10.3	11.0	11.6	12.1	10.9

The average temperature of the specimen heated for 4 minutes at a room temperature stood at 60℃. It was found that the longer the heating time, the higher the surface temperature. The temperature of the specimen heated for 15 minutes stood at 98℃, approaching 100℃. The temperature rose rapidly for the first 6 minutes, but the increase in temperature slowed between 6 minutes and 8 minutes, which seems to be because the temperature reached the first thermal equilibrium while heating[11].

The water content of the specimen at a room temperature was distributed in the range of 9~10%. As indicated in Table 3, the specimens heated for 4 minutes and 6 minutes showed an increase in water content, but they had water content similar to the specimen at a room temperature before heating, which was uneven overall.

When heated for 8 minutes, the thermal distribution was shown to be similar at each point, and when heated for 12 minutes, the temperature distribution was shown to be almost similar, of which water content converged at a certain level. The water of the wood heated by microwave moved to the outer surface from within and then evaporated. The water content at the surface rose until 12 minutes of microwave heating, which is believed to be because the water moved to the external surface from within. When heated for 15 minutes, the specimen showed a decrease in the surface temperature, which is believed to be because the water content decreased while the temperature increased due to a reduction in the water moving to the outer surface from within and the giving off of the heat from the wood itself.

Therefore, based on the test results, the mechanical properties of the specimen were analyzedby applying microwave heating for 15 minutes, at which the water content on the surface of the specimen decreased and then reached a constant level.

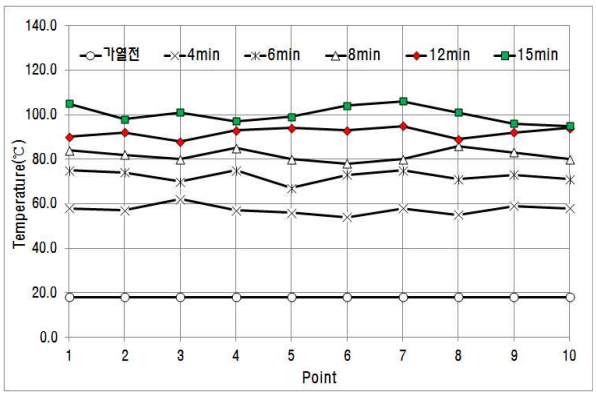


Figure 6. Surface structure for each point of the test piece

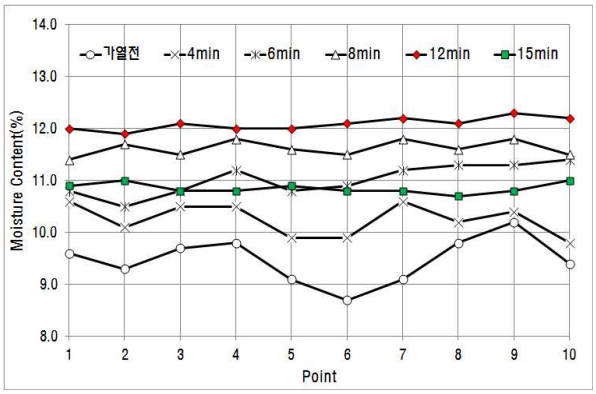


Figure 7. Water content leveling for each point of the test piece surface

4.2 Shear strength

To assess the shear strength for each adhesive material, the specimens were heated and bonded for 15 minutes according to the test results shown in 4.1. Table 4 indicates the results of shear strength test drawn using Equation (1), and the sizes and

load points of the specimens and the shear fraction form after the test are shown in Figures 8 and 9.

Table 4. adherend shear strength(MPa)

Division		Breaking load (kg/f)	Pmax (N)	Shear area (A)	Shear Strength (N/mm^2, MPa)
Plain		486.40	4 769.95	500.00	9.54
Liquid	Polyvinyl acetate	570.06	5 590.38		11.18
	Vinyl acetate	700.48	6 869.36		13.74
Plate	PVB	653.34	6 407.08		12.81
	AL metal	479.17	4 699.05		9.40

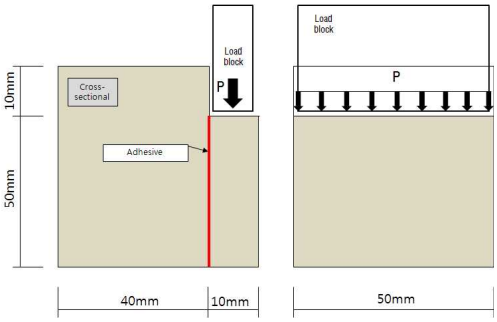
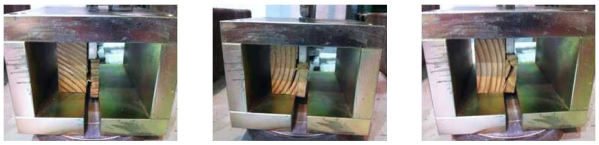


Figure 8. Size and load point of shear test piece



(a)plain (b)Vinyl acetate (c)PVB

Figure 9. Shear fracture form

From the shear fraction form, it was determined that the entire bond shear was separated, as shown in Figure 9(a). When using vinyl acetate resin as in Figure 9(b), fracture was found on the annual ring in the apparent wood shake form. In addition, when using PVB as in Figure 9(3), the shear fracture form was shown to be similar to those of specimens with plain d vinyl acetate, or a partial fracture was found at the shearing surface.

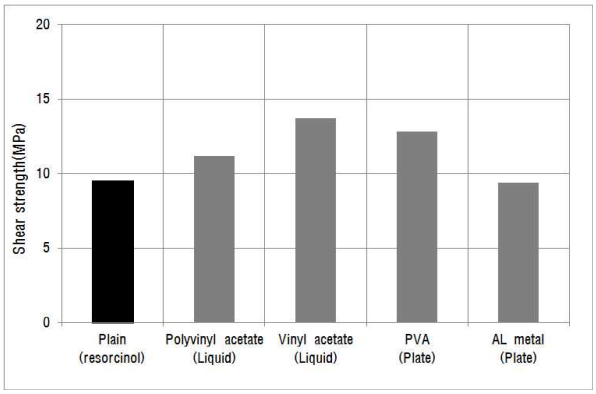


Figure 10. Shear strength of the wood adhesive bond according to the adhesive

The shear strength at the bonds of all specimens was shown to be higher than the KS F 3021 shear strength standard (7.1MPa) regardless of adhesive type, Plain, liquid and plate. When using liquid vinyl acetate resin, the shear strength was improved by about 30% compared to that using Plain, and when using plate PVB resin, the shear strength was improved by about 25%. However, when using AL metal film adhesive, the shear strength was shown to be similar to that using Plain. Of liquid adhesive materials, vinyl acetate resin was reported to have good adhesion[12], and was evaluated in this test to have more improved adhesion, which is believed to be because the liquid type of adhesive was easy to spread on and penetrate into the surface of wood due to the fact that water content distributed evenly all over the wood, and the strength at the bond improved as a result. Of the plate film adhesive materials, PVB resin was evaluated to have similar shear strength as that using liquid vinyl acetate resin, which is believed to be because the plate had a standardized thickness and could be attached to the entire surface of wood, and the adhesive was spread evenly and penetrated into the wood surface as the temperature rose.

On the other hand, the metal film adhesive showed a strength similar to Plain because the film

was thinner and needed less volume of adhesive than liquid and platetypes of adhesive. Nevertheless, considering that the metal film adhesive was stronger than the KS standard, it could be used in a pilot test.

4.3 Bending strength

Equation (2) aims to derive bending strength by adhesive type, and Table 5 indicates the results. Figures 11 and 12 show the shear fracture form after test, load points and sizes of specimens.

Table 5. Bending strength(MPa)

Division		Breaking load(kg/f)	Pmax (N)	2bh2	Bending strength (N/mm^2, MPa)
Plain		479.17	4 699.05		45.11
Liquid	Polyvinyl acetate	535.88	5 255.19		50.45
	Vinyl acetate	618.03	6 060.08	125 000	58.18
Plate	PVB	637.87	6 225.37		60.05
	AL metal	477.83	4 685.91		44.98

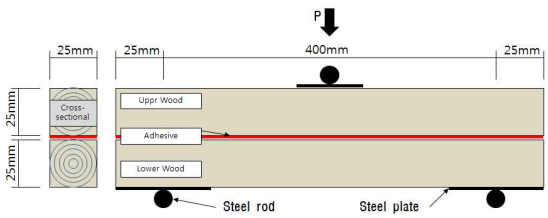


Figure 11. Bending strength specimen size and Load point

(a)Simple shear (Adhesive area eliminated)

(b)PVB specimen (Horizontal shear)

(c)PVB, After destruction (Cross-sectional shape)

Figure 12. Bending fracture form

In terms of bending strength by adhesive type, the specimens using polyvinyl acetate resin and AL metal film were shown to be low among liquid and plate materials, respectively. Unlike shear strength, the specimen using PVB resin was shown to have the highest bond strength. The specimen using AL metal film was approximated to that using Plain, as was in shear strength.

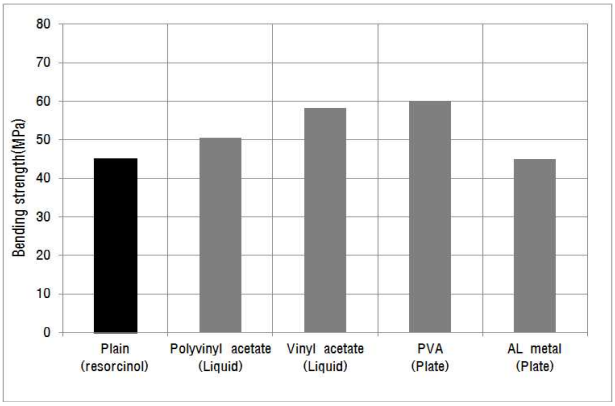


Figure 13. Bending strength of the wood adhesive bond according to the adhesive

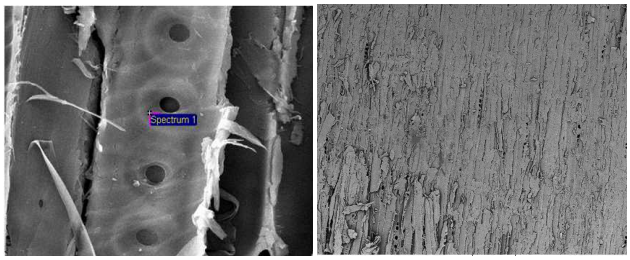
Bending fractures are usually simply tensile fractures, as shown in Figure 12(a), and the bond was separated after the specimen was bent vertically at a load point. However, plate PVB resin was not torn or separated after horizontal shear fracture form and wood fracture as shown in Figure 12(b). PVB is found to reduce abrupt or uneven fractures compared to liquid adhesives, which is believed to be because PVB resin was evenly attached on the bonded surface of the wood.

4.4 Fracture surface analysis with SEM

The fracture surfaces were observed using SEM (Scanning Electron Microscopy)[13] after the shear strength test, and the test results are shown in Tables 15, 16, and 17. In Figure 14, the components of resorcinol resin applied on the bonded surface of Plain specimen were analyzed, and there was resin found between fibers, but it did not penetrate the

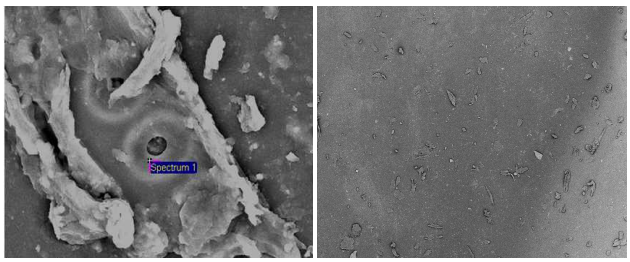
fibers that act as a valve on the fiber wall, such as cell-wall pits. In Figure 15, it was verified that liquid resin penetrated the fiber tissues of the wood, and the vinyl acetate resin was found at cell-wall pits and surrounding fibers. It is believed that the shear force was improved due to the easy penetration into the inside of the wood, because the adhesive applied on the wood surface permeated the space from which internal water was evaporated by microwave heating.

The bonded surface using PVB resin is shown in Figure 16. Unlike liquid resin, the PVB resin, whose layer was still found even after bonding, was completely removed to analyze the bonded surface. Through the analysis it was revealed that PVB resin was evenly applied all over the wood surface, and the fiber cells were also distributed evenly, as was liquid resin. From this, it can be interpreted that the entire surface of the wood, which showed a constant temperature rise during microwave heating, provides an appropriate condition for the melting of PVB resin as a core material.



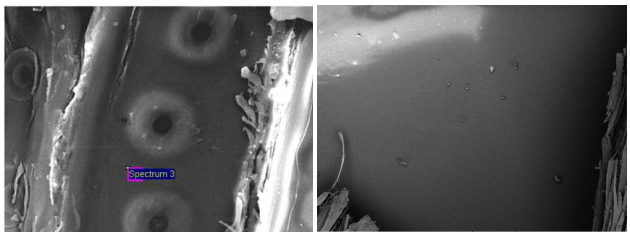
(a)Cell-wall pit(2.00kx) (b)Attached wood surface(200x)

Figure 14. Plain adhesive cross-section(resorcinol resin, liquid)



(a)Cell-wall pit(2.00kx) (b)Attached wood surface(200x)

Figure 15. Polyvinyl acetate resin adherend(Liquid)



(a)Cell-wall pit(2.00kx) (b)Attached wood surface(200x)

Figure 16. PVB resin adherend(plate)

5. Conclusion

To manufacture composite wood with better adhesion in a shorter period of time, the water content leveling was analyzed using microwave. The specimen that showed the most consistent results was manufactured by simultaneously heating the wood and adhesive and then pressing them together. The results of an analysis of mechanical tests and the bonded surface observed through the SEM are as follows:

1) An analysis of water content leveling to improve the adhesion to wood showed that in terms of temperature change at each surface point over microwave heating, the longer the heating time, the higher the temperature. There was a temperature deviation of about ±5℃. In terms of water content change, the longer the heating time at uneven distribution, the more constant the water content on the surface when heated for 12 and 15 minutes.
2) Through the test of shear strength at the bonded surface, the specimen using vinyl acetate resin was shown to be strongest, followed by that using PVB plate adhesive. There weresome differences between bending and shear strength, but there was little difference in strength less than 1%, indicating that the two resins had good adhesion. This is because the wood was simultaneously heated with the adhesive, which might help the resins

penetrate inside of the wood easily.

3) The fracture surface was observed using the SEM after the bond strengthtest. Plain made through a general process was found between fibers but hardly penetrated micro tissues. However, when heated with wood by microwave and then compressed, liquid vinyl and plate PVB could easily penetrate micro tissues as the temperature of the wood rose gradually, and spread evenly all over the wood, which is believed to help improve shear strength and bending strength.

The simultaneous microwave heating of the wood and adhesive provided even adhesion on the bonded surface of the composite wood manufactured in this study, and improved shear strength and bending strength compared to Plain. The performance should be verified through application to an actual construction site in order to use and apply the composite wood as structural material.

Acknowledgement

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