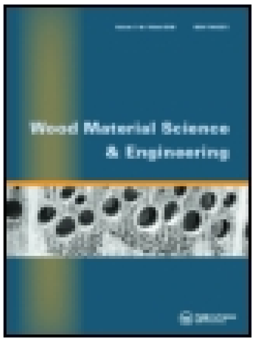

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Short-term performance of wooden windows and facade elements made of thermally modified and non-modified Norway spruce in different natural environments

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ABSTRACT
Thermally modified wood is becoming an increasingly popular material for different applications in buildings. Laboratory tests indicated a positive effect of thermal modification on durability, dimensional stability and thermal conductivity of wood. Therefore, windows and facade elements made of thermally modified Norway spruce and non-modified Norway spruce were tested in the field and installed in different test objects which were exposed at five locations in Europe (Slovenia, Germany, Sweden, and Spain). Results from monitoring showed that elements and windows made of thermally modified spruce (TMS) had considerably lower wood moisture content compared to the ones made of non-modified spruce and that wax further positively influenced moisture performance. Colour changes of TMS were more intensive compared to non-modified spruce but were successfully retarded by adding pigments to the wax. Mould and stain growth was largely dependent on the location, amount of precipitation and relative humidity.

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Norway spruce; thermal modification; wax; wooden facades; wooden windows

Introduction

Timber is alongside concrete, bricks and metal one of the most important materials in the building sector. It is used in many applications such as construction elements, carpentry, or wooden joinery. Based on the use of timber in buildings, it is essential to select appropriate wood species and wood treatments to assure a long lifetime of specific elements and consequently the entire building. Modern timber windows in Slovenia are mostly made of Norway spruce (*Picea abies*), Siberian larch (*Larix Sibirica*) and oak (*Quercus* spp.) (no official statistics are available and these data are based on internal market knowledge of M SORA). Scots pine (*Pinus sylvestris*) and other pine species are also widely used for wooden windows in Europe (Bencsik *et al*. 2011, Tarantini *et al*. 2011, Hrovatin *et al*. 2013, Gobakken and Alfredsen 2018). Larch for windows is frequently imported from Russia (*Larix sibirica*) as it is being widely planted and grown in Siberia whereas Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) are more widely available European wood species (Wagenführ 1996). Facade elements are usually made of softwood species and generally not surface treated, whereas windows are coated with synthetic coatings or oils. In the recent decade, a trend to use domestic wood species has been perceived (Connell 2004). The prime reason originates in the reduced transport costs and associated carbon emissions, and negative perception of wood species from tropical regions, as the use of tropical wood species is frequently associated with deforestation (Sohngen *et al*. 1999). As defined by the European standard EN 350 (2016), the majority of the European wood species does not have durable wood and belong to the durability classes 3, 4 and 5 (Brischke and Meyer-Veltrup 2017). Hence there is a need for an appropriate treatment to improve the durability and prolong the service life of installed elements. For example, in the recent version of EN 350 (2016), Norway spruce is classified in the durability class 4–5 (slightly durable to non-durable) and European larch is classified in the durability class 3–4 (moderately to slightly durable). These data clearly indicate that these two wood species should not be used in more exposed applications in use classes 3.2 (above ground without construction protective measures), 4 (in the ground) or 5 (in sea water) (EN 335 2013). Five use classes are defined in EN 335, that represent different service situations to which wood and wood-based products can be exposed. EN 335 also indicates the biological agents relevant to each situation. Thermal modification is a convenient and one of the most environmentally friendly procedures which increases durability and hydrophobicity, and decreases thermal conductivity of spruce by almost 20% (Mayes and Oksanen 2002, Rep *et al*. 2004, Esteves and Pereira 2009,

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Ugovšek *et al*. 2015). To further protect the wood, the hydrophobicity of the wood surface should be increased to slow down the moistening of wood. Application of natural waxes is an emerging and innovative way to treat wood and increase the hydrophobicity of the surface (Lesar and Humar 2011). In the scope of the WINTHERWAX project (Horizon 2020, SME Instrument) various wood species with or without coatings were exposed to the natural environment at different places in Europe to confirm a positive synergistic effect of wax and thermal modification which has already been proven in laboratory conditions (Humar *et al*. 2017). Different characteristics of wood were monitored to gain information about the influence of different climatic conditions, wood species, thermal treatment and surface treatment on the properties of timber used as windows and facade elements. Spruce and thermally modified spruce (TMS) in facade elements and windows were considered in this paper and wood moisture content (MC), colour changes and mould and stain growth were evaluated at different locations.

Materials and methods

Windows and facade elements presented in this research were made of non-modified Norway spruce (NMS) and Silvapro® TMS and installed in the test cube (Figure 1). Window profiles had a thickness of 110 mm with two integrated sealings and aluminium covers on bottom casement and frame, whereas entire window included triple insulated glass unit with warm-edge TGI spacer (Technoform Glass Insulation spacer) and dimensions of 600 mm × 1000 mm (width × height). Facade elements had dimensions of 493 mm × 50 mm × 25 mm (length × height × thickness) and the space between them was 15 mm. Each facade element was numbered and screwed to basic wooden construction with stainless steel screws. Spruce for windows was thermally modified at the maximum temperature of 220°C, whereas spruce for facade elements was modified at the maximum temperature of 230°C for 3 hours according to Silvapro® (Silvaprodukt d.o.o.) thermal modification method in vacuum. Maximum modification temperatures were chosen based on the previous results, where relevant properties of thermally modified wood had been studied in detail (Rep *et al*. 2004, 2012, Humar *et al*. 2015). During a thermal wood modification process, wood was placed into a wood modification kiln, heated to a chosen maximum temperature in an oxygen + free atmosphere and cooled down to the ambient temperature again after the modification process has finished. TMS elements were surface treated with naturally based Silvacera® wax (TMS-W) (Silvaprodukt d.o.o.) and synthetic coating (TMS-C) (Remmers Baustofftechnik GmbH). Wax was applied on the surface of elements with the initial dipping of specimens for 30 s in the form of water emulsion. Elements with applied wax were further heated at 120°C for 1 h. The synthetic coating was applied with flow coating of initial two layers and spraying of the final top layer. All elements were exposed at constantly rotating test objects (frequency of one revolution per hour) with dimensions of 1.5 m × 1.5 m × 3 m and regulated internal temperature of 25°C at the following five locations around Europe since October 2015: Žiri and Ljubljana (Slovenia), Hannover (Germany), Skellefteå (Sweden) and Madrid (Spain) (Figure 2). Outside air temperature and RH were monitored at all locations by sensors (Gigamodule, Scanntronik Mugrauer GmbH, Germany). Wood MC was determined in the core of facade elements and window profiles. MC was determined through measurements of electrical resistance, whereby insulated electrodes (stainless steel screws) were applied at various positions and linked to electrical resistance measuring equipment (Gigamodule, Scanntronik Mugrauer GmbH, Germany). Electrodes with the length of 25 mm were chosen for monitoring of the MC of façade elements, whereas 40 mm long electrodes were chosen for windows. Electrodes of different lengths were chosen, as we were interested in the MC in the central part of the monitored samples. The method was validated using parallel samples that were preconditioned at various RH and temperatures in a climate chamber to achieve various target concentrations as described by Kržišnik *et al*. (2018). This equipment enables accurate wood MC measurements between 6% and 60%. MC was logged twice per day, at midnight and noon, at the same time as the temperature. Wood species-specific resistance characteristics were developed based on the methodology described by Otten *et al*. (2017). Colour changes of materials were recorded before initial exposure of test objects at final locations and

Figure 1. Test cube (right), detail of installed window and facade elements (middle) and detail of window profile (left).

Figure 2. Test cubes with installed test windows and facade elements at different locations.

after 12 months with a mobile Erichsen EasyCo 566 colorimeter (reflection included). Colour changes were evaluated using CIE $L^*a^*b^*$ colour system and ΔE was calculated and used for comparison of colour changes among different specimens according to Equation (1).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}\,. \tag{1}$$

Average values of each facade element were calculated from at least 21 measurements (three measurements per facade element), whereas average values of window materials were calculated from four measurements. Results for a period of 12 months since the beginning of the exposure of wood MC, colour changes (ΔE) and fungal growth (mould) are presented in this paper. The intensity of colour disfigurement due to fungi and moulds was evaluated visually according to Humar *et al.* (2015). This rating scheme was developed from the rating scheme in standard EN 152-1 (1996).

Results and discussion

The wood MC of TMS facade elements (Figure 3) was lower compared to NMS facade elements. The difference was

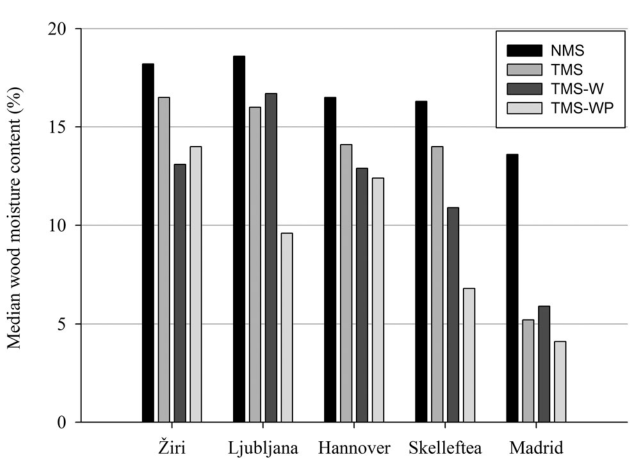

Figure 3. Median wood MC of facade elements for a period of 12 months from October 2015 until September 2016.

lower than expected which is most probably correlated to lean shape of facade specimens and especially their uncovered transverse surfaces. The MC difference between TMS and NMS was much more prominent in the case of windows (Figure 4) and also the MC of all materials was much lower compared to facade elements due to larger dimensions of samples (window elements), lesser exposure and covered transverse surfaces. Windows were installed in the structure of the test cube and therefore less exposed to external climate conditions compared to facade elements which were installed at the shell of test cube. This makes a comparison between these two elements more complicated. In addition, it should be considered that there were thermal and moisture gradients present within the window elements, as the inner part of the cubes was air conditioned. On the other hand, there was no such a gradient for façade elements. Due to mentioned reasons, the MC of windows and facade elements can not be easily compared, but the comparison between different wood and surface treatments of the same product is relevant. Comparison of the performance of these two elements was not based only on the geometry but on complex thermo-hygroscopic behaviour. Calculation of this is beyond the objectives of the respective manuscript and could be the topic of future research.

Wax impregnated elements (TMS-W) exhibited lower MC due to increased hydrophobicity of wooden elements. Facade elements with a synthetic coating (TMS-C) were the driest, whereas in the case of windows this difference was not prominent due to less severe exposure, greater thickness of elements and exposure only from outside compared to facade elements which were exposed from all six sides (both cross section, tangential and radial surfaces). The objective of the respective manuscript was not to compare the exposure of the windows and façade, but the prime interest of the respective research was to elucidate the efficacy of various coatings systems in combination with thermally modified wood. As evident from the respective data, the wax treatment proved to be efficient. It should be considered that wax treatment is cheaper than the respective surface coating. Locations, such as Madrid and Skellefteå, exhibited the lowest median wood MC, which was expected because of the dry and hot/

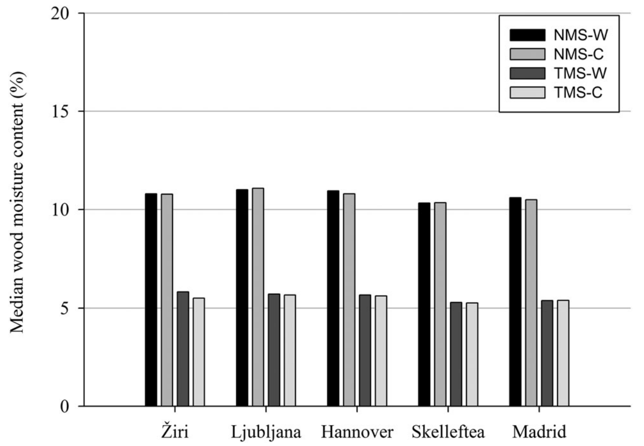

Figure 4. Median wood MC of windows for a period of 12 months from October 2015 until September 2016.

Table 1. Climate data, relative Scheffer Climate Index and relative dose of test locations.

	Žiri	Ljubljana	Hannover	Skellefteå	Madrid
Average annual temperature (°C)	9.8	10.4	8.8	1.9	13.7
Average January temperature (°C)	0.1	−0.1	0.3	−11.0	5.0
Average July temperature (°C)	19.4	20.4	17.1	15.5	24.0
Annual precipitation (mm)	1271	1290	666	559	450
Relative Scheffer Climate Index (–)	1.17	1.44	1.44	0.67	0.61
Relative dose (–)	2.03	2.42	1.75	0.63	0.65

cold climate of these locations (Table 1). Žiri, Ljubljana and Hannover have similar results as the climate is very much alike in these locations. Results indicate a strong influence of environmental conditions on the MC of wood.

The colour change (total colour distance Δ*E*) of facade elements after 12 months (Figure 5) was significantly affected by the intensity of rain events and of UV light. In order to correlate colour changes with local climate, various models could be applied. At the very moment, dose–response models were found to be the most predictive (Thiis *et al.* 2016). This model indicated that colour changes were predominately associated with increased MC (due to rain, wind driven rain or high RH), solar radiation and susceptibility of the material for blue-stain growth. At this time, the models are not developed enough for detailed prediction, hence they were not applied in the respective object.

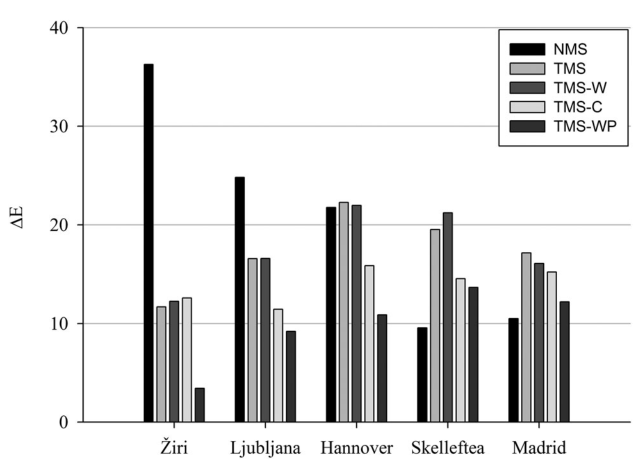

Figure 5. Colour changes of facade elements after 12 months of exposure from October 2015 until September 2016.

Δ*E* of NMS was greater than Δ*E* of TMS in Žiri and Ljubljana, whereas Δ*E* of NMS in Skellefteå and Madrid was lower compared to TMS. As Δ*E* is combined with *L**, *a** and *b** coordinates, this should be analysed more precisely. It was noticed that NMS samples in Ljubljana and Žiri were darkening (negative Δ*L**) more intensively than TMS samples were lightening (positive Δ*L**). This trend was opposite in Skellefteå and Madrid, where NMS samples were darkening less intensively than TMS samples were lightening. Darkening intensity of NMS and lightening intensity of TMS was similar in Hannover. Δ*a** (change of colour to green – negative *a** and red – positive *a**) and Δ*b** (change of colour to blue – negative *b** and yellow – positive *b**) are additional parameters which show the behaviour of elements at different locations and could be correlated to the greying of wood if *a** and *b** is turning to green and blue, respectively. Δ*a** of NMS was negative (turning to green) in Ljubljana, Žiri and Hannover whereas Δ*a** was positive (turning to red) in Skellefteå and Madrid. Δ*a** of TMS was negative at all locations but the intensity in Skellefteå and Madrid was lower compared to other locations. Δ*b** was negative (turning to blue) at all test sites but again much lower in Skellefteå and Madrid compared to Žiri, Ljubljana and Hannover. These changes showed the influence of the amount of precipitation (Table 1) and consequently leaching of degraded products which influenced colour changes. Further on, colour changes of weathered surfaces are indicators of various biotic and abiotic factors (Ayadi *et al.* 2003). Chemical changes caused by UV exposure cause greying of the surface. In contrast, blue-stain fungi darken the wood (Zink and Fengel 1989, Hon 2001). In terms of the susceptibility of various materials towards colour changes, the highest was determined on light-coloured, non-treated specimens (e.g. NMS). On the other hand, Δ*E* of synthetic coated elements (TMS-C) were less prominent and more equal among different locations. Wax (TMS-W) did not contribute to lower Δ*E* due to the lightening of the surface (higher Δ*L** compared to Δ*L** of TMS) but prevented extensive greying, whereas addition of brown pigments (TMS-WP), which absorb the UV radiation, showed good and promising results. The better photo-stability of thermally modified wood compared to non-modified wood could be caused by an increase in lignin stability due to the condensation during thermal modification (Ayadi *et al.* 2003, Deka and Petrič 2008).

Fungal growth (0 – no colour disfigurement, 4 – extensive colour disfigurement) or intensity of moulds (Figure 4) was dependent especially on precipitation.

Madrid and Skellefteå revealed the lowest evaluation score, whereas Žiri, Ljubljana and Hannover revealed the highest evaluation score. Results fit well to the Scheffer Climate Index and relative dose presented in Table 1, even though both models are used for estimation of decay hazard. TMS showed lower mould and stain growth

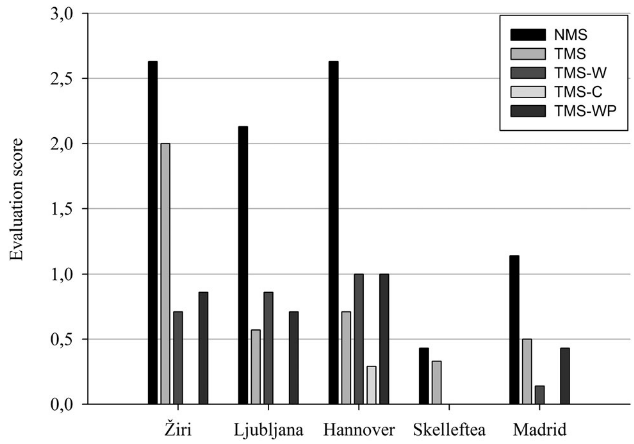

Figure 6. Mould and stain growth of facade elements after 12 months of exposure from October 2015 until September 2016.

evaluation score results compared to NMS at all locations. TMS-W received similar or lower evaluation scores whereas TMS-C exhibited almost no mould (Figure 6).

Conclusions

NMS and TMS windows and facade elements were exposed to the natural environment at five different locations in Europe (Slovenia, Germany, Sweden and Spain). MC, colour changes and mould and stain growth were evaluated after one year of exposure. Wood MC in facade elements varied between locations and was the lowest in Madrid and highest in Ljubljana and Žiri. Generally, TMS had lower MC compared to NMS. Wax (TMS-W) additionally decreased the MC, whilst applying a synthetic coating (TMS-C) decreased the MC even more. Colour changes were dependent on specific location and its weather conditions, where the amount of precipitation played an important role. Wax does not inhibit colour changes of TMS but the addition of pigment in wax (TMS-WP) showed very promising results and slowed colour changes. Mould intensity was the highest in Žiri, Ljubljana and Hannover, whereas in Madrid and Skellefteå little or almost no fungal growth occurred. Although still in an early phase of exposure, for the time being it can be concluded that especially wood MC and mould and stain growth correlates well to calculated Scheffer Climate Index and Dose values of all locations. Visual changes of samples in Madrid and Skellefteå are much less prominent compared to other three locations. So far, TMS-W and TMS-WP show good results in terms of MC as well as in terms of colour stability but results can be intended only as preliminary after one year of exposure.

Disclosure statement

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