EVALUATION OF FLAME RETARDANT IMPREGNATION IN PERFORATED HINOKI (*CHAMAECYPARIS OBTUSA*) PLYWOOD

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Abstract. Recently, perforated plywood has been widely used as an indoor sound absorber. Flame retardant treatment is essential for the utilization of wood materials as indoor building materials. Among the various flame retardant treatment methods, we focused on pressure impregnation of water-soluble phosphate flame retardant in commercial Hinoki (*Chamaecyparis obtusa*) plywood. Experimental perforation rates were 0.06%, 0.1%, 0.3%, and 1.7%, and impregnation times were 30, 60, and 90 min. Then, we evaluated the impregnation as a function of plywood perforation frequency and impregnation time using Pearson's coefficient correlation analysis and multilinear regression analysis. The greater the perforation frequency and impregnation time, the greater the impregnation. Increasing impregnation correspondingly improved the performance of the flame retardant.

Keywords: Flame retardant, WPFR, Hinoki, *Chamaecyparis obtuse*, impregnation, perforated plywood.

INTRODUCTION

Wood possesses inherent natural characteristics, providing stability, and aesthetic appeal (Shen et al 2021; Jang 2022b). In addition, wood can capture atmospheric carbon dioxide, which can contribute to climate change mitigation (Howard et al 2021; Jang 2022a).

Commercial wood materials are broadly divided into solid wood, fiberboard, particleboard, and

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plywood. Plywood has been used since ancient Egyptian times, and its use began to expand in the mid-19th century (Fekiač et al 2021). Plywood products rose to prominence in the early 1900s due to two significant advancements: the introduction of synthetic waterproof adhesives and the subsequent development of robust and long-lasting wood composites (Hughes 2015). These products have extensive applications in furniture manufacturing as a versatile decorative element and in residential construction projects (Li et al 2021; Mai et al 2022).

The COVID-19 pandemic greatly increased the time spent indoors (Andargie et al 2021; Jang 2022c), drawing more attention to comfortable indoor environments. Critical factors for creating such an environment are temperature and humidity control, indoor air quality, lighting, and noise control (Ncube & Riffat 2012). In particular, noise can disrupt work and activities and also contribute to stress (Wallenius 2004). The easiest way to overcome these challenges is by introducing sound-absorbing materials into the indoor space (Jang 2023). In Korea, interest in perforated plywood, an eco-friendly sound-absorbing material, is increasing. Perforated plywood can act as a resonant sound-absorbing material when the size and frequency of its perforations and the distance from the back space are adjusted (Song et al 2016; Peng et al 2018; Fekiač et al 2021).

Although perforated plywood has excellent sound absorption performance, it has a dangerous disadvantage of flammability as an interior building material. Therefore, many countries have mandated flame retardant treatment for wood as a building material (Vojta et al 2017; Park et al 2020; Xiong et al 2020). However, the lack of regulation regarding the flame retardancy of wood in various interior applications is a reality in many countries.

Applying flame retardant treatment to wood can significantly improve its fire safety. Flame retardant chemicals often include elements such as halogens, nitrogen, boron, phosphorus, aluminum, iron, magnesium, or their various combinations (Chen et al 2021).

Two methods are commonly employed to apply flame retardants to wood: coating (Hu & Sun 2021; Chu et al 2022) and impregnation (Fu et al 2017; Lu et al 2022). These methods bear similarities to wood preservation treatments. We focused on flame retardant impregnation of perforated plywood.

In a previous study, Jang and Kang (2023b) investigated the impregnation of larch (*Larix kaempferi*) and pine (*Pinus koraiensis*) wood with preservatives. Multiple regression analysis was performed to determine the influence of pressure, temperature, and time on wood impregnation. The results revealed that pressure had the most significant effect on the impregnation process. In addition, Jang and Kang (2023a) introduced a steam explosion treatment to improve the chemical impregnation capacity of wood and reported improved impregnation through the creation of microcracks in the cell walls of the wood, increasing the open pore content.

Based on the results of these previous studies, we investigated the effect of perforation frequency on the impregnation of flame retardants in perforated plywood. We hope that our findings will enable improvements to the flame retardant impregnation of perforated plywood.

MATERIALS AND METHODS

Sample Preparation

In this study, we prepared commercial Hinoki (*Chamaecyparis obtusa*) plywood obtained from Gaonwood in Jeonju, Korea. The plywood was thermoformed using a 1.7-mm veneer with a petroleum resin adhesive, and its dimensions were 1220 mm (W) × 2440 mm (L) × 18 mm (T). The MC (MC) was measured as 10.6 (0.6, standard deviation) % using an electric MC meter.

We cut a piece of plywood to a size of 180 mm (W) × 360 mm (L) and used a computer numerical control to drill 5-mm-diameter holes. Figure 1 shows drawings of the samples with different hole spacing. Sample A represents unperforated plywood, whereas Samples B, C, D, and E have perforation rates of 0.06% (5 mm diameter, hole spacing of 120 mm), 0.1% (5 mm diameter, hole spacing of 90 mm), 0.3% (5 mm diameter, hole spacing of 60 mm), and 1.7% (5 mm diameter, hole spacing of 30 mm), respectively.

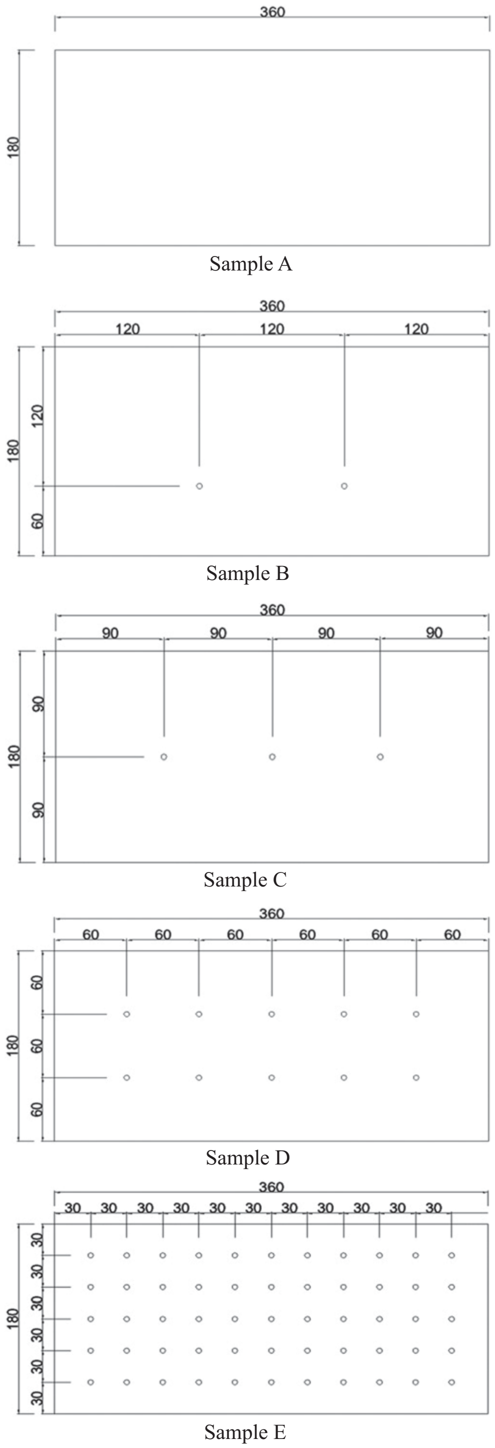


Figure 1. Schematics of Hinoki plywood with different perforation spacings.

Flame Retardant

We used a water-soluble phosphate flame retardant (WPFR) provided by Samwha Paints Industrial Co., Ltd (Seoul, Korea) for impregnation. The composition of WPFR includes ammonium phosphate polymer, guanylurea phosphate, phosphoric acid, and additives. WPFR has a resin content of 25%, a specific gravity of 1.13, and a pH of 7.6. To visually identify the flame retardant penetration into the plywood, we mixed WPFR and water-soluble blue ink in a 30:1 ratio.

Impregnation Process

We applied the four-step WPFR impregnation process model, as shown in Fig 2. In Step 1, the specimen was placed inside a cylinder and subjected to depressurization at −0.098 MPa for 5 min using a vacuum pump to remove any air trapped inside the specimen. In Step 2, the cylinder was filled with WPFR while maintaining the reduced pressure. In Step 3, the pump was activated to pressurize the cylinder to 1.5 MPa. The pressurization duration was 30, 60, or 90 min. Finally, the cylinder was depressurized for 5 min at −0.098 MPa.

Visual Inspection

After the impregnation process, the specimens were dried in a laboratory oven at 100°C for 12 h.

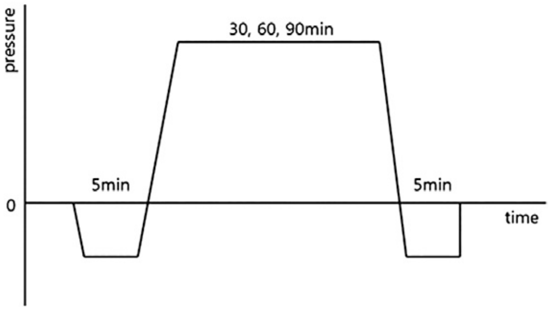


Figure 2. Water-soluble phosphate flame retardant impregnation.

The samples were cut through the center of the perforation to observe the surface.

Evaluation of WPFR Impregnation

We measured the mass of WPFR impregnation as the difference in weight of the specimen before and after impregnation (Eq 1) (Wang & Zhao 2022).

$$\text{WPFR impregnation}\left(\text{g/cm}^3\right) = \frac{M_\text{a} - M_\text{b}}{V} \quad (1)$$

where M_a is the mass of the specimen before impregnation (g), M_b is the mass of the specimen after impregnation (g), and V is the volume of the air-dried sample (cm^3).

Pearson correlation analysis was used to determine the influence of individual factors (impregnation time, perforation rate) on WPFR impregnation. In addition, we performed a multiple linear regression analysis to determine the combined effect of impregnation time and perforation rate on WPFR impregnation (Eq 2). This study used IBM SPSS Statistics 26 (Armonk, NY) for statistical analysis.

$$Y = \alpha_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad (2)$$

where Y is the WPFR impregnation, X_1 is the impregnation time, X_2 is the perforation rate, and ε is the residual (error term).

Combustion Test

A 45° angle combustion test was performed to evaluate the flammability of the samples (Nguyen et al 2012). The combustion test apparatus utilized a McClelland burner (SJTK-008-B, Sejin, Korea). The plywood panels were installed at a 45-degree angle, and the burner flame length was set to 65 mm for 2 min (KFIA 2017). Subsequently, the carbonized length and area of plywood were measured. This test was conducted on untreated plywood, Sample A, and Sample E.

RESULTS AND DISCUSSION

Visual Inspection

Figure 3 presents cross-sectional views of impregnated Hinoki plywood samples with varying impregnation rates and times. Overall, higher perforation frequencies and longer impregnation times result in improved penetration of the chemical solution.

Effect of Hole Spacing on Impregnation

Figure 4 provides the impregnation results for the perforated Hinoki plywood for different impregnation times and perforation rates. In nonperforated plywood (Sample A), the WPFR impregnation mass was 0.37 ± 0.01 g/cm^3 (± is standard deviation) after an impregnation time of 30 min. However, for the 1.7% perforated plywood (Sample E), the WPFR impregnation mass was 0.46 ± 0.01, indicating an approximately 1.2-fold increase in impregnation mass compared with the nonperforated condition. This difference was statistically significant ($p < 0.01$) based on Tukey's test using ANOVA.

For Sample A, the 60-min impregnation mass was 0.53 ± 0.01 g/cm^3, and the 90-min impregnation mass was 0.63 ± 0.01 g/cm^3. When perforated by 1.7%, the WPFR impregnation mass was improved by about 1.2 times compared with no perforation ($p < 0.01$). Further, after an impregnation time of 90 min, the impregnation mass of

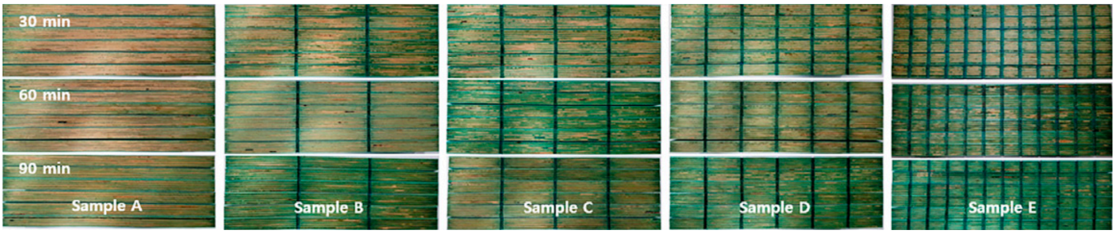
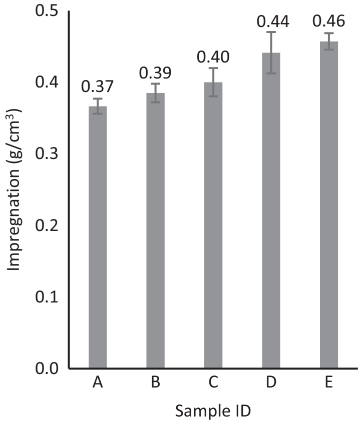
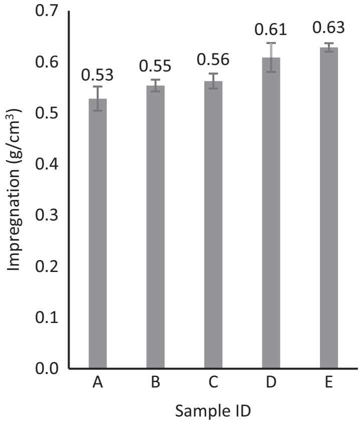


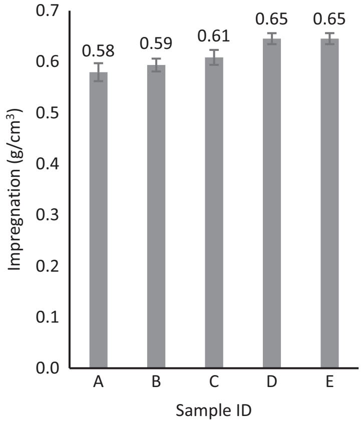
Figure 3. Photographs of impregnated Hinoki plywood with different perforation rates and impregnation times.



(a) 30 min



(b) 60 min



(c) 90 min

Figure 4. Impregnation-time- and perforation-rate-dependence of WPFR impregnation of perforated Hinoki plywood. (a) 30 min, (b) 60min, (c) 90 min.

Table 1. Pearson's coefficient correlation analysis.

	Impregnation time	Perforation rate
Impregnation mass	0.868[a]	0.261[a]

[a] Significant difference at the 1% level ($n = 90$).

Sample A was 1.1 times higher than that of Sample E. Consequently, perforations in the plywood contributed to enhancement in impregnation.

Table 1 presents the results of Pearson's coefficient correlation analysis that examined the effects of impregnation time and perforation rate on WPFR impregnation mass. Impregnation time was positively correlated to impregnation mass, as was perforation rate. The correlation coefficients between all coefficients were statistically significant at the 1% level. The absolute value of the correlation coefficient was greater for impregnation time than for perforation rate. Thus, it can be inferred that impregnation time has a more substantial impact on WPFR impregnation mass than does perforation rate.

Table 2 displays the results of the multiple linear regression analysis. Impregnation time (β_1) was positively significant at the 1% level, as was perforation rate (β_2). These results suggest that increases in impregnation time and perforation rate increase WPFR impregnation mass. All F-values were significant at the 1% level, indicating a good fit for the estimated regression results. The adjusted R^2 was 81.8%, indicating the high explanatory power of the regression model.

Table 2. Multiple linear regression analysis.

	$Y = \alpha_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$			
Variables	Coefficient	Standard coefficient	t-stat.	VIF
Intercept	0.312	—	26.306	—
X_1	0.003	0.868	19.203[a]	1.000
X_2	0.039	0.262	5.784[a]	1.000
Adjusted R^2		81.8%		
F-value		201.096		
p-value		<0.001		

[a] Significance at the 1% level ($n = 90$).

Y, impregnation mass; X_1, impregnation time; X_2, perforation ratio; ε, residuals (error term); VIF, variance inflation factors.

Standardized Pearson's coefficient values were used for each estimate, ensuring a uniform unit of measurement. These coefficients allow assessment of the relative significance of each independent variable, even in situations involving diverse units of measurement (Sreejesh et al 2014). Therefore, the standardized coefficient can identify which independent variable has the greatest influence on the dependent variable in a multiple regression model. In this multiple linear regression analysis, the standard coefficients were 0.868 for impregnation time and 0.262 for perforation rate. As the absolute value of the coefficient was greater for impregnation, impregnation time had a larger effect on improving impregnation mass than does the perforation rate. All variance inflation factors were less than 10, suggesting that multicollinearity is not significant (Jang et al 2020; Jang & Kang 2021).

Combustion Test

Figure 5 shows photographs of the samples after the 45° angle combustion test. According to the flame retardant performance standards of boards in Korea, the average carbonized area of untreated plywood must be less than 50 cm (KFIA 2017) under these tests. The carbonized area of untreated plywood was 56.30 cm^3, which fell short of this standard. However, the carbonized area of Sample A was 22.7 cm^3, which met the standard. Further, the carbonized area of Sample E was 19.1 cm^3, which shows approximately 15% better flame retardant performance than Sample A.

The level of flame retardant impregnation was related to longer impregnation time, which is consistent with previous studies (Jang & Kang 2023b, 2023a). Additionally, impregnation increased when the spacing between holes was narrower. The permeability of wood can be more accurately measured in a cross-sectional sample compared with radial and tangential sections. The perforation of plywood increases not only the overall specific surface area of the plywood but also the exposure of its cross section. It can be inferred that a higher perforation rate, resulting in high permeability, leads to a more pronounced impregnation effect. In addition, the high impregnation effect contributed to the improvement in flame retardant performance.

A limitation of this study was that the perforation rate was applied only up to 1.7%. In future research, we plan to evaluate impregnation by increasing the perforation rate as much as possible until there is no significant change in the physical properties of the plywood.

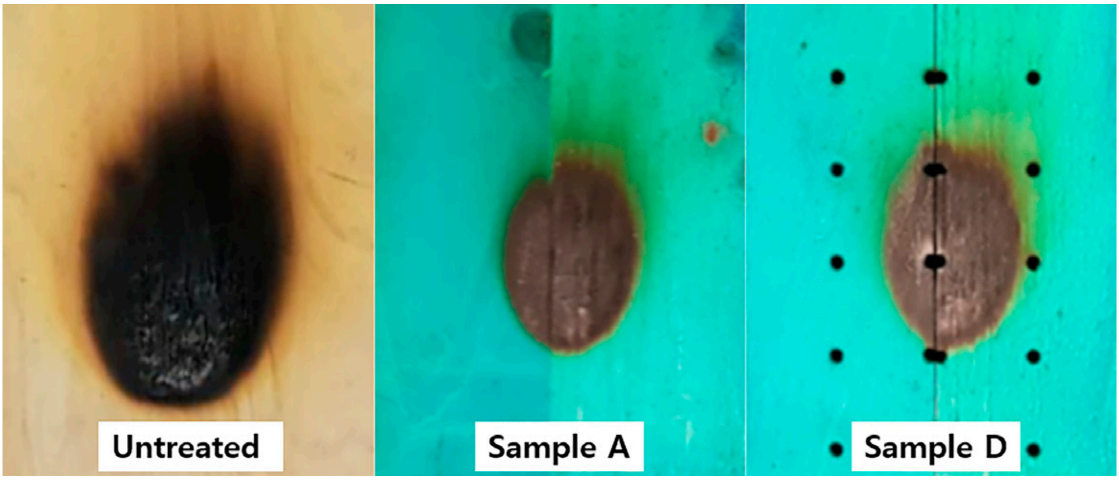


Figure 5. Photographs of samples after the 45° angle flammability test.

CONCLUSIONS

This study aimed to assess the impregnation of WPFR in perforated Hinoki plywood. Pearson correlation analysis revealed that perforation frequency and impregnation time had significant effects on WPFR impregnation. Furthermore, multiple linear regression analysis confirmed the significant positive influence of both variables on WPFR impregnation. Notably, in this study, impregnation time exhibited a greater impact on WPFR compared with perforation frequency. Depending on the impregnation capability, the flame retardant performance also improved. In future research, we intend to increase the perforation rate beyond 1.7% to examine whether the effect of the perforation rate on impregnation can be further enhanced.

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