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Effect of Weathering on Surface Functional Groups of Charred Norway Spruce Cladding Panels

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Abstract: Norway spruce cladding panels were surface charred with a prototype device utilizing a hot plate method. The panels were used to construct a test wall that was exposed to natural weathering for a period of two years. The changes in functional groups were evaluated with photoacoustic FTIR spectroscopy. The analysis revealed degradation of the thermally modified lignin component, indicating poor stability in weathering. Improvements in the prototype device process conditions, such as increased surface pressure and slower feed speed, and future research needs regarding surface charred wood are discussed.

Keywords: char; claddings; surface modification; weathering; wood

1. Introduction

For wooden claddings to retain optimal performance and maximal service life, they require coating and repetitive maintenance operations in the use phase. Wood degrades in outdoors conditions due to UV-radiation, rain, frost, and decay-causing organisms, which greatly affect the service life of structures. The moisture load causes dimensional changes and cracking, while the photodegradation from UV-radiation affects the lignin component that acts as an adhesive in the wood structure. Because of preferential lignin degradation, the surface is enriched with loosely bonded cellulose that washes off, resulting in a rough, uneven surface. A flaked and cracked coating allows moisture to penetrate and may lead to decay, and the eroded surface serves as a poor bonding base for finishing chemicals. Thus, other reconstructive measures are required before repainting, adding to the environmental and economic impacts. The coating type affects the durability of a cladding, but the exposure site and orientation of the wall have even higher impacts [1–3]. In northern conditions, wooden claddings need to be recoated every 2–15 years [4,5]. The paint and painting process have a relatively high environmental load and, in fact, longer painting intervals with resulting shorter service life of a façade may lower the overall environmental impacts [2].

The popularity of surface charred claddings is increasing fast. The material is seen as natural, organic, and aesthetic, and it is also marketed as long-lasting and maintenance-free option. The original Japanese method, yakisugi (also known as shou sugi ban in the West), is based on long tradition and the producers protect their manufacturing recipes carefully. Outside Japan, the demand has led to heterogeneous market formed by varying techniques and raw materials having little scientific background. An original yakisugi siding is said to last for up to several decades with little maintenance needs [6,7]. A material with a long service life and reduced maintenance requirements would lower the environmental impact of the building envelope during the building lifetime.

The IPCC [8] climate models predict that Northern regions will experience higher rainfall and more extreme weather conditions in the near future. This will increase the environmental loads of exterior structures and cause both technical and aesthetic problems as well as reduced service lives of traditional cladding solutions [9]. It is therefore important to find materials that improve the durability of façades and prolong the building service life while reducing the maintenance requirements. Wood surface charring is a relatively fast process implemented only on the outside of a board and used instead of coating. The char layer is hydrophobic and chemically stable making it presumably long-lasting and care-free option for wooden surfaces [10,11], but its factual weatherability has not been thoroughly reported. Charring is a harsh treatment where the wood components will be degraded and modified until only a char residue remains. It is speculated that the modified components, namely, the lignin, forming the char may resist photodegradation. It is well known that the sorption properties of wood char are altered in comparison to unmodified wood, which may further delay weathering. Regarding surface charred Norway spruce, Kymäläinen et al. [10,11] have reported decreased adsorption and wettability of samples manufactured using a hot plate. This paper studies the properties of surface charred wood in natural weathering in South-Eastern Finnish conditions, and reports the results based on changes in surface functional groups, measured with photoacoustic FTIR spectroscopy. The aim is to find out, whether the modified lignin component resists weathering, namely photodegradation. The paper also describes a prototype device for surface charring, where a modified hot plate method is utilized.

2. Materials and Methods

2.1. Material Preparation

Norway spruce (*Picea abies* (L.) Karst.) planks were sourced from Southern Finland. The planks were planed to 20 × 145 mm UTV profile with Weinig Unimat 260 Super molder (Weinig AG, Tauberbischofsheim, Germany). The UTV tongue-and-groove profile is one of the most common outdoor cladding profiles in single family houses and other small-scale buildings in Finland. The panel surfaces were charred with purpose-build prototype machine at the wood laboratory of South Eastern University of Applied Sciences (XAMK) in Mikkeli. The device has a heated plate on the bottom, and rollers on top to facilitate continuous board feed. The rollers generate a small surface pressure to keep the board as level as possible and to ensure contact between the wood and the hot plate. The boards were charred at 400–500 °C. The inverter was set between 3 and 7 Hz, where 3 Hz roughly corresponds to a process time of one minute. After modification, the samples were stored at 65% RH, 20 °C. Charred wood surface was examined with a light microscope (Olympus SZX10, Tokyo, Japan) to determine the thickness of the char and thermally modified transition layers.

2.2. Natural Weathering of Experimental Wall Structure

The experimental wall was constructed from the charred UTV-panels at the end of year 2017 (Figure 1), using horizontally laid boards in three directions. The front was positioned towards south. The process time (0.8–1.3 m/min) for front wall boards was generally longer than the process time used for the sides, i.e., the front wall boards had a slightly thicker char layer than those on the sides. The boards were charred at 400–520 °C. The boards on the left side were modified at a median temperature of 477 °C (range 430–510 °C), the front at 440 °C (range 400–520 °C) and the right at 480 °C (range 410–500 °C).

2.3. FTIR Spectroscopy

After two years of outside exposure, small samples were cut from two panels modified at app. 450 °C, which was considered as an average modification condition. Samples from the first panel had been stored inside at 20 °C, 65% RH while the other had been attached to a frame adjacent to the experimental wall, facing south. The surface shavings were oven-dried at 103 °C and subjected to photoacoustic Fourier infrared (PAS-FTIR) analysis (Bio-Rad FTS 6000 Spectrometer, Cambridge, MA, USA). A background spectrum of carbon black was run before analyzing the samples. Each measurement consisted of 400 scans for three replicates at a wavelength range of 4000–500 cm^{-1}. The data was processed with Win-IR Pro 3.4 software (Digilab, Randolph, MA, USA). The spectra were baseline corrected according to the spectra minima and normalization was to maximum absorbance at 1600 cm^{-1}. Difference spectrum was calculated between the sample stored inside and the sample attached to the wall to highlight changes caused by the weathering.

Figure 1. (**A**) The prototype charring device; (**B**) a charred spruce panel; (**C**) the experimental wall.

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3. Results

3.1. Microscopicalexamination of Surface Charred Spruce

The charring temperature of app. 450 °C and feed speed of 0.8–1.3 m/min produced a char layer with a thickness of 0.3–0.1 mm. The length of the hot plate was 0.5 m, leading to a modification time of 23–40 s depending on feed speed. Some flaming occurred, although this was not desired. There was a thermally modified transition layer (pyrolysis layer) extending to a depth of approximately 0.2–1 mm (including the char layer) (Figure 2). Differentiating the char layer from the pyrolysis layer, and the pyrolysis layer from the virgin wood, is subjective. Several measurements were made, but wood macro- and microstructure, as well as occurrence of flaming affect the thickness. Therefore, values presented are approximate.

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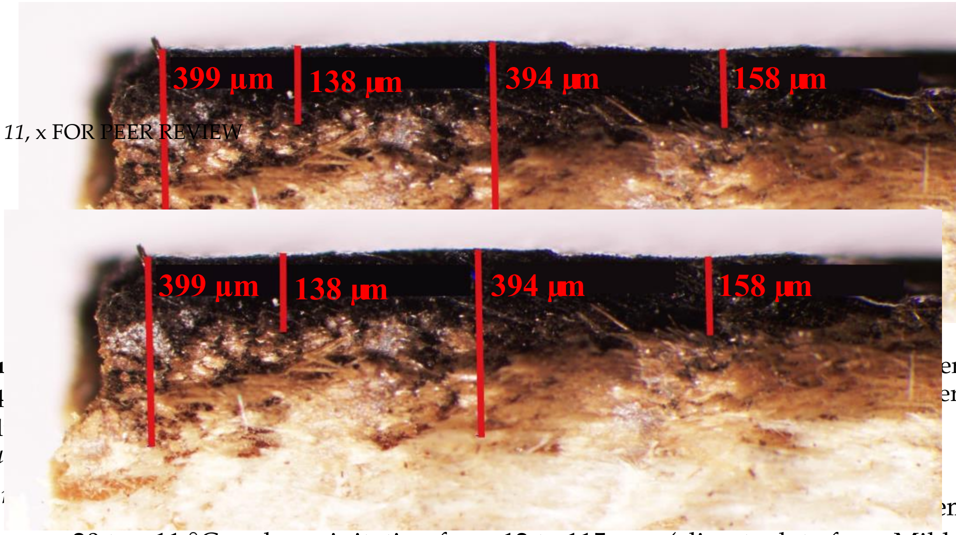

Figure 2. Microscope image example showing the approximate thickness of the char and thermally modified transition layers. Contrast enhanced to highlight char and transition layers.

3.2. Natural Weathering Experiment

The test wall was exposed to weathering for two years in 2017–2019. Monthly average temperatures ranged from +20 to −11 °C and precipitation from 12 to 115 mm (climate data from Mikkeli airport, Finnish Meteorological Institute; Figure 3). The wall was examined qualitatively after weathering. The char layer, evaluated by thickness, was mostly unaltered, but at places, pieces of the char had fallen off (Figure 4). The underlying wood had been revealed and turned to grey. The tongues of the panels had experienced most damage, clearly showing the importance of char layer thickness. Insufficient charring on these areas had subjected the surface to normal weathering of unmodified wood.

Changes in absorption can be detected in the OH and CH regions, where the weathered sample shows higher intensity, as well as in the characteristic lignin bands 1600–1100 cm^{-1} where the weathered sample shows decreased intensity. The changes are easily distinguishable in the difference spectrum, which was found a useful tool for comparison (Figure 6). The negative values depict new structures formed during weathering, while positive values show degraded structures. The difference spectrum shows newly formed structures between 3500 and 3000 cm^{-1}, and most noticeably at 1729 cm^{-1}.

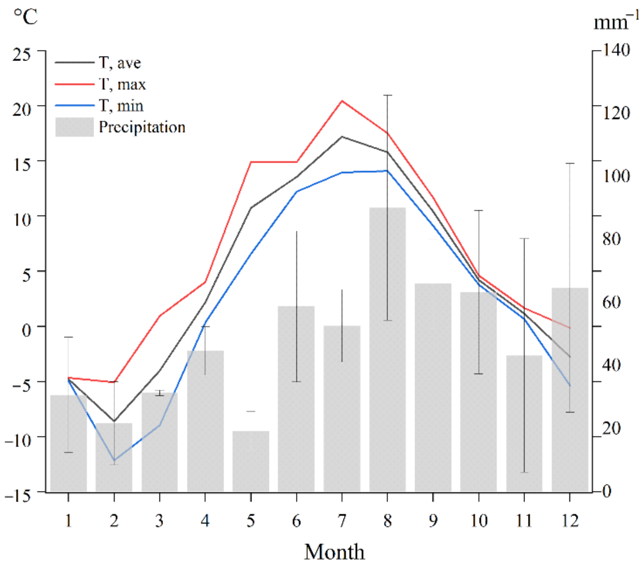

Figure 3. Climatic data (temperature and precipitation) from exposure site in 2017–2019.

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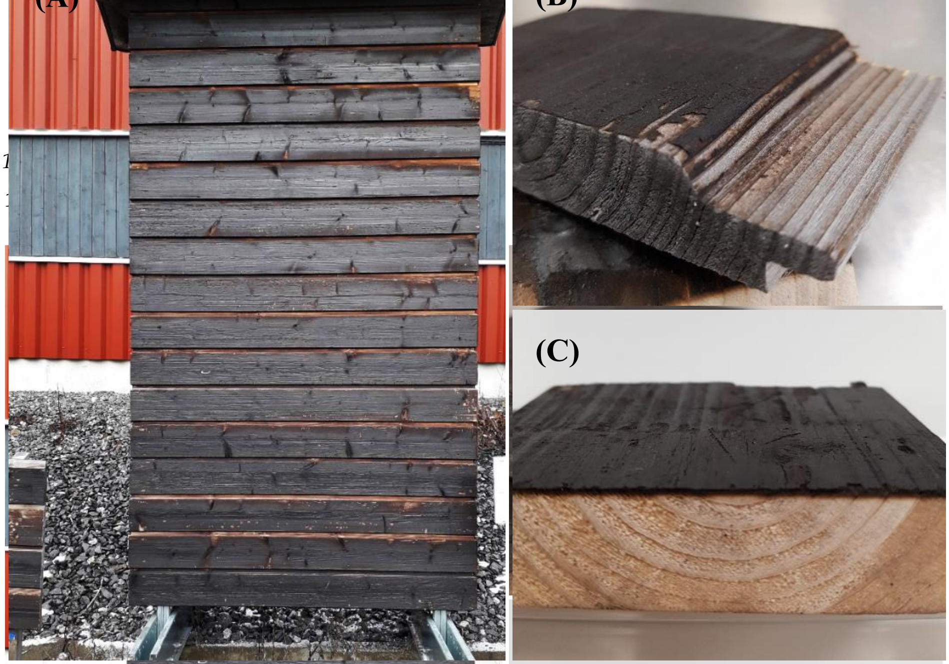

Figure 4. (**A**) The wall in January 2020, 2 years into weathering experiment. The examined panel is situated highest in the left corner; (**B**) detail of the tongue of the panel; (**C**) surface on a cut-out of the same panel showing intact, well-preserved char layer and underlying, unmodified wood.

The PAS-FTIR spectra of wood samples charred at 450 °C (one stored inside and one subjected to natural weathering) are shown in Figure 5. Changes in absorption can be detected in the OH and CH regions, where the weathered sample shows higher intensity, as well as in the characteristic lignin bands 1600–1100 cm^{-1} where the weathered sample shows decreased intensity. The changes are easily distinguishable in the difference spectrum, which was found a useful tool for comparison (Figure 6). The negative values depict new structures formed during weathering, while positive values show degraded structures. The difference spectrum shows newly formed structures between 3300 and 3000 cm^{-1}, and most noticeably at 1729 cm^{-1}.

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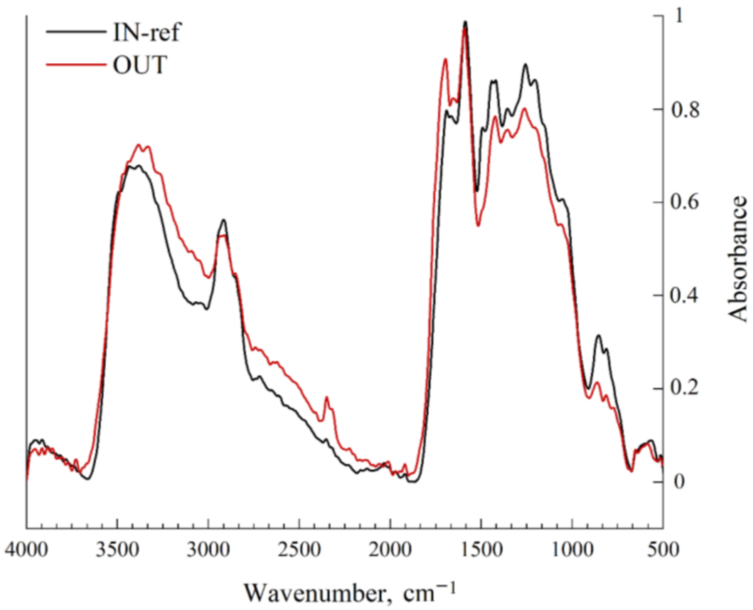

Figure 5. Photoacoustic Fourier infrared (PAS-FTIR) spectra of samples charred at 450 °C stored inside (IN-ref) and attached to the wall (OUT).

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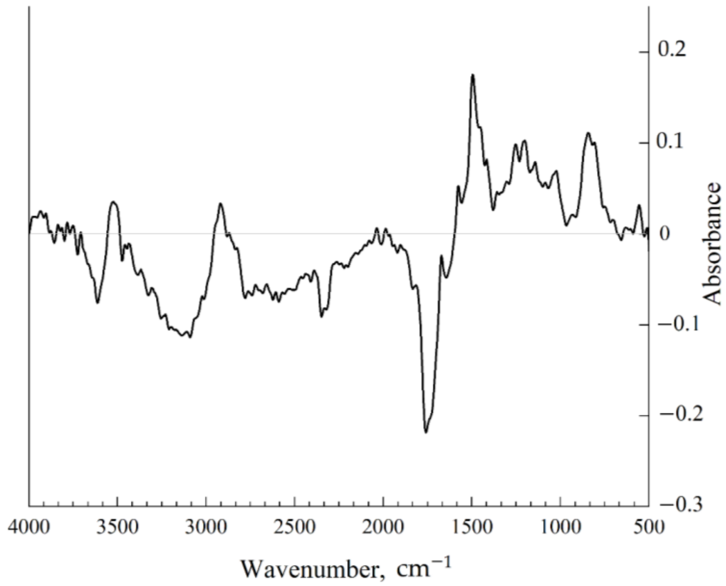

Figure 6. Difference spectrum of samples stored inside and attached to the test wall. Samples charred at 450 °C.

4. Discussion

Wood weathers mainly due to photodegradation of the lignin component. Free radicals are generated that react with oxygen to produce hydroperoxides, which in turn are decomposed to chromophoric groups, such as carbonyl and carboxyl groups [12,13]. Driving rain creates mechanical abrasion, and degraded surfaces are washed off revealing undamaged wood. It is also noteworthy, that water may enhance degradation reactions by facilitating light penetration [14]. In addition to natural wood surfaces, UV-light and moisture damage coated surfaces by causing chalking, cracking, and flaking of coatings [15,16]. The color stability and weathering resistance of thermally modified wood has been studied quite much. For example, Ayadi et al. [13] found thermally modified wood to show much less discoloration in comparison to unmodified wood after UV-exposure. It was speculated that the more stable color was partly explained by increased phenol content and stability of the condensed lignin. Baysal et al. [17] reached a similar conclusion and noted that a longer modification time resulted in more stable surface. Nuopponen et al. [18] and Tomak et al. [19] have also reported positive effects. However, Jämsä et al. [20] witnessed extensive greying, increased surface roughness and cracking after a five-year weathering trial. Srinivas and Pandey [21] also stated that thermal modification was actually ineffective in restricting color changes and suggested that the condensed structures formed in modification were actually more susceptible to UV-induced degradation.

Surface charring is a form of thermal modification, but the modification conditions are much harsher than in the traditional modification processes. The hypothesis behind this study was that the char should be quite stable because of intense structural degradation and chemical changes of components. When wood undergoes pyrolysis, the residue is mostly thermally modified lignin. The aromaticity of this residue increases with increasing temperature, and the end product is chemically quite stable against biological degradation. The soluble sugars have been depleted and adsorption capacity has decreased [11]. Kymäläinen et al. [11] studied the properties of surface charred wood modified by a heat plate combined with compression. As expected, major changes could be seen in the characteristic carbohydrate and lignin bands, with increasing aromaticity and decreasing hydroxyl group concentration with increasing severity of modification conditions. McBeath et al. [22] showed, that above 400 °C, aromatic carbon already accounts for over 90% of the carbon in charcoal. The question is whether the thermally modified lignin is less reactive towards photodegradation. The difference spectrum in Figure 6 shows new structures at around 3300–3000 cm^{-1}, and most noticeably at 1729 cm^{-1}. According to Rosu et al. [23], these stand for oxidized lignin. In the baseline corrected

According to Rosu et al. [23], these stand for oxidized lignin. In the baseline corrected spectra, the peak at 1729 cm^{-1} shows some increase after weathering and a slight shift towards higher wavelengths. Srivinas and Pandey [21] noted a rapid decrease in the intensity of lignin associated absorption band during photodegradation, especially the aromatic lignin C=C band (1508 cm^{-1}), which almost disappeared. The lignin in thermally modified wood degraded also with a significant increase in C=O band at 1725 cm^{-1} similar to unmodified wood subjected to weathering. Similar changes can be seen in Figure 5. There is also a sharp decrease in intensity at 1508 cm^{-1} (visible as the high positive peak in difference spectrum), which indicates lignin degradation in the aromatic C=C band [21] and formation of new carbonyl groups [23]. Therefore, lignin is photodegraded also on the charred surface. Similar changes were reported also by Kamke and Pfriem [24] in short-term artificial weathering of charred spruce surfaces. The magnitude still needs to be assessed with more detailed comparisons of different surfaces, since thickness of char layer is speculated to be crucial [24].

Naturally, the results hold true only for spruce char formed at about 450 °C. The further the thermolysis continues, the more the original wood structure is altered. As was mentioned before, surface charring can be implemented in several ways that may create differing char structures. The "original" method entails tying boards into a pillar, then setting fire from beneath. In this method, open fire will burn the surface, while a chimney effect ensures effective spread of flames. Okamura et al. [7] recorded surface temperatures of about 430 °C, one meter from the point of ignition. The flame temperature tends to fluctuate, but at the root it may be closer to 600 °C (red flame). A mechanized form of yakisugi may involve built-in burners and continuous feed of boards. Process times are fast and the formed carbonized layer thin [7], such as was the case also in this study. Utilizing a gas flame, such as butane or propane, is often seen as the DIY option. Under the torch, temperatures exceed 1000 °C, and while obtaining a homogeneous surface may be difficult, the char formed is very aromatic. At above 700 °C, onion-like (ordered) and graphite structures may be formed [25–27] that may react entirely differently to UV-radiation.

The advantage of a hot plate, compared to flame, is that the exposure temperature is easily controlled, but simultaneous compression is required to keep the board level. When using continuous feed, it was noted that defects such as knots may reduce the penetration of heat markedly and the resulting char layer is very thin, if not non-existent. Same was observed on the tongues of the panels, which turned grey during weathering. This was mainly due to insufficient compression, as the board was pushed up from the plate by the hard knots, and there was also not enough surface pressure on the edges of the panels (tongue). Lower feed speed would also enhance the char layer thickness, which seems vital in providing the needed durability in weathering. Another advantage of the hot plate is that flaming can be avoided. Flaming causes heterogeneity of the surface, and prediction of service life related properties may not be accurate. Flaming also consumes char, though this would only become important in longer processes, such as the ones Kymäläinen et al. [10,11] investigated. However, some flaming occurred in the prototype process. Again, this could have been solved by higher compression pressure, as a tight connection between the wood and the hot plate create anoxic, or near anoxic conditions. The reactions would take place at slightly higher temperatures than in presence of air but would also be more predictable. Less volatiles and more char is produced. Even in presence of air, flaming can be avoided at 280–500 °C as long as evolved pyrolysis gases, or sufficient pressure, exclude oxygen from the wood surface. The charcoal formed cannot burn and is left to accumulate [28]. Relatively low temperatures also take advantage of slow pyrolysis, where, according to Browne [28], decomposition proceeds in an orderly manner to formation of increasingly stable molecules.

5. Conclusions

Spruce cladding panels were charred from one side with a prototype device and the resulting surfaces were evaluated in respect to their tolerance to natural weathering. Chemically, measured by PAS-FTIR, the surface was not as stable as expected, as the modified lignin was degraded from the surface. New oxidized lignin and carbonyl structures were detected. Qualitative, the surface remained unaltered, but char layer thickness seems vital for durability in weathering. The prototype device used in this study would need tuning in terms surface pressure to ensure tighter connection between the wood and the hot plate. This would help reduce heterogeneity of surface around knots and panel tongues, as well as reduce flaming combustion of the wood surface. Further, a lower feed speed is suggested for the creation of a thicker char layer. The results presented here create interesting questions on the weathering tolerance of surface charred wood, specifically regarding the preparation method. Future research needs include investigation of higher temperature modified lignin structures and their resilience to UV-radiation induced photodegradation.

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