Real test-bed studies at the ETH House of Natural Resources – wood surface protection for outdoor applications

Estudios reales en banco de pruebas de la Casa ETH de Recursos Naturales – protección superficial de la madera para aplicaciones exteriores

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ABSTRACT

The increasing demand for sustainable construction materials used in urban areas calls for novel wood protective coatings, which retain the natural appearance of wood while minimizing maintenance intervals. This work reports on three different wood surface modification processes and evaluates their protective effect against weathering after installation at a testing façade of the ETH House of Natural Resources (HoNR), a recently opened living lab located in Zürich, Switzerland. We monitored the discoloration upon outdoor exposure of subsequently improved generations of thin metal oxide coatings developed in our lab. We target almost transparent and durable coatings with water repellent properties to diminish discoloration due to UV light and biological attack. This should lead to wooden facades with increased reliability and thereby boost an enhanced utilization of the renewable and CO₂ storing resource wood.

Keywords: wood surface modification, façade, UV-stability, weathering, living lab, ETH House of Natural Resources (ETH HoNR).

RESUMEN

La creciente demanda de materiales de construcción sostenibles en áreas urbanas requiere nuevos recubrimientos protectores de madera, que conservan el aspecto natural de la madera al tiempo que minimizan los periodos de mantenimiento. Este trabajo presenta tres procesos diferentes de modificación de superficies de madera y evalúa su efecto protector contra la intemperie después de la aplicación en una fachada de prueba de la Casa de Recursos Naturales ETH (HoNR), un living lab recientemente abierto ubicado en Zürich, Suiza. Se controló la decoloración después de la exposición al aire libre de las formulaciones mejoradas de revestimientos delgados de óxido de metal desarrollados en el laboratorio. Se hizo hincapié en recubrimientos casi transparentes y duraderos con propiedades hidrófugas para disminuir la decoloración debida a la luz ultravioleta y al ataque biológico. Esto debería conducir a fachadas de madera con una mayor durabilidad y, por lo tanto, impulsar una utilización mejorada de recursos renovables y de almacenamiento de CO₂.

Palabras clave: modificación de superficie de madera, fachada, estabilidad a los rayos UV, envejecimiento, living lab, Casa ETH de Recursos Naturales.

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Cómo citar este artículo/Citation: Guo, H., Michen, B., Burgert, I. (2017). Real test-bed studies at the eth house of natural resources - wood surface protection for outdoor applications. *Informes de la Construcción*, 69(548): e220, doi: <http://dx.doi.org/10.3989/id.55202>

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Recibido/Received: 27/01/2017
Aceptado/Accepted: 28/02/2017
Publicado on-line/Published on-line: 14/02/2018

1. INTRODUCTION

The ETH House of Natural Resources, which was opened in June 2015, serves as a living lab to transfer research developments from lab-scale to real test-bed conditions for further market implementation. The performance of materials and innovative structural elements can be monitored and the results are used for further improvement in feedback loops. Most of the projects are dedicated to new concepts for the utilization of wood as a building material including post-tensioned timber frames and timber-concrete hybrid floors made of beech wood as well as novel facade elements with improved UV stability. The purpose of this article is to present the monitoring of the UV resistance and related protection against weathering of the wooden facade at the ETH House of Natural Resources (HoNR). In June 2015 a frame was installed at the surface envelope, which allows to fix wooden lamella for a prototype facade with an area of around 6m² and to monitor the impact of natural weathering on reference slats and those with surface modification (Figure 1).

The natural weathering by means of sunlight and rain leads to discolorations of natural wooden façades and to surface destruction. In particular lignin, a wood cell wall constituent with a content of around 30 %, is a good UV absorber and therefore degraded in photo-oxidation reactions (1, 2). The resulting bond cleavages lead to the formation of radicals (3) and a fragmentation of lignin into low molecular weight units, which can be washed out by water (4). The residual surface becomes greyish and rougher (5, 6, 7) and more prone to fungi attack (8), which can lead to a substantial darkening of affected areas. Further, in the course of lignin degradation, the wood surfaces become more hydrophilic which promotes the formation of cracks and deformations by swelling and shrinking due to wood moisture changes.

To significantly reduce the photo-degradation of wood on a long-term basis, various techniques for wood surface protection have been developed and are partially applied. Most of them are water-based coatings (varnishes and opaque paints) usually carrying organic or inorganic UV absorbers and radical scavengers. Studies on the UV protection efficiency of these combined products consisting of inorganic UV absorbers (ZnO, TiO₂, CeO₂) and a transparent coating such as water-based acrylic systems or maleic anhydride modified polypropylene or polyurethane were reported in several studies (9, 10, 11, 12, 13). An addition of nano-fibrillated cellulose for carrying and homogenously distributing of UV absorbers for wood coatings was reported by Grüneberger et al. (14, 15). However, the UV radiation causes a self-degradation of the applied polymer coatings, which affects the long-term performance of such systems. Predominantly, still at the laboratory level are wood surface coatings that try to avoid polymers in the wood surface coating and are entirely based on thin inorganic layers. For this purpose metal oxide nanorods were grown on the wood surface based on various chemical treatments, which should form a dense inorganic layer for an efficient UV-protection (16, 17, 18).

Without an efficient coating, the interplay of all weathering factors heavily reduces the aesthetic value of the façade, which in consequence demands rather short maintenance intervals and may finally require a replacement after a too short period of installation. This problem is true for single-house, but becomes even more demanding for multi-storey buildings made of wood, which are currently recapturing the urban space and are erected as lighthouse projects in various cities. For such buildings a better performance in terms of long-term (color) stability and durability of wooden facades is highly needed as a periodic scaffolding of the entire building for façade maintenance would not be accepted by building companies or users. Hence, to have wooden facades for

Figure 1. The House of Natural Resource (HoNR) located at the ETH campus Hönggerberg in Zürich, Switzerland. The red arrow points to the facade used to test the protective effect of wood surface treatments under outdoor conditions.

multi-storey buildings in the urban environment, long-term protection that retains the natural aesthetics of wood needs to be developed and established as a market product.

2. MATERIALS AND METHODS

2.1. Wood surface modification

Spruce and fir panels were cut into two different dimensions of 690 mm × 142 mm × 15 mm and 610 mm × 142 mm × 15 mm in longitudinal × radial × tangential direction, respectively (Figure 2a). Before modification all wood panels were stored in a climate room with a temperature of 20°C and a relative humidity of 65 %. Surface modifications were carried out by the immersion of wood panels into a container that was filled with the precursor solution specific to the first, second and third generation treatment (Figure 2b).

First generation: This surface modification used a two-step and water-based chemical bath to deposit a layer of ZnO on spruce. The process was adapted from a procedure we reported previously (19, 20) and was carried out in a stainless steel container. The first seeding step required a heat treatment at 80°C. In the second step, ZnO crystals were grown from the spruce wood surface in an aqueous solution containing Zn ions. Finally, the coating was hydrophobized by attaching stearic acid onto the ZnO surface.

Second generation: A thin TiO₂ coating was deposited on the spruce surface by immersing the wood panels into an alcoholic solution containing a Ti-based precursor. The modification process was carried out in a Polypropylene (PP) container (800 × 600 × 220 mm³) at room temperature and ambient pressure. The precursor solution was prepared in an ultrasonic bath prior to the transfer of 6L of this solution into the

PP container. Three wood panels were soaked for 48h in the container that has been covered by a lid to reduce the moisture content during the impregnation. This is important because the precursor reacts easily with H₂O. After that, the spruce wood panels were removed from the solution and dried.

Third generation: This surface treatment also results in a TiO₂-based thin layer on the wooden surface and is an improved process of the second-generation modification. Here, a stabilization compound has been added to the precursor solution to reduce the reactivity with moisture. This enabled us to reuse the precursor solution multiple times and better control the coating morphology. The third generation of surface modification has been applied to two wood species, namely spruce and fir.

2.2. Wooden façade installation

Two metal hooks were pinned on the backside of the wooden panels as shown in Figure 3a. Four plastic rods were installed on the metallic frame on the wall of ETH House of Natural Resource as shown in Figure 3b. The wooden panels were hung up on the plastic rods for the natural weathering test. A drain tray was placed under the bottom of the wood panels to collect the rain-wash that was used to analyse leaching of wood compounds. The drain tray caused water splashes on the lower parts of wooden panels to accelerated erosion and fungi growth.

2.3. Colour change measurement

Colour measurements were carried out on the upper row wooden panels, which were not affected by fungi, i.e. without dark staining. The colour evaluation of wood panels during the natural weathering test was conducted by the CIE L*a*b* system using a spectrophotometer CM-700d (Konica, Minolta Sensing, Inc., Japan). In CIE L*a*b* colour space, L* represents the lightness from black (0) to white (100), while a* and b* are the chromaticity indices, where +a* is the red, -a* is the green, +b* is the yellow, and -b* is the blue direction. The total colour change is defined by the followed equation:

$$[1] \quad \Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

2.4. Analysis of the rain-wash

The rain-wash fluid can be collected by the underneath container for each façade section. Rain-wash from the 1st generation modification segment was poured into a quartz tube after removal of solid particles by filtration of the fluid. The solution was then analysed by a UV-Vis spectrometer (Lambda 850, PerkinElmer).

3. RESULTS AND DISCUSSION

Three different generations of protective wood surface treatments have been applied to wood panels, which were installed on the façade at the ETH house of Natural Resources during the past one and a half years. Figure 1 shows a photograph of the wooden façade taken on 5th of September 2016. It displays the appearance change of the modified and unmodified wooden panels in each generation (Figure 4a) and shows a time line indicating the time of installation of each individual surface treatment generation (Figure 4b).

Figure 2. In a) photograph of the wooden panels used to assemble the façade. A schematic illustration of the chemical bath process applied to modify the surface of wood is shown in b).

Figure 3. In a) a photograph of the backside of wooden panels with metal hooks; b) the frame used for hanging up the wooden panels; c) shows the drain tray installed under the wooden façade for the collection of rain-wash liquid.

The 1st generation of modified spruce panels (green frame in Figure 4a) was coated by UV light absorbing ZnO and an additional hydrophobic layer of stearic acid. This thin layer of stearic acid endowed the wooden panels with water repellence as well as protected the ZnO coating from erosion due to rain. This first generation of protective coatings was installed on 1st of June 2015. The control (unmodified spruce) samples were installed for comparison at the same date. The 2nd generation of modified spruce panels, which was installed in the beginning of September 2015, was coated with a thin TiO₂ layer (red frame in Figure 4a). Also the 3rd generation (blue frame in Figure 4a) attached a TiO₂ based coating to the wood surface. By stabilizing the precursor solution, the amount of precursor used for the modification could be reduced and the thickness of the coating could be increased to achieve a significant protection. This third generation was installed on 5th of August 2016. The detailed analysis of colour change and protective effect against weathering of each generation of surface modification treatments will be discussed below. Note that the 1st and 2nd generation of modified panels as well as the reference were removed from the façade starting middle of December 2015 till end of March 2016, because of a reconstruction of the façade frame.

The performance of the first generation modified wood coatings is summarized in Figure 5. The weathering protection efficiency of the modified wood surface was assessed by colour measurement determined in the CIE L*a*b* colour space. These colour parameters were monitored for a period over 500 days with varying intervals and the results of modified spruce with corresponding reference are displayed in Figure 5a. The unmodified samples underwent a loss in lightness and the redness factor increased gradually in the first 150 days of outdoor exposure. After this time L* and a* underwent only minor changes for the next 350 days. The yellowness (b*) increased rapidly in the first month from about 20 to 35 and decreased afterwards slowly to about 23. This change is due to the photo induced oxidation of lignin in wood by sunlight, mostly UV light (21). The lignin is decomposed into

hydrophilic fragments (21, 22), which will leach from the wood surface during rain periods resulting in the decrease of the yellowness index (b*).

The 1st generation of modified spruce showed very good colour stability. The total colour change, ΔE , was less than 3.5 after 500 days outdoor exposure. However, the coating process itself caused an initial total colour change of about 15 compared with the natural spruce wood. This is evident from the green line in Figure 5a, which refers to the total colour change relative to the unmodified spruce. The photograph in Figure 5b shows the alteration of the wood appearance for a coated (left) and uncoated (right) panel after 525 days of exposure.

The inset in Figure 6 shows a photograph of the collected rain-wash fluids from the unmodified (1) and modified (2) panels. The difference in colour illustrates the higher concentration of leached compounds from unprotected spruce. The leaching of the lignin fragments could be further confirmed by analysing the rain-wash fluids by UV-Vis spectroscopy (Figure 6). The spectrum of the fluid collected from unmodified spruce (blue dashed line) showed an absorption starting from 500nm. The absorption steadily increased in intensity towards the UV range. The fluid collected from ZnO coated spruce showed the similar absorption spectra but 4 times lower in intensity than that of the uncoated panels (solid red line). Therefore, the ZnO coating protects the wood surface from erosion and leaching induced by weathering. This is very important as the loss of lignin compounds results in wood surfaces with exposed cellulose, which facilitates fungi attack as we observed for uncoated spruce (Figure 5b, right). While this first generation of coatings showed only minor colour changes and reduced erosion upon weathering during a real outdoor test conducted at the HoNR, the main drawback is the high initial colour change which affects the natural appearance of wood after modification.

To avoid a pronounced initial colour change induced by the coating itself, we developed the 2nd generation of protective coating, which is based on a thin TiO₂ layer attached to the

Figure 4. The wooden façade of the House of Natural Resources at ETH Zürich showing the three different generations of surface modifications along with controls in (a). The 1st generation is shown in a green frame, 2nd generation in a red frame and 3rd generation in a blue frame. The photograph was taken on 5th September 2016. In b) a time line is shown indicating the time of installation of each generation of modified wooden panels as well as the corresponding references.

Figure 5. In a) the changes of lightness factor (L^*), redness factor (a^*), yellowness (b^*) and total colour change (ΔE) of the 1st generation modified spruce as well as the reference are plotted over the outdoor exposure time (varying measurement intervals). In b) a photograph shows the appearance of the modified (left) and unmodified (right) 525 days after their installation.

Figure 6. UV-Vis spectra of rain-wash fluids collected from the drain trays installed underneath the façade. A strong absorption was recorded for unprotected spruce (blue dashed line) while the 1st generation of ZnO coated spruce (red solid line) showed significant reduced absorption indicating the efficient protection against leaching. The inset shows the liquid collected from uncoated (1) and coated (2) spruce panels.

wood surface. This process highly preserved the aesthetic appearance of spruce panels. Spruce panels modified in this fashion were installed in the end of August 2015 (Figure 4). This technology could efficiently protect the spruce panels from yellowing as well as reduce the loss of lightness due to fungi colonization. Figure 7a illustrates the colour change of the TiO₂ modified panels. The lightness index of the modified

spruce slightly decreased in the first 80 days from 83 to 80 and stabilized afterwards. Almost no change in the redness index could be detected for TiO₂ modified spruce. Interestingly, the yellowness index of the modified spruce remains constant in the first 80 days at about 22 and starts to decline thereafter. A strong decrease of the yellowness index, to approximately 13, was observed after 360 days. This value is significantly lower than uncoated spruce exposed for a similar duration (Figure 5a), and may indicate that an additional discoloration effect took place, for instance, a photocatalytic interaction between TiO₂ coating and the wood surface. Thus, the discoloration of the wood surface instead of yellowing under solar irradiation may owe to the catalytic effect of the coating. Consequently, the TiO₂ modified wood panels experienced a total colour change of about 10 after 420 days of outdoor exposure. The photography of the TiO₂ modified spruce (Figure 7b, left) demonstrates that fungi colonization is significantly reduced compared to the unmodified spruce panels (Figure 7b, right).

Based on the progress made for the TiO₂ modification of the second generation, it was possible to apply a coating that is almost transparent and preserves the natural appearance of the wood during the modification, which is an improvement compared to the 1st generation of modification. In addition, the immersion step of the 2nd generation coating process was realized at room temperature, which reduced the energy costs in comparison to the first generation. However, the fast hydrolysis of the titanium precursor, limited the reuse of the precursor solution for several cycles of surface modification. Furthermore, the colour stability of this coating generation was not sufficient in outdoor exposure.

Figure 7. In a) time dependence of lightness factor (L^*), redness factor (a^*), yellowness (b^*) and total colour change (ΔE) of the 2nd generation of modified spruce and the reference (varying measurement intervals). In b) a photograph shows the appearance of the unmodified (right) and modified (left). Please note that the pictures are only shown for a general comparison as the unmodified samples were longer exposed than the modified ones.

Figure 8. In a) the time dependence of lightness factor (L^*), redness factor (a^*), yellowness (b^*) and total colour change (ΔE) of the 3rd generation modified spruce along with the corresponding reference (varying measurement intervals). In b) a photograph showing the appearance of the modified (right) and unmodified (left) panel after 90 days of outdoor exposure.

Figure 9. In a) time dependence of lightness factor (L^*), redness factor (a^*), yellowness (b^*) and total colour change (ΔE) of the 3rd generation modified fir with corresponding reference (varying measurement intervals). In b) a photograph showing the appearance of the modified (right) and unmodified (left) after 90 days of installation.

In order to overcome the shortages of the 2nd generation related to the fast hydrolysis of the precursor solution, a stabilization agent was added to the precursor solution. Furthermore, this stabilized precursor solution allowed for a better control of the coating thickness. Now, the immersion into the Ti-based precursor solution could be repeated several times to increase the coating thickness and lead to a dense and continuous TiO₂ layer on the wood surface. The performance of this 3rd generation of wood surface modification, which has been installed on the 5th of August 2016, is shown in Figure 8a. The unmodified spruce panels become dark, red and yellow rapidly resulting in a total colour change of about 17 after 50 days of outdoor exposure. The TiO₂ modified panels showed only a slight colour change in the first 25 days, which stabilized afterwards. Specifically, the lightness index of the modified samples decreased from 85 to 80 after 25 days, the redness index increase from 3 to about 4.5 before stabilization. The yellowness index increased from 19 to a maximum value of 24 after 25 days outdoor exposure and then experienced a gradual decline almost to the initial value after 65 days of installation. The initial colour change is about 5 due to the coating process and reveals an almost transparent coating (green line in Figure 8a). The photography in Figure 8b shows the wooden panels installed in the bottom row of the façade and illustrates that there is not only a severe colour change on the uncoated spruce (left) but also fungi colonization after 90 days outdoor exposure, whereas the modified spruce (right) remains the natural appearance of the spruce wood without any sign of fungi colonization.

To demonstrate the adaptability of this technology to other wood species, fir panels were modified following the same procedure and installed at the ETH HoNR. The unmodified fir and the 3rd generation modified fir panels show a very

similar colour change during the natural weathering test as observed for spruce. The preliminary results are summarized in Figure 9. We will continue to monitor the weathering protection on the 3rd generation of modified fir and spruce, which will support us in further improving our protective wood surface coatings.

4. CONCLUSION AND OUTLOOK

Based on the testing period at the ETH HoNR, it can be stated that for spruce, which is one of the most common wood species in the European building sector, a promising coating technology has been developed, that results in substantial UV protection, but retains the aesthetical appearance of the wood surface. Especially, the 3rd generation of surface modification resulted in an effective protection by an almost transparent coating while the stabilization of the precursor solution improved the utilization of chemicals compared to previous generations. In spite of this, further improvement is needed: Firstly, an efficient way should be found to suppress the radicals induced by the photo catalysis effect of the TiO₂ coating so that the yellowness index of spruce and fir can be stabilized during long term outdoor exposure. Secondly, the modification processes need to be further optimized for an economically relevant up-scaling of these novel technologies. The HoNR located at the ETH Hönggerberg campus in Zürich, Switzerland, is an ideal platform to test the next generations of wood surface modifications developed in our lab.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support by EIT Climate-KIC in the framework of the BTA flagship program (Building technology accelerator) and the CTI (Commission for Technology and Innovation in Switzerland).

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