Physical Properties of Silver Fir (*Abies alba* L.) Wood Cladding Modified by Traditional Japanese Charring Method

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Silver fir (*Abies alba* L.) wood samples were charred on one surface using an enhanced version of the traditional Japanese Yakisugi method. The 15 charred boards obtained from five charring chimneys were divided into three different zones and investigated for their physical properties. The density profile, water absorption after 24 h of water submersion, and Brinell hardness were analyzed. In general, the temperature-time regime, which causes inside surface carbonization, was more evident at the bottom than at the top of the chimney. The density profile of the specimens revealed that the surface charring treatment decreased the surface density of the wood significantly. A gradient was visible from 383 kg/m² at the bottom to 424 kg/m² at the top. Water absorption measurements showed that a thicker carbonized layer could take up more water as a result of increased porosity. While 3,684 g/m² were absorbed at the bottom, the top accounted for only 2,533 g/m². Furthermore, with increasing thickness of the charred layer, the hardness gradually decreased. The average of the charred specimens reached only 3.2% of the hardness of the uncharred back side of the specimens.

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Keywords: Wood charring; Wood cladding; Surface charring; Thermal degradation; Yakisugi method; Wood modification

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INTRODUCTION

The number of residential and industrial wooden buildings is increasing. In addition to a positive CO_2 footprint, wooden constructions offer a comfortable living environment, which drives not only private builders but also public clients to choose to make buildings of wood (Wolf *et al.* 2020). Timber buildings need to be protected against environmental influences. Claddings made of wood could do this job. Durability, design, and maintenance intervals play a significant role in making this a good choice, as does the cost (Schober *et al.* 2010; Kymäläinen *et al.* 2020). Today there is strong demand for environmentally friendly and sustainable treatment processes for wooden cladding (Hill 2006; Sandberg *et al.* 2017). In Europe and the USA, surface-charred façades with a rich, deep black color (Miller 2016; Hasburgh *et al*. 2021) are becoming increasingly established and used by architects and designers for modern houses. Customers seeking a modern style of architecture find that this type of wood surface treatment appears natural and is visually appealing. Even though the surface charred boards are commonly advertised as long-

lasting and maintenance-free, the scientific evidence for this is still very limited (Ebner *et al.* 2021). One way of approaching this demand is a method that has been used in Japan for centuries, *i.e.*, the traditional charring technique, Yakisugi method. Timber boards are charred on one surface by fixing three planks together to create a triangular prism that performs as a chimney (Ebner *et al*. 2021, 2022).

Yakisugi uses the high temperatures created during wood burning to modify the surfaces. Hemicellulose is the first wood component to undergo thermal decomposition. The temperature at which reactions starts depends on the heating rate, species, density, and moisture content (MC). The literature (Beall and Eickner 1970; Friquin 2011; Lowden and Hull 2013; Bartlett *et al*. 2015) reports a wide range from 120 to 300 °C for hemicellulose degradation. Cellulose starts to decompose at 240 to 400 °C. Lignin pyrolyzes at 280 to 500 °C. At 400 to 450 °C, lignin yields more char than cellulose – approximately half of the lignin remains as char. Softwoods have more lignin, which results in a higher char yield. At 300 to 500 °C, exothermic reactions increase the temperature rapidly. This results in residual char, which is less easily volatilized than the native wood (Bartlett *et al.* 2018).

In the Yakisugi carbonization process high temperatures are reached in a short time. Kymäläinen *et al*. (2022) suggest that, to produce a weather-resistant façade, temperatures higher than 320 °C may be needed. This study deals with temperatures much higher than this. However, the temperature cannot be precisely controlled and as a result the boards build up a thicker carbon layer at the bottom of the chimney. This not only has to do with the manufacturing method, heating rate, and temperature, but is also affected by MC, density, and wood species (Ebner *et al*. 2021, 2022). Charred surfaces have already been tested in various studies for their physical and mechanical properties (Gosselink *et al*. 2004; Čermák *et al*. 2019; Kymäläinen *et al*. 2020; Šeda *et al*. 2021). A parameter for these properties is the density of the remaining uncharred wood after the charring process. Šeda *et al*. (2021) report that one-sided charred beech wood decreases in density according to the time-temperature process by 15% to 33%. These investigations were mostly carried out under laboratory conditions in which a controlled heat supply was possible to char well-chosen, clear samples.

In this work, the authors dealt with the following question: What do the results look like at different positions on a Yakisugi method charred board? Might different properties occur as a function of height in the chimney? With reference to previous results (Ebner *et al.* 2021, 2022), it was hypothesized by the authors that various properties such as density, water absorption, and hardness could be changed by a different char layer thickness. The level or amount of these differences, which are important for the practical use and lifespan of façade elements produced from charred wood, was sought to be revealed by the aim of this study. The objective of this study is to unveil the extent of these differences, which hold significance for the practical application and longevity of façade elements crafted from charred wood.

EXPERIMENTAL

Material and Methods

The authors studied silver fir (*Abies alba* L.) wood from an Upper Austrian lumber mill (Holz Reisecker, Roßbach, Austria), grading the plain sawn boards of dimensions 24 × 170 × 4,000 mm^3 Class III or IV according to Austrian standards. First, the boards were dried, and then the surface charring was carried out according to the method reported by

Ebner *et al.* (2022), utilizing the traditional Yakisugi method enhanced with gas. The charring process was performed outdoors in winter conditions, *i.e.*, at -1 to +4 °C. In total, 15 boards were charred using five chimneys (triangular prism). The authors investigated one board from each chimney (Fig. 1A) for density profile, water absorption, and Brinell hardness.

Moisture Content before Charring

The authors determined MC of the samples using a dielectric sensor and high frequency device (Hydromette Compact A, GANN, Gerlingen, Germany) immediately before the charring process. The measurement was taken at Positions 1 (bottom), 2 (center) and 3 (top) as shown in Fig. 1A. The average MC obtained was 24%.

Oven-dry Density

Oven-dry density of the wood planks was evaluated according to EN 322 (1993) standard on material cut from an overlength portion of the boards (Fig. 1B) before charring. The samples were conditioned at 20 °C and 65% relative humidity in a climate chamber (Model FD115, Binder, Tuttlingen, Germany), and then weighed. Three samples were taken from each board. The average density was 488 kg/m³.

Wood Charring

The authors tied three boards together using wet ropes to create a triangular prism and form a chimney.

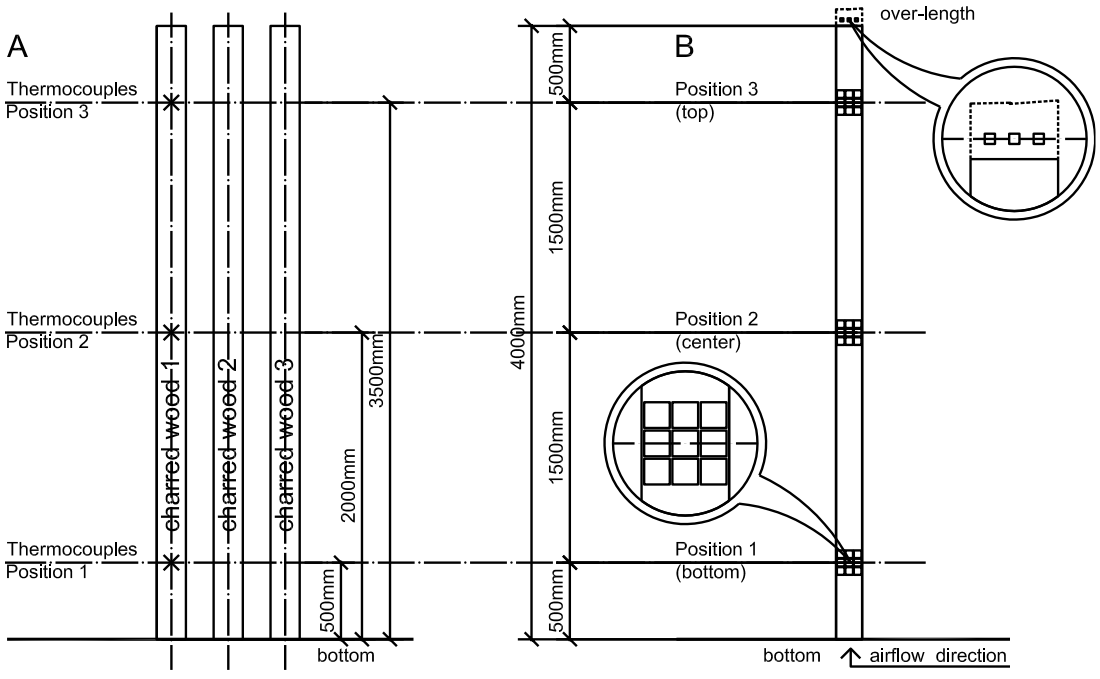

Fig. 1. Position of thermocouples at three heights in the wood chimney (A) and positions for samples after charring 1 to 3 (Thickness measurement, density profile, water absorption and Brinell hardness, and the over-length location for the samples as references (B)

Unlike the traditional Japanese technique (Ebner *et al*. 2021), in which a ball of newspaper filled with wood chips generates the starting energy, a conventional gas burner was used (RoMaxi, Rothenberger Industrial, Kelkheim, Germany) for this purpose (Ebner

et al. 2022). The temperature inside the chimney rose to inflame the wood boards when the MC was reduced to 0%. The wood started to burn on the inner side of the chimney at the bottom area (close to the gas burner head) first and then the fire rose to the top. Due to the varying MC, the specified burning time of 180 s was adjusted by +- 20 s to achieve similar char layer thicknesses. After 160 to 200 s the chimney was flipped to the ground and the ropes removed, at which point the charring process stopped immediately.

Temperature and Time Measurements

During the charring process, the temperature inside the chimney was monitored by placing three NiCr-Ni thermocouples (Type K) in one of the three boards in 8-mm holes drilled perpendicular to the surface. The thermocouples were located on the mid-line of the samples at heights of 500; 2,000; and 3,500 mm, measured from the bottom of the chimney, as depicted in Fig. 1A. The measuring method corresponds to the sequence previously used in studies published by Ebner *et al*. (2021 and 2022).

Thickness Measurement of the Samples Charred Layer

The measurement of the charred layer thickness was conducted using a digital caliper known as Precise PS 7215 with an accuracy of 0.01 mm. This measurement was taken on a single board from each chimney, specifically at positions 1 to 3 on the board's mid-line, as depicted in Fig. 1B. The average thickness of the charred layer was determined to be 2.7 mm.

Density Profile of the Samples

The density profiles of the charred samples (50 × 50 mm² with vertical growth ring orientations towards the measuring direction) were determined using X-ray densitography (Dense-Lab X, Electronic Wood Systems, Hameln, Germany). One board from each of the 5 chimneys was examined. Nine samples each were examined at positions 1 to 3. The non-charred surfaces were aligned towards the measuring sensor. Measurements were taken every 0.05 mm throughout the sample thickness, starting at the uncharred surface. An average value from a 30-mm measuring range were determined. Figure 2 illustrates the systematics of the standing sample and the 30-mm measuring range for the determination of the density profile. Specimens with wood defects were excluded, such as dead, loose or tight knots, from the evaluation.

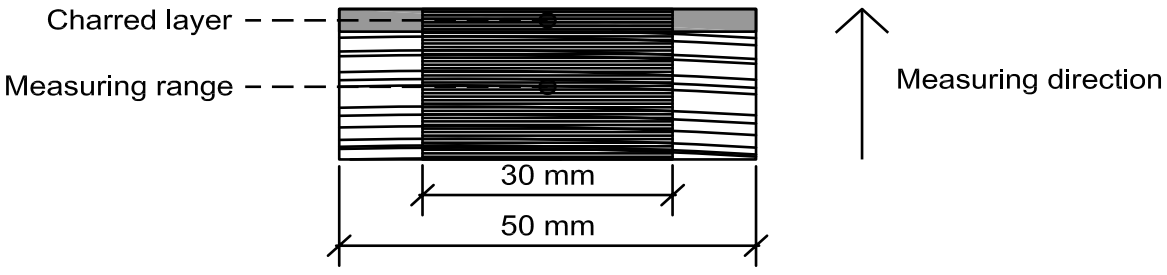

Fig. 2. Systematics of the measuring range and the measuring direction of the density profile measurement

Water Absorption of the Samples

One board was tested from each of the five chimneys. Untreated samples were cut from the over-length portion (Fig. 1B) and charred samples from positions 1 to 3 (Fig. 1B)

into pieces of dimensions 50 mm × 50 mm (tangential × longitudinal). Of the untreated samples, three were sealed on the radially cut sides and back side (Fig. 3B) and three were tested without sealing (Fig. 3A). Of the charred specimens at positions 1 to 3, three each were sealed on the radially cut sides and back side (Fig. 3D) and a further three specimens per position were tested unsealed (Fig. 3C). The samples were sealed with a transparent sealing compound, 20% elastic (Allseits Kleben and Verfugen, transparent, Meinl, Austria). After conditioning to 65% relative humidity (RH) at 20 °C, the samples were weighed, placed in water according to EN 317 (1993) standard and weighed again after 24 h. Before weighing, the surface was slightly dried with a paper tissue.

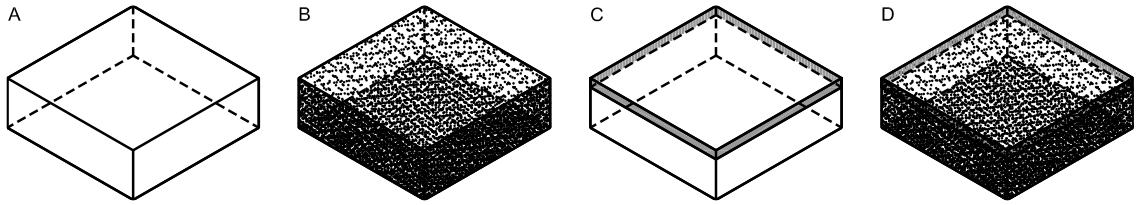

Fig. 3. Samples (50 mm × 50 mm) for water absorption after 24 h: Untreated, unsealed (A), untreated, sealed (B), charred - unsealed (C), and charred - sealed (D)

Brinell Hardness of the Samples

The Brinell hardness test was completed according to EN 1534 (2020) standard using the depth method. A Test Automatic M4U 075 (EMCO, Hallein- Taxach, Austria) was used to measure the charred side and the uncharred back side of each sample. One board was tested from each of the five chimneys at positions 1 to 3 (Fig. 1B), with nine samples from each position.

RESULTS AND DISCUSSION

At each position where samples were examined, temperature, time, and measurements of the charred layer thickness were determined (Table 1).

Table 1. Time, Temperature, Charred Layer Thickness, and Initial MC Results

	Chimney #1			Chimney #2			Chimney #3			Chimney #4			Chimney #5		
	Top	Cen.	Bot.	Top	Cen.	Bot.	Top	Cen.	Bot.	Top	Cen.	Bot.	Top	Cen.	Bot.
MC Before Charring (%)	23.0	21.9	20.3	26.0	35.0	27.6	22.2	20.5	20.5	20.9	16.8	17.2	21.9	19.8	17.7
Time (s) to reach > 400 °C	70	110	120	70	140	140	70	110	120	110	130	140	120	130	140
Aver. time (s) for > 400 °C	560	799	788	394	681	839	602	688	799	666	792	763	619	730	711
Max. temperature (°C)	641	952	872	522	877	962	709	795	995	770	954	855	796	910	810
Charred layer (mm)	2.0	3.3	3.7	1.3	2.0	3.3	2.0	2.3	3.2	2.3	2.3	3.3	2.0	2.7	4.7

Density Profile

Three average density profiles were determined using X-ray technology. Figure 4 shows the average value of positions 1 to 3 (Fig. 1B). The density of the tested fir wood

had an average value of 488 kg/m³ in the oven-dry state. All three density profile results were somewhat lower than the reference value. Position 3 (top) had on average the highest density of 433 kg/m³, whereas Position 2 (centre) was 405 kg/m³, and Position 1 (bottom) was 398 kg/m³. The loss of density ranges from 11.3% to 18.5% compared to the uncharred reference. Bartlett *et al*. (2018) report that, on heating, the constituent natural polymers present in timber degrade, producing inert and combustible gases, liquid tars, a solid carbonaceous char (typically around 20% the density of native wood (Friquin 2011)), and inorganic ash (Bartlett *et al*. 2019). However, those results may be partly attributed to measuring methodology, where not all tested specimens were necessarily at same MC level after charring process.

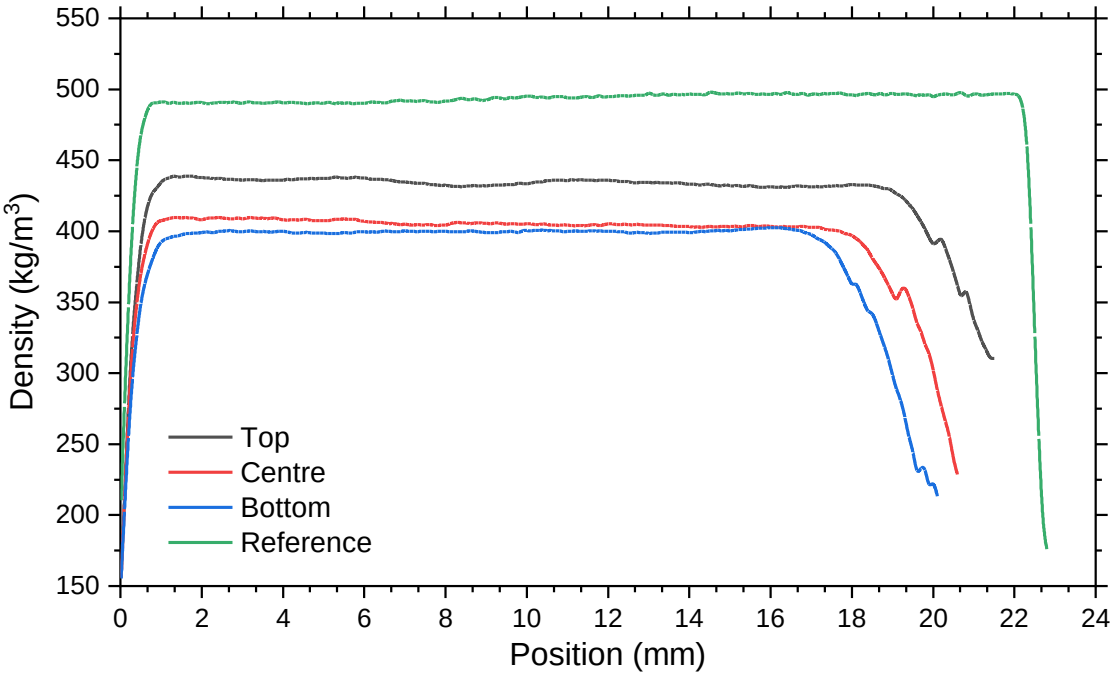

Fig. 4. Density profiles of charred specimen compared to the reference

After giving a steady density value through the uncharred wood the average density profile indicated a decreased trend. At position 1 (bottom), the value had a turning point at 16.50 mm and ended at 20.10 mm. This turning point marked the switch between uncharred wood and the char. The difference between this value was 3.6 mm, which is congruent with the average of the charred layer thickness measured (Fig. 5B). The position 2 (centre) turning point was at 17.75 mm and ended at 20.65 mm. The difference was 2.9 mm and the average char thickness was 2.5 mm. Position 3 (top) turned at 19.10 mm and ended at 21.50 mm with a difference of 2.4 mm, while the average char thickness was 1.9 mm (Fig. 5B). Positions 2 and 3 did not hit the value exactly as position 1 did. This may be related to the measurement of the carbon layer thickness, which was done in this study manually with a digital caliper that did not have the precision of the X-ray machine.

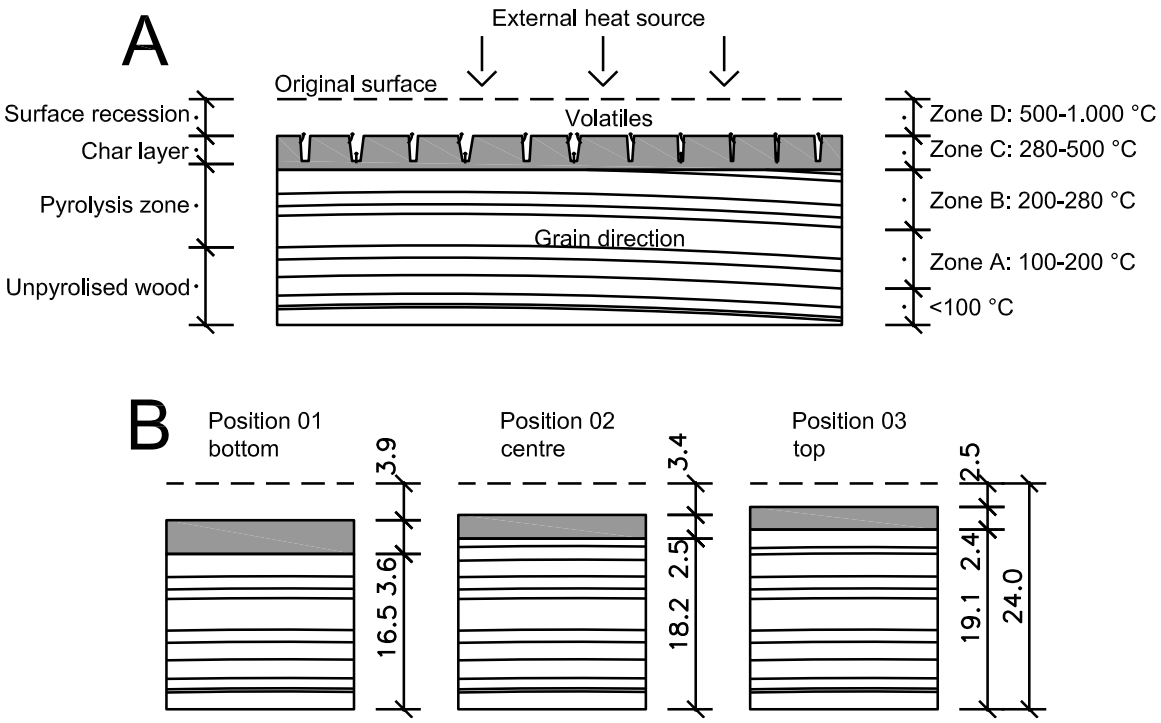

Fig. 5. Temperature zones in a wood cross-section exposed to fire (A); and cross section Positions 1 to 3 (B)

The plain sawn boards had a general thickness of approximately 24 mm before they were tied together to create a chimney (triangular prism in Fig. 1A) for the charring process. Afterwards, at position 1, the remaining total thickness (residual char + uncharred wood) was 21.50 mm, which was a reduction in thickness of 3.90 mm compared to the initial thickness. At position 2 the value was 3.35 mm and at position 3 it was 2.5 mm. To explain the reduction in density and the loss of wood thickness, Friquin (2011) summarizes descriptions of the combustion of wood by different authors (Browne 1958; Jönsson and Pettersson 1985; Carling 1990; Mikkola 1991; Parker 1992; White 2000; Buchanan and Abu 2001). Parallel to the exposed surface four characteristic zones can be distinguished (Fig. 5A):

Zone A: Temperatures lower than 200 °C: In this zone, temperatures are lower than 200 °C but higher than 100 °C. At this temperature, lignin, cellulose, and hemicelluloses start to decompose, which causes a reduction in density.

Zone B: Temperatures from 200 to 280 °C: This zone allows a still and slow pyrolysis. The gases released are non-combustible. According to Buchanan and Abu (2001), the heated layer is approximately 35 mm thick.

Zone C: Temperatures from 280 to 500 °C: At this stage the physical structure breaks down and forms char rapidly, which results in a reduction in density. The combustion takes place outside of the char layer, because the gases must mix with oxygen to ignite.

Zone D: Temperatures higher than 450 to 500 °C: At this zone, the production of volatiles is complete, but the charcoal continues to smolder and oxidize, which causes further mass loss. Looking at the uniform assumption of the density and considering Buchanan's (2001)

statement that Zone B is approximately 35 mm thick, it can be assumed that the board heats up so much that Zone A is unlikely to be present in this study.

Water Absorption after 24 h

In the sealed samples, where the water was only absorbed through the charred surface, the absorption was greatest in the lower area of the chimney (Position 1), and this decreased towards the top (Position 3). As displayed in Table 1, the lower areas had a higher temperature, resulting in a thicker layer of char (Stelzer 2017; Ebner *et al*. 2021; Ebner *et al*. 2022). This thicker layer allowed more water to be absorbed than thinner layers of char, as porosity of charred layer is significantly increases. There was a little more water absorption at position 1 – with an average of 3,684 g/m² – than at position 2 with 3,286 g/m², while position 3 gained only 2,533 g/m². For comparison, the untreated reference sample had an average water gain of 1,856 g/m². Roughly speaking, the water absorption doubled for each 2-mm increase in the carbon layer.

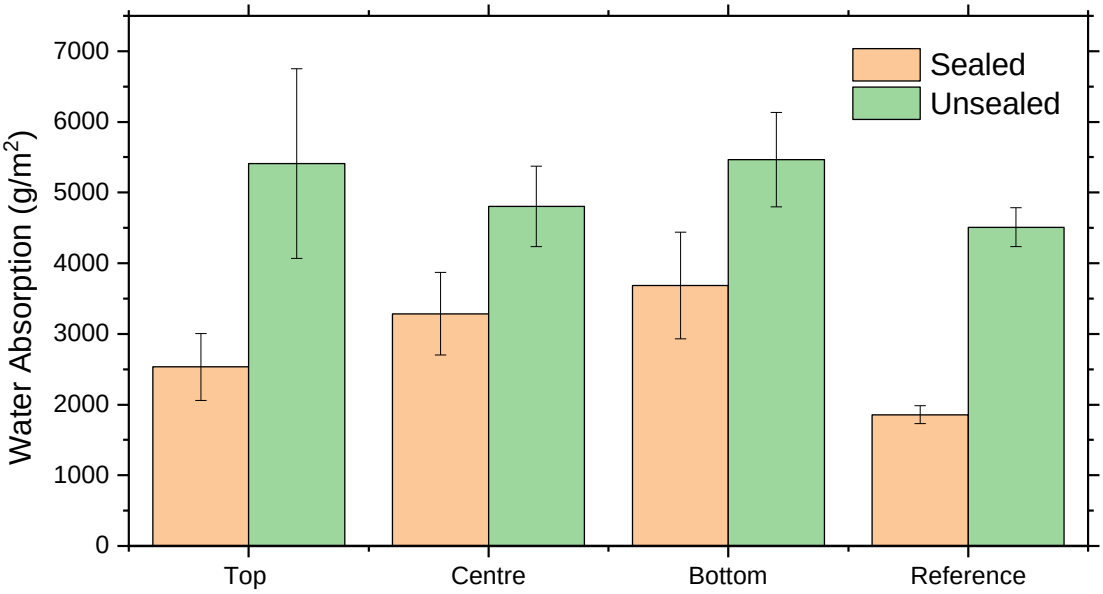

Fig. 6. Water absorption after 24 h (g/m²) of the sealed/unsealed samples at positions 1 to 3 and reference

While the sealed samples displayed water absorption increases from bottom to top and significant difference when compared to reference (Fig. 6), this was noticeably different with the unsealed samples. Unsealed samples had exposed end grain on two sides (cross section) and radial surface on the other two sides. The water absorption of unsealed charred samples ranged between 5,466 g/m² (position 1) and 5,412 g/m² (position 3), whereas reference samples had 4,508 g/m² water absorption. This can be mostly attributed to water absorption in the longitudinal direction, which is significantly higher when compared to the radial and tangential surface water absorption. The water absorption in the different anatomical directions is highly affected by wood permeability. The longitudinal permeability can be even 1,000 times greater than the transverse permeability in softwoods (Siau 1984; Skaar 1988; Candanedo and Derome 2005), and therefore the noticeable difference between charred and reference samples become to be negligible when end grain surfaces are unsealed.

Brinell Hardness

All tested samples showed that the Brinell hardness of the carbonized surface was lower than the uncharred back side of the samples. The average value of the charred surfaces was 0.296 N/mm², and the uncharred revealed 9.237 N/mm² (Table 2). Comparing the values at positions 1 to 3 (bottom to top) the values at position 3 (top) were higher than the values at position 1 (bottom). On the charred side, this was related to the thickness of the carbonized layer, which was thicker in the lower part (Stelzer 2017; Ebner *et al*. 2021; Ebner *et al*. 2022). The thicker the char layer, the more the surface was broken up during the charring process. This results in a brittle or fragile surface, where there were some extreme values in the measurement results. These 'harder' values result when the test ball hits a ditch directly or encounters wood defects such as dead, loose, or tight knots. These extreme values were not considered in the evaluation (marked as *).

Table 2. Brinell Hardness (N/mm²) at Positions 1 to 3

	Charred					Uncharred			
	Top	Centre	Bottom	Ave.		Top	Centre	Bottom	Ave.
Chimney #1	0.360	0.200	0.155			9.523	7.683	7.498	
Chimney #2	*0.952	0.286	0.250			10.814	8.618	8.140	
Chimney #3	0.450	0.259	*0.562			15.136	9.570	*18.071	
Chimney #4	0.466	*0.455	0.305			*21.835	*10.255	8.739	
Chimney #5	0.248	0.227	0.347			7.989	9.173	7.959	
Average	0.381	0.243	0.264	**0.296**		10.866	8.761	8.084	**9.237**

The non-charred back side showed a drop in hardness from top to bottom, just as on the charred front side. This can be explained by the decrease in density because of heat. The hotter and longer the charring process, the greater is the decrease in density, which results in a decrease in hardness.

CONCLUSIONS

1. Studying silver fir (*Abies alba* L.) wood charred on one surface revealed intriguing insights. The density profile analysis of the examined specimens unveiled a decrease in sample weight due to the surface-charring treatment. This reduction in density extended beyond the carbonized surface, affecting the entire cross-section of the samples.
2. Water absorption measurements demonstrated that a thicker carbonized layer exhibited higher water absorption capacity. Interestingly, the thickness of the charred layer directly correlated with its softness.
3. In general, it can be said that the physical properties measured alter from the bottom to the top of a burning chimney (triangular prism). The temperature-time process, which causes the inside surface carbonization, is stronger in the bottom area than in the top area of the chimney. At the bottom area, the density and the hardness decreased, and the surface could take up more water than in the top area.

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