



Physical and mechanical properties of particleboard mixed with waste ACQ-treated wood

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Abstract

In this study, we recycle alkaline copper quaternary (ACQ)-treated wood used as a material for pyrolysis and gasification. The physical and mechanical properties of particleboards manufactured according to the mixing ratio and resin type (phenol–formaldehyde resin; PF, urea–melamine formaldehyde resin; UMF) were compared as materials for particleboard, which are used for wood recycling. According to the increase of ACQ particle input ratio, the PF particleboard did not differ in density; however, the thickness swelling rate (TSR) and water absorption rate (WAR) decreased. The density of the UMF particleboard increased and the TSR and WAR also decreased. Although the bending strength (BS) of the PF particleboard increased, the internal bond strength (IB) did not show a difference. The UMF showed no difference in BS, but the IB improved. Through physical and mechanical properties, the mixing ratio of ACQ particle and untreated particles was 70:30 as the optimal mixing ratio. The surface was activated by the copper ions of the ACQ treated, which affected the improvement of adhesion and physical and mechanical properties. When ACQ-treated wood, which is classified as waste, was reused as a particleboard, its properties were superior to that of a board manufactured with untreated particles.

Keywords Waste wood · ACQ-treated wood · Recycling · Particleboard · Water resistance

Introduction

With the declaration of carbon neutrality in 2021, considerable attention is being paid to the role of forests in absorbing carbon dioxide and the carbon storage effect of wood. Unlike inorganic materials such as plastics and metals, wood is an organic material comprising carbon, hydrogen, oxygen, and nitrogen [1]. Wood is suitable for use as a material for

various purposes such as children’s playgrounds, educational materials, and building materials because of its advantages such as eco-friendliness, stability, functionality, beautiful design, excellent color, and emotional stabilization effect [2]. In addition, wood products have the effect of reducing the concentration of carbon dioxide in the atmosphere by storing carbon stored in forests for a long time until disposal [3]. Therefore, to improve the carbon storage of wood products, it is necessary to expand the use of wood within the scope of sustainability and to extend the useful life, which is the carbon storage period of products, based on the principle of step-by-step circular use [4]. In South Korea, interest in long-lived wood products, circular use of wood resources, and recycling of waste wood is increasing [4–9].

Waste wood contains additives (adhesives, varnishes, etc.) and various contaminants (preservatives, heavy metals, etc.). The heterogeneity contained in waste wood complicates the recycling process. Accordingly, the wood waste management strategy is based on (1) landfill, (2) energy recovery, and (3) material recovery [10]. Among them, although the material recovery process is complex, it is configured and developed by a “cascade” based on recycling through the product of new materials. Cascading is “the efficient use of resources

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using residues and recycled materials for material use by expanding the total biomass availability in a given system” [11]. As a result, the cascading effect allows for extended carbon storage in the material and delays its release in the form of CO₂ until it is used as fuel at the end of its life [12].

Wood has the disadvantage of shortening its lifespan due to decay and decomposition by fungi and insect damage caused by insect invasion [13]. To compensate for this disadvantage, preserved wood with pressurized injection of preservatives is used to extend the life span and improve durability of wood exposed to moisture and used outdoors [14–16]. Preserved wood contains heavy metals and is classified as waste after the expiration date. Preserved wood is classified into three grades according to the classification criteria according to the “classification and recycling standards of waste wood” announced by the Ministry of Environment in South Korea [7]. Grade 1 is waste wood that is in its raw wood or is mechanically processed and treated and is not contaminated with paint, oil, preservatives, etc., during the processing and treatment process. Grade 2 is waste wood that has been contaminated with or used substance such as adhesives, paints, oil, and concrete in the process of processing, handling, and using. Grade 2 belongs to wood-based materials such as particleboard and fiberboard, and most wood materials use formaldehyde-based adhesives such as urea resin, melamine resin, and phenol resin [17]. Grade 3 corresponds to waste wood used with halogenated organic compounds or preservatives in the process of processing, treatment, and use. Currently, waste wood classified as Grades 1 and 2 is recycled as raw material for particleboard and fiberboard. Alternatively, Grade 3 waste wood is used as a raw material for pyrolysis and gasification, shortening the life span of wood [5, 18, 19].

Reuse of waste wood is currently considered in the particleboard industry, and wood waste has recently been included and reused in the inner layer of medium-density fiberboards [11, 20]. The recycled wood proportion in particleboard varies by country. It is used in countries such as Italy (100% reuse), Belgium, England, Denmark (approximately 50% reuse), Germany, France and Spain (15–30% reuse), and South Korea [11]. Waste wood is not only reused as wood-based materials, but is also being developed into waste wood-plastic and wood-concrete composites for cascading use [21, 22].

There is growing interest overseas in recycling preservative wood, classified as Grade 3 waste wood in South Korea [7]. Wood and wood-based materials impregnated with Cu-based preservative have very high costs and environmental impacts due to storage and incineration of wood waste. It has been reported that recycling or upcycling wastes that contain preservatives has great potential for global warming and carbon sequestration in the wood industry [23, 24].

The Cu-based preservative currently is used copper and quaternary ammonium (alkylammonium copper quaternary; ACQ) and is water-soluble [25, 26]. Hingston, Temiz, and Kim et al. studied the leaching performance of preservatives injected into wood [27–29]. Temiz (2006) investigated the copper leaching of CCA and eco-friendly wood preservatives and reported that ACQ had the highest copper leaching [27]. Hingston reported that the number of heavy metals contained in treated wood was initially high in leaching [28]. Kim et al. studied the change in copper content of wood pole specimens according to time after ACQ-treated wood pole installation [29]. As a result, the initial copper content was 3550.46 mg/kg and rapidly decreased to 1.495 mg/kg after 1 year and 1.12 mg/kg after 2 years. It is a water-soluble preservative and is easily soluble in water; therefore, the initial leaching amount was very high due to rainwater and other factors during the period of use when exposed outdoors. In addition, it passed the copper regulation standard of 3 mg/L or less of the Waste Management Act, suggesting the need to review the waste standard of the ACQ-treated wood pole [29].

Therefore, to recycle ACQ-treated wood, which is used as a raw material for pyrolysis and gasification after being classified as waste, this study aims to compare and analyze the physical and mechanical properties of particleboard manufactured according to the mixing ratio as raw materials for particleboard, which is an existing wood recycling purpose.

Materials and methods

Materials

For ACQ-treated wood, rainscreen bar-treated wood to be discarded from Daelim Wood (Gyeonggi-do, Korea) was supplied and used as a raw material. Rainscreen is an air layer constructed between exterior materials and walls in a wooden house to smoothly discharge moisture, and preservative wood is used to prevent damage to wood when exposed to moisture. The dimension of the supplied treated wood was 15(T) × 38(W) × 3600(L) mm, and the moisture content was 11% (±0.6%). The supplied treated wood was cut to a length of less than 5 cm and chipped through a chipper, and chips with a size of 1–4 mm were used as a raw material for particleboard (Fig. 1).

To manufacture a particleboard mixed with waste ACQ-treated wood, untreated particles were supplied from Dongwha Co., Ltd. (Incheon, South Korea) and used. After the particles were classified to make the chips the same size as the ACQ particle, chips with a size of 1–4 mm were used as raw materials for particleboard. The moisture content of the particles was 6.5% (±0.3%).

Fig. 1 **a** Waste ACQ particles and **b** untreated particles; Particle size: 1–4 mm



Table 1 Properties of concentrated PF and UMF

	Solid content	pH	Viscosity (cps)
Concentrated PF	55.4% ($\pm 0.3\%$)	10.77	72.00
UMF	55.7% ($\pm 0.4\%$)	7.57	167.8

Phenol–formaldehyde resin (PF) and urea–melamine–formaldehyde resin (UMF), which are representative adhesives used in manufacturing wood-based materials, were used to compare the difference in physical properties of particleboard according to the types of particles and adhesives. PF and UMF were received from SUN&L (Incheon, South Korea). The PF was an E0 resin used for manufacturing structural plywood, and the solid content of the resin was 40.8% ($\pm 0.2\%$). Typically, the solid content of adhesives used in particleboard manufacturing is 55% [30]. To increase the solid content of the PF, it was concentrated for 1 h at 60 °C using a rotary evaporator (Rotavapor R-100, BUCHI, Swiss). As the UMF, E1 resin used in the manufacture of fiberboard and particleboard was used. The properties of the concentrated PF and UMF are shown in Table 1.

Manufacturing of particle board mixed ACQ and untreated particles

To compare the physical properties of particleboards according to the mixing ratio of ACQ particles (AP) and untreated particles (UP), AP:UP ratio of 0:100, 30:70, 50:50, 70:30, and 100:0 were mixed and used as raw materials for particleboard. The particleboard to be manufactured had a size of 10(T) \times 400(W) \times 400(L) mm and a target density of 0.7 g/cm³. The resin content, which is the amount of adhesive added, was added at 12% based on the dry weight of the particles. The mixed particles were used after being dried for 24 h or more before particleboard



Fig. 2 Hot pressure for particleboard manufacturing. The gauge ram of the hot pressure: 15 cm; the temperature of the top and bottom plates < 200 °C; the pressure is 100 kgf/cm³

manufacturing to equalize the moisture content. For the uniform application of the adhesive to the dried particles, the mixture was mixed for 15 min using a mixer. The mixed particles were moved to a deckle box, molded, and manufactured using a hot pressure (Fig. 2). The curing agent and hot pressure schedule added according to the type of adhesive are shown in Table 2. The curing agent was prepared and used as a solution having a concentration of 20% for mixing with the adhesive. The manufactured particleboard was cut into specimen for comparing physical and mechanical properties after cold pressing at 20 °C (± 2 °C) for more than 24 h.

Table 2 Hardener and pressure condition

	Hardener		Pressure conditions		
	Type	Addition rate	Temperature	Pressure	Schedule
PF	Calcium carbonate	3% of adhesive solid contents	145 °C	40 kgf/cm ²	40 s/mm
UMF	Ammonium chloride		125 °C		20 s/mm

Physical and mechanical properties

To compare the physical and mechanical properties of particleboard according to the AP mixing ratio, the specimens were cut and tested as shown in Table 3.

For the density and moisture content, the weight and dimensions (thickness, width, and length) of the specimen were measured and then dried in an oven-dryer set at 103 °C (± 2 °C) until a constant weight was reached. The weight of the dried specimen was measured, and the moisture content (MC) and density were calculated using Eqs. 1 and 2

$$MC = \frac{m_2 - m_1}{m_1} \times 100(\%) \quad (1)$$

$$\text{Density (g/cm}^3\text{)} = \frac{m_1}{v} \quad (2)$$

The MC, m_1 , m_2 , and v are the moisture content (%), weight after drying (g), weight before drying (g), and volume before drying (cm³), respectively.

The rates of thickness swelling (TSR) and water absorption (WAR) were measured at U1, U2, M1, and P1 after measuring the initial thickness and weight of the specimen. Under this condition, the specimen is immersed in a constant temperature (20 °C, 70 °C, 100 °C) water bath for a certain period of time so that it does not float. After the test was completed, the surface of the specimen was wiped dry, and the thickness and weight were measured and calculated using Eqs. 3 and 4 [31].

$$TSR = \frac{t_2 - t_1}{t_1} \times 100(\%) \quad (3)$$

$$WAR = \frac{w_2 - w_1}{w_1} \times 100(\%) \quad (4)$$

The TSR, t_1 , t_2 , WAR, w_1 , and w_2 are rate of the thickness swelling (%), thickness before soaking (mm), thickness after soaking (mm), rate of water absorption (%), weight before soaking (g), and weight after soaking (g), respectively.

As mechanical properties, the bending strength (BS) and internal bonding strength (IB) were compared; the test was performed after pretreatment for more than 7 days in a constant temperature and humidity chamber at a temperature of 20 °C and a relative humidity of 65% to uniformize the water content of the material. For the bending test, a three-point load test was performed with a span of 150 mm, a distance between load points of 75 mm, and a load speed of 10 mm/min. The load was tested using a 5-ton universal testing machine (Hounsfield-H50KS, USA) to be perpendicularly applied to the axial direction of the particleboard. The MOR was calculated according to Eq. 5 because of the dimensions (thickness, width, and span) of the test specimen and the maximum load [31].

$$BS = 3PL/(2bt^2) \quad (5)$$

The BS, P , L , b , and t are bending strength (MPa), maximum load (N), span (mm), width of specimen (mm), and thickness of specimen (mm), respectively.

Table 3 Test method and specimen dimension

		Dimensions of test specimen (mm)	Test species (ea)	Standard	
Physical properties	Density and moisture content	50(W)×50(L)	5	KS F3104 [31]	
	Thickness swelling and water absorption	20 °C–2 h (U1)	50(W)×50(L)		5
		20 °C–24 h (U2)	50(W)×50(L)		5
		70 °C–2 h (M1)	50(W)×50(L)		5
		100 °C–2 h (P1)	50(W)×50(L)		5
Mechanical properties	Bending strength (BS) (span: 15 times of thickness)	50(W)×200(L)	10		
	Internal bond strength (IB)	50(W)×50(L)	10		
Free-formaldehyde emission test Dessicator method		50(W)×150(L) (total surface area (cm ²))	12	KS M1998 [32]	

An IB test was conducted to compare the adhesive strength of the particleboards manufactured according to the ACQ particle mixing ratio. The IB test was performed by attaching an I-shaped aluminum block to the top and bottom of the specimen and applying a tensile load perpendicular to the surface of the specimen. At this time, the tensile load speed was 2 mm/min and the IB was calculated according to Eq. 6 with the maximum load during delamination and the dimensions (width and length) of the specimen.

$$IB = \frac{P_m}{bl} \quad (6)$$

The IB, P_m , b , and l are IB (MPa), maximum load (N), width of specimen (mm), and length of specimen (mm), respectively.

To compare the amount of formaldehyde released according to the type of adhesive and the mixing ratio of AP, the amount of formaldehyde released by desiccator method was tested. The specimens were weighed every day under a standard condition of 20 °C (± 2 °C), 65% ($\pm 5\%$), and were pretreated until the difference was less than 0.3%. Distilled water of 300 mL contained in a glass beaker was placed at the center of the desiccator, and a specimen support and 12 specimens were installed on it. Only distilled water was installed without installing the specimen in the desiccator to measure the background concentration. After sealing the desiccator, a release test is started for 24 h (± 10 min) in a space where the internal temperature is maintained at 20 °C (± 2 °C). After the release test is completed, put 25 mL each of acetyl acetone-ammonium acetate solution, which is a color developing reagent, into an Erlenmeyer flask, mix, and then shade. The Erlenmeyer flask containing the mixed solution was heated in a constant temperature water bath set at 65 °C (± 2 °C) for 10 min and then cooled in a shaded state until it reached room temperature, and then, the absorbance was measured at a wavelength of 412 nm using a UV/Vis spectrometer (HS-3700, Humas, Korea) [32]. The formaldehyde concentration was calculated according to Eq. 7 by applying the absorbance and cross-sectional area.

$$G = F(A_d - A_b) \times 1800/S \quad (7)$$

G , F , A_d , A_b , and S are the formaldehyde concentration of the specimen (mg/L), slope of calibration curve on the standard solution of formaldehyde (mg/L), absorbance of test solution, absorbance of blank solution, and total surface area (cm²), respectively.

Fourier-transform infrared (FTIR) spectroscopy

The chemical functional groups of particleboards manufactured with urea melamine formaldehyde (UMF) resin were qualitatively analyzed using FTIR spectroscopy. IR was

measured in a 4000–450 cm⁻¹ scanning range using the FTIR Spectrum Two (Perkin-Elmer, USA).

Inductively coupled plasma (ICP) analyses

The manufactured particleboards were ground and used for analyzing the copper content by ICP. The ground samples (~0.5 g) were weighted, placed in a microwave digestion tube, and nitric acid (15 ml) was added. The digestion tube was sealed in digestion vessels and the carousel was placed in a microwave oven for a pre-programmed digestion sequence [33]. After the decomposition (20 min), each container was quantitatively prepared to have a 100 ml volume using distilled water. The copper contents of the prepared samples were measured using ICP mass spectrometry ICP-MS (Perkin Elmer Nexion 1000, PerkinElmer, Inc. USA).

Statistical analysis

SPSS 26 (IBM, V26.0.0, New York, USA) statistical program was used to verify the significance of the physical and mechanical properties according to the mixing ratio of AP and the type of adhesive used. One-way ANOVA was performed, and Duncan's multiple tests were performed to verify the significance. According to the p value of the significance test result, $p < 0.05$ was marked with “*,” $p < 0.01$ with “**,” and $p < 0.001$ with “***.”

Result and discussion

Physical properties

The results of particleboard density and moisture content according to the ACQ particle mixing ratio are shown in Fig. 3. The higher the mixing ratio of AP in the particleboard, the higher the density (Fig. 3a). In the case of using PF particleboard ($F = 2.59$, $p = 0.061$), the density according to the ACQ particle addition ratio showed the same level of results. Alternatively, when UMF particleboard ($F^{**} = 6.899$, $p = 0.001$) was used, the density increased as the ACQ particle mixing ratio increased, and the same level of density was shown when the AP:UP ratio was 30:70 or higher. When the mixing ratio of AP was the same, the PF particleboard showed higher density than the UMF particleboard. According to Kim et al. (2018) and Varodi et al. (2019), the UMF specific gravity is 1.2 at 50% ($\pm 1\%$) solid content and 1.28–1.295 at 66% ($\pm 1\%$) solid content [34, 35]. According to Atta-Obeng et al. (2013) and Varodi et al. (2019), the specific gravity of PF is 1.23 at 55% solid content and 1.17 ($\pm 0.03\%$) at 50% ($\pm 2\%$) solid content [35, 36]. At 50% solid content, the resin specific gravity difference was 0.03, which is higher for

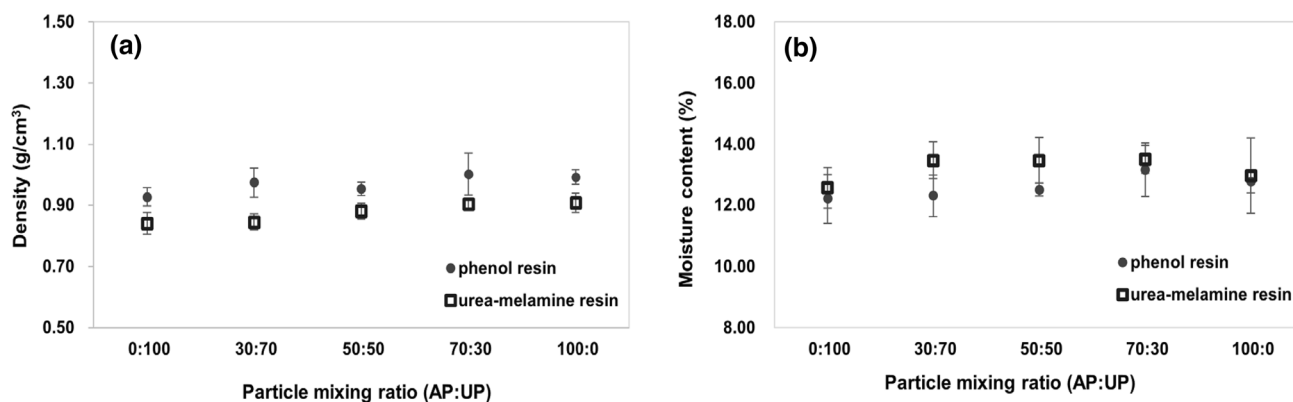


Fig. 3 Result of **a** density and **b** moisture content. Range of mixing ratios of ACQ particles (AP) and untreated particles (UP):0:100 TO 100:0 ($N=5$)

UMF, but the density of particleboard with PF showed a higher result. Rather than the effect of product density by specific gravity of resin, the effect on adhesion of AP and resin type should be considered. Lee (1994) reported that surface activation treatment of wood is necessary to improve the adhesion of particleboard [37]. It was reported that by treating wood with an acid or oxidizing agent, reactive groups such as $-OH$ groups and $-COOH$ groups can be generated on the surface to directly interact with each other or react with a crosslinking agent to improve adhesion [37]. Sun et al. (2009) found that the zeta potential of a solution prepared by mixing water-soluble PF with distilled water at a concentration of 50 mg/L had a negative charge of -38.08 mV, and according to Yang et al. (2016), the zeta potential of wood was reported to have a negative charge of -22.8 mV [38, 39]. AP were surface activated with positive charges by reacting with copper ions, which are cations, and $-OH$ and $-COOH$ groups, which are negatively charged in wood, by injecting preservatives.

The positively charged AP reacted with the negatively charged PF to improve adhesion and density.

For the moisture content of the manufactured particle board, there was no difference in the moisture content according to the ACQ particle mixing ratio (PF particleboard $F=1.796$, $p=0.161$, UMF particleboard $F=1.406$, $p=0.261$) and was no difference in moisture content ($t^*=-2.862$, $p=0.006$) according to the type of resin. This is considered because the press temperature and press time are different according to the type of resin during particleboard manufacturing, the PF particleboard with a high press temperature, and a long press time has a low moisture content.

The thickness swelling and water absorption rate (TSR and WAR), which are water resistance to moisture, were compared according to the ACQ particle mixing ratio and the type of resin, and the results are shown in Figs. 4 and 5. In the case of the PF particleboard, the TSR ($F^{***}=12.83$, $p=0.000$) of U1 showed the same level except for the 0:100

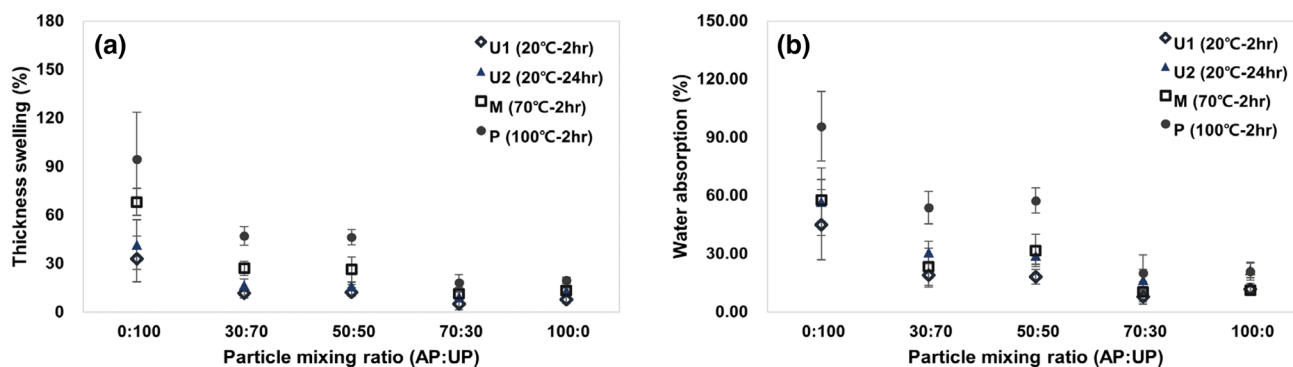


Fig. 4 **a** Thickness swelling rate (TSR) and **b** Water absorption rate (WAR) for PF particleboard. Time of measurement for thickness and weight change 2 h or 24 h of soaking in a constant temperature water

bath maintained at a temperature according to U, M, and P types ($N=5$). And similar modifications of figure captions in other figures (Fig. 5)

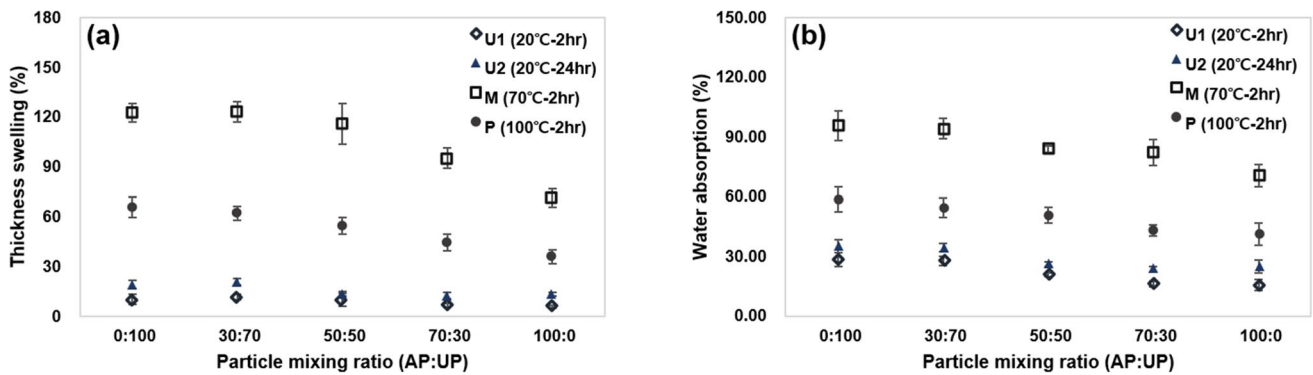


Fig. 5 a Thickness swelling rate (TSR) and b Water absorption rate (WAR) for UMF

(AP:UP) mixing ratio. The significance of the TSR and WAR from 30:70 to 100:0 (AP:UP) ($F^* = 6.745$, $p = 0.003$), which showed an equivalent level, was verified. As a result, the mixing ratio of 30:70 and 50:50 (AP:UP) were equivalent, and the mixing ratio of 70:30 and 100:0 was equivalent. Under the U1 condition, when the AP are mixed at a mixing ratio of 70:30 or more, the thickness expansion rate with respect to moisture is 8% or less. The TSR ($F^{***} = 14.551$, $p = 0.000$) of U2 showed the same results as the TSR of U1. Except for the 0:100 mixing ratio, the significance of the TSR from 30:70 to 100:0, which showed an equivalent level, was verified, and as a result, ($F^{***} = 8.929$, $p = 0.000$) 50:50, 30:70, 100:0, and 70:30 showed low TSR in that order. The longer the soaking time at 20 °C, the higher the TSR of 100:0, and rather, the water resistance decreased when manufactured 100% AP. The TSR of M condition was 0:100, 30:70 \approx 50:50, 70:30 \approx 100:0, showing low TSR, and the soaking conditions of M and P showed the same results. The WAR also showed the same results as the TSR, and the WAR of 70:30 mixing ratio showed the lowest distribution of less than 20% in the U1 and U2 soaking conditions. Therefore, when considering moisture resistance, the mixing ratio of ACQ and untreated particles is optimal at 70:30.

In the case of the UMF particleboard, the TSR ($F^* = 5.1002$, $p = 0.004$) of U1 is 0:100 \approx 30:70 \approx 50:50, 70:30, 100:0, showing high TSR in the order of mixing ratio. The TSR ($F^{***} = 21.921$, $p = 0.000$) of U2 showed high TSR in the order of mixing ratio of 0:100 \approx 30:70, 50:50 \approx 70:30 \approx 100:0. The significance of the TSR of the mixing ratio of 50:50 70:30, and 100:0, which showed an equal level, was verified, and no difference was found in the TSR when AP were mixed at an equal level of 50:50 or more. The TSR ($F^{***} = 43.167$, $p = 0.000$) of M showed a low TSR of 0:100 \approx 30:70 \approx 50:50, 70:30 \approx 100:0. The TSR ($F^{***} = 31.261$, $p = 0.000$) of P was 0:100 \approx 30:70, 50:50, 70:30, 100:0 under the soaking conditions of M and P showed the same result. The WAR also showed similar results to the TSR, and showed a difference in WAR

according to the ACQ particle mixing ratio at a mixing ratio of 70:30 or more.

Depending on the type of adhesive, PF showed lower TSR and higher WAR than UMF. PF is used in the exterior-grade structural panels and exhibits high strength, water resistance, and excellent thermal stability [33, 39]. UMF is cheaper than PF and can express high adhesive strength with short compression time at low temperature, but its water resistance is lower than that of PF [40]. Therefore, the results according to the type of adhesive were consistent with previous studies, and the mixing ratio of AP and untreated particles was 70:30, which is the optimal condition, but the adhesive should be applied differently depending on the environmental conditions of use.

Mechanical properties

The bending strength (BS) and internal bond (IB) according to the AP mixing ratio were compared, and the results are shown in Fig. 6. BS showed different results depending on the type of adhesive (Fig. 6a). The BS ($F^{***} = 9.715$, $p = 0.000$) of the particleboard using PF showed high BS in the order of 0:100 \approx 30:70 \approx 50:50, 70:30 \approx 100:0. As the mixing ratio of AP increased, the BS improved. Alternatively, there was no significant difference at the 5% significance level with the BS of UMF ($F = 2.181$, $p = 0.1$), but in Duncan's multiple test, 30:70, 0:100 \approx 50:50 \approx 70:30, and 100:0 showed high results in that order. The BS of the particleboard according to the AP mixing ratio increases as the mixing ratio increases, and at the 5% significance level, the increase in the AP mixing ratio affects the BS of the PF particleboard.

IB, which is the adhesive strength of particleboard, showed that the average IB increased as the AP mixing ratio increased. In addition, it showed higher adhesive strength than UMF, similar to the results of density and BS. The PF particleboard ($F = 1.752$, $p = 0.199$) did not show a difference in IB as the ACQ particle mixing ratio increased at

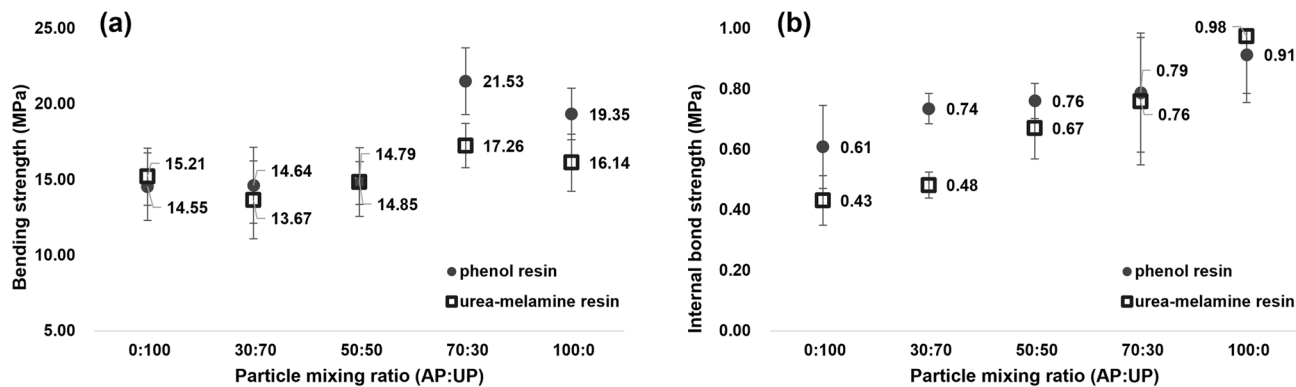


Fig. 6 **a** Bending strength (BS) and **b** Internal bonding strength (IB). The span of bending strength was 15 times the thickness, and the loading speed was 100 mm/min ($N=10$). The Internal bonding strength loading rate was 2 mm/min ($N=10$)

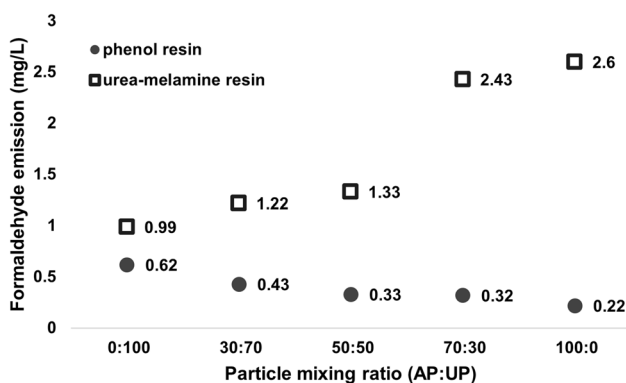


Fig. 7 Result of formaldehyde emission. Formaldehyde emission was tested by the desiccator method. It is released for 24 h in a space where the internal temperature is maintained at 20 °C (± 2 °C). The test solution in the desiccator is mixed with acetyl acetone-ammonium acetate solution, a color reagent, and reacted at 65 °C (± 2 °C) for 10 min. After measuring absorbance at a wavelength of 412 nm, formaldehyde emission was calculated

the 5% significance level. Alternatively, UMF ($F^{***} = 8.87$, $p = 0.000$) showed higher IB in the order of 0:100 \approx 30:70, 50:50, 70:30, and 100:0 than untreated particleboard. The adhesion of ACQ particleboard was improved by 2.1 times. In Lee (1994) study, wood surface activation treatment was performed with boric acid, but AP have improved BS and IB due to surface activation treatment with preservatives [37].

Formaldehyde emissions

The results of formaldehyde emission according to the type of adhesive and the mixing ratio of AP are shown in Fig. 7. E0 PF and E1 UMF were used, and formaldehyde emissions were expected to be E0 (average 0.5 mg/L, maximum 0.7 mg/L) and E1 (average 1.5 mg/L, maximum 2.1 mg/L). As a result, the particleboard to which the PF was applied showed a formaldehyde emission of 0.22–0.62 ppm, and

the formaldehyde emission decreased as the AP mixing ratio increased. PF resin is a thermosetting adhesive that is completely cured in the hot pressure process, resulting in low formaldehyde emission, consistent with previous studies showing that formaldehyde emission is reduced during surface activation of particles [37, 41]. Particleboard manufactured using PF and mixing AP is expected to be applicable as an external wall of wooden construction exposed to existing moisture due to improved water resistance, BS, IB, and reduced formaldehyde emission.

Alternatively, the particle board of UMF increased the formaldehyde emission as the AP mixing ratio increased from 0.99 to 2.6 ppm. After 70:30 mixing ratio, the formaldehyde emission increased rapidly. It is closely related to density. The surface activation of AP increases the bonding strength between AP and adhesive, which affects the increase in the amount of formaldehyde emission due to the high content of the adhesive per unit area. Even if the physical and mechanical properties are improved by increasing the AP mixing ratio, the increase in formaldehyde emission is not possible due to environmental regulations; therefore, it is necessary to study formaldehyde reduction when applying UMF.

Characterization of the AP: UP ratio by FTIR spectroscopy

Figure 8 shows the FTIR results of the surfaces according to the AP:UP mixing ratio, and the FTIR band assignments are given in Table 4. The O–H stretching vibration was in the wavelength range of 3200–3600 cm^{-1} , indicating the presence of alcohol and cellulose [42]. As the AP content increased, the O–H peak intensity decreased. This was consistent with the TSR and WAR results, showing that the higher the AP content, the lower the reactivity to moisture. In addition, the copper remaining in AP improves the bonding strength between the adhesive and wood, affecting

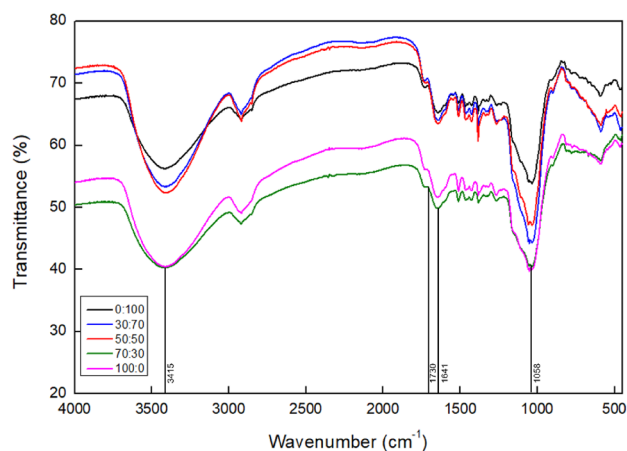


Fig. 8 Fourier-transform infrared spectra of particleboard according to mixing ratio of AP:UP. Wavenumber 3415 cm^{-1} : O–H stretching; 1730 cm^{-1}

Table 4 Summary of FTIR band assignments

Wavenumber (cm^{-1})	Band assignment	References
3415	O–H stretching	[44]
1730	COOH group	[43]
1641	C=O group	[45]
1058	C–O–C group	[46]

Table 5 Copper contents of particleboard according to AP:UP ratio

AP:UP	0:100	30:70	50:50	70:30	100:0
Copper contents (ppm)	13.4	536	783	1120	1710

the O–H peak reduction and adhesion improvement. The –COOH group has a wavelength range of $1710\text{--}1730\text{ cm}^{-1}$ [43]. The intensity of the –COOH peak decreased at 70:30 and 100:0 ratios. In the same way the –OH peak, the wood reactivity was reduced, resulting in improved resistance to moisture and adhesion, verified through a decrease in the intensity of the functional group peak in FTIR spectra.

Copper contents

The copper content results according to the AP:UP mixing ratio are shown in Table 5. As the AP addition ratio increased, the copper content also increased. Considering the FTIR results showing a decrease in the intensity of –OH and –COOH groups among the functional groups, it was confirmed that the copper contained in ACQ activated the wood surface, affecting the improvement of adhesion and physical and mechanical properties.

Particleboards were manufactured using ACQ-treated wood impregnated with a copper-based preservative, and their physical and mechanical properties were compared. As a result, ACQ-treated wood was surface-activated with copper ions remaining on the wood surface, contributing to improve adhesion when manufacturing wood-based materials. This was consistent with the study of Lee (1994) and the FTIR results showing the reduction of the intensity of –OH and –COOH groups [36]. New material products must be developed by cascading wood containing Cu-based preservatives to store CO_2 for a long time [12]. In addition, it will be possible to develop a new product with water resistance, high internal bonding, and natural decay resistance from particleboards used for furniture, along with the particleboard industry that uses waste wood.

Conclusion

As a study to recycle ACQ-treated wood used as a raw material for pyrolysis and gasification, the physical and mechanical properties of particleboards manufactured according to the mixing ratio and resin type were compared as raw materials for particleboard, which is an existing wood recycling purpose.

- (i) The physical properties were improved as the ACQ particle mixing ratio increased. The particleboard to which the PF was applied showed no difference in density and improved water resistance. Particleboard with UMF showed improved density and water resistance as the ACQ particle mixing ratio increased, and the mixing ratio of 70 (AP):30 (UP) was the optimal mixing ratio. This was surface activated because of the components such as copper ions of the ACQ preservative contained in the AP, and physical properties were improved.
- (ii) The mechanical properties were improved as the ACQ particle mixing ratio increased. The BS of the PF particleboard increased, but the IB had minimal effect on the ACQ particle mixing ratio at the 5% significance level. Alternatively, in the case of UMF particleboard, the increase in the ACQ particle mixing ratio has a negligible effect on the BS at the 5% significance level, but it is decided to have a significant effect on the BS. Increasing the ACQ particle mixing ratio had a considerable effect on improving the mechanical properties.
- (iii) The formaldehyde emission of particle board using PF decreased as ACQ particle mixing ratio increased. Alternatively, the UMF particleboard increased formaldehyde emission as the ACQ particle mixing

ratio increased. It is considered that PF is suitable for the recycling of AP.

- (iv) The mixing ratio of untreated particles and ACQ particles is optimal at 70:30 (AP:UP) ratio, it is suitable to use PF as adhesive, and ACQ-treated wood can be recycled. In addition, as the water resistance is improved, it can be applied as an external wall panel for wooden buildings exposed to existing moisture.

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Declarations

Conflict of interest The authors declare that there are no financial or commercial conflicts of interest.

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