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AIR PERMEABILITY OF THERMALLY MODIFIED HEMLOCK WOOD

PLINSKA PERMEABILNOST TERMIČNO MODIFICIRANEGA LESA ZAHODNE ČUGE

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Abstract / Izvleček

Abstract: Western hemlock (*Tsuga heterophylla*) is a prevalent coastal species in British Columbia (BC). Its wood has a high potential for thermal modification, a process that can affect numerous physical properties, including air permeability. The current study investigates the longitudinal air permeability of hemlock wood modified at three temperature levels, 170 °C, 212 °C, and 230 °C, and a two-hour treatment length. Permeability values obtained using Darcy's law and the water-falling volume displacement method were positively correlated with treatment temperature up to 212 °C, after which the permeability decreased slightly. ANOVA followed by the Duncan test revealed that thermal treatment at 212 °C and 230 °C significantly increased air permeability, whereas it was insignificant at 170 °C.

Keywords: wood, thermal modification, western hemlock, longitudinal air permeability, specific permeability, temperature effect

Izvleček: Zahodna čuga (*Tsuga heterophylla*) je prevladujoča obalna vrsta v Britanski Kolumbiji (BC) z velikim potencialom za termično modifikacijo lesa, ki lahko vpliva na številne fizikalne lastnosti, vključno s plinsko permeabilnostjo. Ta študija preučuje vzdolžno plinsko permeabilnost lesa čuge, termično modificiranega pri treh temperaturah, 170 °C, 212 °C in 230 °C, ter 2-urni obdelavi. Vrednosti plinske permeabilnosti, določene iz Darcyjevega zakona z metodo izpodrivanja prostornine vode, so bile pozitivno povezane s temperaturo obdelave do 212 °C, nato pa se je permeabilnost nekoliko zmanjšala. Analiza variance (ANOVA) skupaj z Duncanovim testom mnogoterih primerjav sta pokazala, da je termična obdelava pri 212 °C in 230 °C znatno povečala plinsko permeabilnost, medtem ko so bile spremembe pri 170 °C neznačilne.

Ključne besede: termična modifikacija, zahodna čuga = *Tsuga heterophylla*, vzdolžna plinska permeabilnost, specifična permeabilnost, vpliv temperature

1 INTRODUCTION

1 UVOD

The increasing demand for sustainable construction materials calls for improved wood performance, including UV-stability, fire resistance, and anti-fungal properties, because future bio-economies rely on renewable biomaterials to design and manufacture new products. Wood as a raw material has a wide variety of applications, such as furniture, construction, many objects, and toolmaking. However, wood has several shortcomings that restrict its application. For example, it can easily absorb water (moisture), resulting in dimensional instability, checking, and biodegradation by wood-destroying organisms such as fungi and insects (Bahmani et al., 2016; Bahmani & Schmidt, 2018). Researchers have developed different chemical methods such as acetylation (Hill et al., 1999) and salinization (Donath et al., 2006) to reduce wood's hydrophobicity and hygroscopicity, and thus improve dimensional stability. Thermal modification is a non-chemical method of decreasing hygroscopicity with an increasing market acceptance that improves specific properties and results in a material that does not pose an environmental hazard compared to chemically treated wood. Thermally modified wood

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has various applications in furniture construction, flooring, sauna/bathroom furnishings, doors, and cladding (Hill, 2006).

Permeability is a critical wood property because it directly affects drying (Perre, 2007; Rahimi et al., 2019; Rahimi et al., 2022) and impregnation with fluids (Mansouryar et al., 2010; Chu et al., 2019a; Chu et al., 2019b; Dong et al., 2020). It is worth evaluating the permeability of thermally modified wood because different levels of permeability are desired based on the application of the modified wood. For example, cladding requires low permeability, whereas post-treatment with fluid fire retardants requires high permeability.

Yuan (1994) reported increased air permeability in eucalyptus that was heat-treated at 140 °C for 5 hours. A study by Kang et al. (2018) revealed that air permeability increased after the heat treatment of malas (*Homalium foetidum*) at 190 °C for 3 hours. Taghiyari and Malek (2014) reported that heat treatment affected air permeability. At temperatures below 60 °C, permeability increased due to bound water reduction and shrinkage. Hermawan et al. (2020) investigated the effects of drying temperatures on preservative retention and penetration of some Malaysian fast-growing species timbers. The results demonstrated that high-temperature drying has a positive impact on preservative penetration. However, other studies revealed no effect of temperature on permeability. Rhatigan et al. (2003) reported no differences in air permeability between lumber dried at conventional and high temperatures. Other studies revealed that heat treatment did not change the permeability of *Populus robusta* (Rousset et al., 2004) or subalpine fir (*Abies lasiocarpa*) (Poonia et al., 2015).

Although thermal modification is a well-developed industrial process in Europe, it is still in its infancy in Canada. Therefore, establishing that such a method adds value to local wood species may lead to the development of new products and markets. Western hemlock (*Tsuga heterophylla*) forms extensive forests along the coastal mountains of the North American Pacific Northwest, and its wood is light in colour and typically resin-free, but the heartwood routinely contains wet pockets and extractives (Ward & Pong, 1980). Its attributes, such as high-quality machinability, smooth sanding, easy gluing, and high nail and screw holding, make it suitable for plywood, roof decking, and general construction (Alden, 1995).

This work hypothesizes that thermal treatment significantly increases permeability in western hemlock, and the treatment temperatures are positively correlated with permeability (Nourian & Avramidis, 2021). As such, the objective here is to evaluate the effects of thermal modification under three temperatures on hemlock air permeability.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE

Two hundred permeability samples of 70 mm × 13 mm × 13 mm in the longitudinal, radial, and tangential directions were cut from second-growth western hemlock lumber that was commercially thermally modified in a past study (Nourian & Avramidis, 2021). Thermal modification was carried out at 170 °C, 212 °C, and 230 °C, with a holding time of 2 hours in a Jartek industrial heat treatment chamber at Scottywood Corporation in Squamish, BC, Canada.

The superficial air permeability (*kg,* m^3 (gas)/m Pa s) of the specimens was measured by the falling-water volume displacement method using an apparatus similar to that described by Siau (1995). The specific permeability (*K*, m^3/m) was thereafter calculated by multiplying *kg* by the air viscosity of $1.81 \cdot 10^{-5}$ Pa s.

Analysis of variance (ANOVA) followed by the Duncan test to determine the significance of the differences between the air permeability of samples in four different groups was performed with the *K* dataset.

3 RESULTS AND DISCUSSION
3 REZULTATI IN DISKUSIJA

Table 1 lists the *K*-values for the four sample groups. The average ± standard deviation in the controls was $0.72 \times 10^{-11} \pm 0.59 \times 10^{-11}$ and $1.00 \times 10^{-11} \pm 1.01 \times 10^{-11}$ for 170 °C. The average specific permeability values for the samples treated at 212 °C to 230 °C were $1.26 \times 10^{-11} \pm 1.01 \times 10^{-11}$ and $1.21 \times 10^{-11} \pm 0.78 \times 10^{-11}$, respectively. After heat treatment at 212 °C, the permeability was 1.75 times greater than the controls. This finding accords with Lin and Kozlik (1971) and Rhatigan et al. (2003) for

Table 1. Central tendency and dispersion for the specific permeability.
Preglednica 1. Osrednja tendenca in razpršenost za specifično permeabilnost.

Statistical parameter	Specific permeability at different thermal treatment levels			
	Control	170 °C	212 °C	230 °C
Measures of central tendency				
Mean ($m^3 \cdot m^{-1} \cdot$)	0.72×10^{-11}	1.00×10^{-11}	1.26×10^{-11}	1.21×10^{-11}
Median ($m^3 \cdot m^{-1} \cdot$)	0.58×10^{-11}	0.70×10^{-11}	0.93×10^{-11}	1.13×10^{-11}
Measures of dispersion				
Standard deviation ($m^3 \cdot m^{-1}$)	0.59×10^{-11}	1.01×10^{-11}	1.01×10^{-11}	0.78×10^{-11}
Coefficient of variation (%)	81.85	101.31	80.09	64.62
Range ($m^3 \cdot m^{-1}$)	2.86×10^{-11}	5.21×10^{-11}	4.80×10^{-11}	3.82×10^{-11}

eastern hemlock, where permeability increased with increasing temperature.

Measures of dispersion (standard deviation, coefficient of variation, and range) indicated a high variation of air permeability within each treatment group. The high variation in the permeability in each group is possibly related to anatomical differences, namely differences in the sapwood and heartwood content in specimens. Table 2 summarizes the ANOVA results of the different temperatures on the permeability of hemlock wood. The effect of different temperatures on the permeability of the samples was statistically significant ($P \leq 0.05$). According to Duncan's test, thermal treatment at 170 °C increased air permeability insignificantly compared to the controls, while thermal treatment at 212 °C and 230 °C significantly increased air permeability. In addition, the air permeability in modified wood showed insignificant changes among the three thermally treated groups.

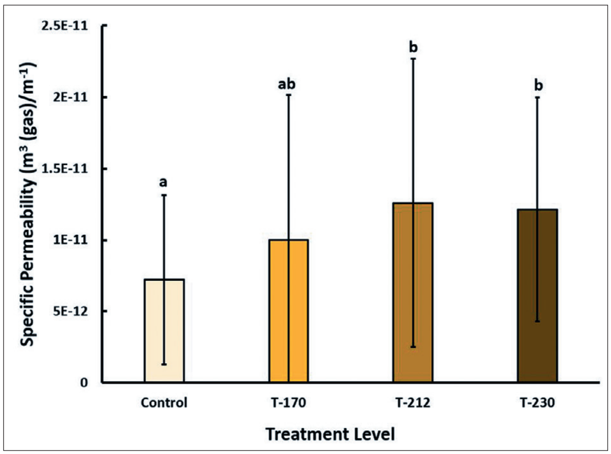

Figure 1 shows a direct relation between permeability and treatment levels until 212 °C. According to several studies, treatment temperature and air permeability are positively correlated (Hermawan et al., 2020; Kang et al., 2018; Yuan, 1994). The one-way ANOVA tests revealed an insignificant difference in permeability values between samples treated at 212 °C to 230 °C, although specific permeability for T–212 °C was slightly higher.

Table 2. Analysis of variance results for the specific permeability.
Preglednica 2. Rezultati analize variance za specifično permeabilnost.

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	0.000	3	0.000	3.985	0.009*
Within groups	0.000	196	0.000		
Total	0.000	199			

*Significant at 95%

Figure 1. Mean and standard deviation for specific permeability in untreated and thermally treated western hemlock. The histograms show the mean, and the whiskers represent the standard deviation. Different letters above the whiskers (a or b or ab) indicate statistically significant differences between groups in the Duncan test.
Slika 1. Povprečje in standardni odklon specifične permeabilnosti za neobdelan in termično obdelan les zahodne čuge. Histogrami prikazujejo povprečje, ročaji pa standardni odklon. Različne črke (a, b ali ab) označujejo statistično značilne razlike med skupinami po Duncanovem testu.

Bordered pits affect wood permeability considerably, and thermal treatment can change or restructure these. In addition, extractives may obstruct the pit membranes, which hinders fluid flow through the wood elements (components). The process of thermal modification also alters the extractives and redistributes them such that they may be deposited on the cell walls and pits (Esteves & Pereira, 2009). Overall, the findings of this study indicate that permeability reaches its maximum at 212 °C. Further research is required to reveal the possible effects of temperature on wood permeability above 230 °C.

4 CONCLUSION
4 ZAKLJUČKI

This project investigated the influence of three different temperatures, namely 170 °C, 212 °C, and 230 °C, on the specific permeability of western hemlock wood. The findings revealed that by increasing the temperature the permeability of the hemlock wood samples increased, where there was a significant difference between the samples heated above 170 °C and the control ones. Moreover, the permeability of the samples heat-treated at 212 °C was 1.75 times greater than that of the control samples. Overall, the findings of this study suggest that thermal modification is potentially an effective method for increasing the permeability of hemlock wood. It is worth mentioning that permeability is strongly affected by anatomical properties, and thus future research should focus on the effects of thermal treatment on different regions of hemlock wood, such as juvenile wood vs. mature wood and sapwood vs. heartwood.

5 SUMMARY
5 POVZETEK

Les je znan kot vsestranska surovina, ki se lahko uporablja na različne načine. Vendar pa je uporaba lesa v nekaterih primerih lahko omejena zaradi njegovih specifičnih lastnosti, vključno s higroskopnostjo in dovzetnostjo za razkroj (Bahmani et al., 2016; Bahmani & Schmidt, 2018). Natančneje, obstajajo nekateri primeri uporabe lesa, pri katerih ima permeabilnost, ki se nanaša na enostavnost prehajanja tekočine skozi porozne materiale pod gradientom tlaka, ključno vlogo (Rahimi et al., 2011). Zato je pomembno oceniti permeabilnost, saj lahko to pomaga pri izdelavi boljših izdelkov za določene uporabe. V tej študiji je bila ocenjena plinska permeabilnost lesa zahodne čuge (*Tsuga heterophylla*, angleško hemlock) pri treh različnih temperaturah termične modifikacije.

Za to študijo je bilo zbranih 200 vzorcev lesa zahodne čuge, ki so bili razrezani na določene dimenzije. Vzorci so bili termično modificirani z industrijsko pripravo za termično modifikacijo Jartek. Glede na temperaturo, pri kateri so bili vzorci termično modificirani, so bile oblikovane štiri skupine: 170 °C, 212 °C, 230 °C in kontrolna skupina. Za določitev plinske permeabilnosti na podlagi poroznosti mikrostrukture lesa je bila uporabljena naprava na osnovi metode izpodrivanja prostornine vode, kot jo je opisal Siau (1995). Plinska permeabilnost vzorcev v štirih različnih skupinah je bila analizirana z ANOVA, ki ji je sledil Duncanov test za določitev značilnosti razlik.

Rezultati te študije so pokazali, da je plinska permeabilnost pozitivno povezana s temperaturo, saj se je permeabilnost vzorcev lesa zahodne čuge, segretih nad 170 °C, bistveno razlikovala od kontrolne. Na podlagi podrobnejšega opazovanja so vzorci, termično modificirani pri 212 °C, pokazali 1,75-kratno povečanje prepustnosti v primerjavi z nemodificiranimi.

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