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Section 2 **Test Methodology and Assessment**

Expert versus multi-sensor evaluation of wood samples after short term weathering

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ABSTRACT

Understanding the influence of weathering factors and the material degradation mechanisms are fundamental for modelling the weathering process of wood. The goal of this work was to investigate the combined effect of time and exposure on the physical-chemical mechanisms of wood weathering. Four exposure directions (North, South, East and West) were investigated. Experimental tests were performed for 28 days through July, which according to previous research is considered as the most severe period for weathering of wood micro-sections. Measurements of samples included: photogrammetry, near and mid infrared spectroscopy, colour measurement, SEM observation and visual assessment. Parameters obtained by measuring the weathered surfaces with various sensors were compared with the subjective visual assessment by an expert evaluator. Algorithm based on multi sensor data fusion allowing calculation of the "weathering indicator" was developed. It was concluded that the progress of degradation is clearly correlated to the solar radiation and the exposure direction seems to have a clear effect on the degradation intensity.

Keywords: wood weathering, service life performance, multi-sensor approach, visual assessment

1. INTRODUCTION

Wood as a building material has been traditionally used for different types of load-bearing structures, decking, façades cladding, doors and windows. Currently the global trend is use of natural resources in sustainable development. Several European countries (Austria, Denmark, Finland, France, Germany, Hungary, the Netherlands, Norway, Sweden and the UK) have already implemented a range of green public purchasing (GPP) policies, which also tend to support wood construction. In consequence the industry takes the lead to promote wood as a sustainable building material by establishing a new European framework in favour of the use of wood for mass-market development and for high standard engineered and architectural solutions. As a result an increasing number of applications of wood as construction and façades materials are noticed. Wood is often chosen due to low maintenance cost, simple processing and easy accessibility (Ruther, 2015). However, an important issue however when dealing with external applications is their technical performance and aesthetic expression during service life. Wooden elements are often exposed to mechanical, environmental or biological alterations during their service life. The most susceptible parts are unprotected surfaces since they are mostly subjected to ageing, weathering or decay.

Various approaches for modelling performance of timber elements and predicting service life of timber components with respect to the range of degrading factors were proposed. The most commonly accepted "factor method" is implemented as the ISO standard 15686-1 (2000). Scheffer (1971) proposed a climate index by correlating climatic data with the hazard for decay. The attempts were followed by various researchers (Van de Kuilen, 2007, Viitanen et al. 2008, Gobakken and Lebow, 2009, Thelandersson et al. 2009, Brischke and Hansson, 2011). Recently Brischke and Thelandersson (2014) reviewed alternative modelling approaches for predicting performance of wood products outdoors. They have concluded that the dose-response models seem to be most frequently applied. In this approach, the dosage of the relevant environmental factors is influencing material properties.

Rüther (2011) stated that in case of wood weathering, solar radiation and wind driven rain are assumed to be the two main driving factors for changes of surface appearance. According to Ott et al. 2015 the moisture exposure is underestimated especially when erecting tall timber buildings. As wood is a moisture sensitive material the challenge is therefore to provide fast dry out conditions after wetting for wooden elements during their service-life. This is of major importance when preventing future risk of fungal decay and material deterioration.

Exploration of non-destructive and "smart" techniques for health monitoring of wooden structures is a way to supply the "response" of the system to the above mentioned "doses". The trend for application of Internet of Things (IoT) in order to continuously monitor the structure and improve energy efficiency of building is observed currently (Casini, 2014). The method for monitoring of buildings by using multiple sensors simultaneously has become more frequent due to better representation of the real-life cases. Multi-sensor monitoring however, generates new issues and challenges, where the fusion of different sources of information is fundamental (Hua et al 2013). Selection of the optimal sensor, measurement strategy, signal processing and interpretations of results are more complex and demanding (Sandak et al. 2013, 2015).

The goal of this work was to investigate the degradation rate of thin wooden samples exposed for short term weathering. Two approaches based on expert evaluation and multi-sensor characterizations are discussed here. The attempt to link the material performance with meteorological data (cumulative solar radiation) is also presented.

2. EXPERIMENTAL METHODS

2.1 Experimental samples

Experimental samples were prepared from one piece of Norway spruce wood (*Picea abies* L. Karst.) on the slicing planner (Marunaka). The thickness of samples was ~100µm and the efficient surface exposed to weathering was 30 x 35mm (width x length respectively). Sets of samples were placed for natural exposure at 45º to the horizon, facing the four directions: North, West, East and South in San Michele, Italy (46°11'15"N 11°08'00"E). Tests were performed in 2015 for the whole month of July, which according to previous research is considered as a most severe for weathering of wood micro-sections (Raczkowski, 1980). For all duration of experiment weather data was stored and are presented in Table 1. Samples were collected after 1, 2, 4, 7, 9, 11, 14, 17, 21, 24 and 28 days exposure to natural weathering. Additionally set of samples was stored in climatic chamber for all the test duration and serve as a reference. Samples were conditioned after collection in the climatic chamber (20°C, 60%RH) to the equilibrium moisture content of ~12%.

Table 1. Meteorological data acquired during weathering test

day of exposure	Temp (mean)	∑radiation (MJ/m2)	∑ insolation (h)	Total rain (mm)	RH%	mean wind speed (m/s)
1	17.8	29.96	14.3	11.4	84.1	0.8
2	20.0	59.63	26.1	0	59.0	1.9
4	21.7	104.56	45.7	1.6	72.5	0.5
7	17.0	162.16	70.4	42.6	92.7	0.5
9	18.3	201.54	89.7	0	68.1	0.9
11	19.8	250.54	108.4	2.0	67.6	1.2
14	22.0	324.02	139.2	0.2	68.0	0.9
17	24.2	407.06	172.8	0	59.8	1.0
21	19.9	469.26	201.7	0	79.5	0.1
24	21.0	526.58	228.5	0	69.6	0.8
28	19.0	580.76	255.1	13.4	88.9	0.5

2.1 Samples characterization

2.1.1 Samples appearance

All samples were visually graded by three experts in random order. The evaluation was performed at the same time for all sets of samples after conditioning them in climatic chamber. The quality grade was provided for each sample as a subjective evaluation. The ranking scale ranged from 6 to 1, where grade "1" corresponded to the superior quality integral surface with light colour, and samples with mould presence were considered as grade "6" The scores used for samples assessment are presented in Table 2.

Table 2. Scale used for visual samples assessment

scale	description
1	Integral samples, very light colour
2	Integral samples, slight yellowing
3	Yellow samples
4	Yellow samples with small cracks
5	Presence of big cracks, samples not integral
6	Presence of mould

Digital colour images of sample surfaces were acquired after the weathering campaign on HP G2710 scanner with resolution of 300DPI. All the images were subjected for further processing and analysis. Examples of samples are presented in Fig. 1.

Figure 1. Thin samples appearance after weathering test (exposed against north)

2.1.2 Microscopic observations

Small pieces of investigated samples were prepared and glued with carbon tape sticker to the sample holder. The samples were placed in SC7620 'Mini' Sputter Coater/Glow Discharge System device and then were plasma coated for 90 seconds with 10 nm gold/palladium (Au/Pd) layer. Such prepared samples were investigated by using Hitachi TM 3030 SEM. An acceleration voltage of 15 kV was used for imaging of samples. Images were captured with three magnitudes (×100, ×500 and ×1500) with dedicated software provided by equipment producer.

2.1.3 Colour measurement

The standardized colour parameters were estimated on the basis of spectra measured by using Maya2000 (Ocean Optics) spectrometer equipped with an integrating sphere. The selected illuminant was D65 and the viewer angle was 10°. The sensor calibration was carried out with the standard white-reference and black-reference provided by the supplier. The light source was both halogen and deuterium, allowing measuring spectra in the range from UV up to NIR (200-1200nm). The colour was characterized according to the CIE L*a*b* system. Three parameters (L*, a* and b*) were computed from each spectra. Additionally samples were measured with MicroFlash 200D spectrophotometer (DataColor Int.), equipped with the integration sphere, and entrance of 18mm diameter. The values of colour coordinates (L*, a*, b*) were computed automatically by the instrument on the base of the illuminant D65 and viewer angle 10º.

2.1.4 Spectroscopic measurement

Both, near infrared (NIR) and mid infrared (MIR) spectroscopy were used for obtaining information about the molecular composition of the weathered wood surfaces. Vector N-22 (Bruker Optics GmbH) Fourier-transform NIR spectrometer equipped with fibre optic probe was used for scanning the spectra in the range from 4000cm^{-1} to 14000cm^{-1}. The spectral resolution was 8cm^{-1} and 32 scans were averaged on each measurement.

ALPHA (Bruker Optics GmbH) FT-IR spectrophotometer equipped with the external reflectance module was used for scanning the spectra in range from 400cm^{-1} to 4000cm^{-1}. The spectral resolution was 4cm^{-1} and 64 scans were averaged on each measurement in order to increase signal-to-noise-ratio. The measurement set-up allowed measurement of weathered surfaces with transmittance mode. OPUS 7.0 (Bruker Optics GmbH) software package was used for instrument control, spectra acquisition, data pre-processing and evaluation.

2.1.5 Weathering coefficient

The concept for calculation of weathering coefficient was previously presented by the authors (2015). The custom algorithm for multi-sensory data fusion and computation of weathering indicator was developed in LabView 2015 (National Instruments). The software normalizes the raw data (parameters) p_i as obtained by different sensors i and summarizes these, considering their importance (weight) w_i. The W_{ind} computation algorithm is mathematically expressed in Equation 1:

$$W_{ind} = \frac{\sum w_i \cdot p_i}{\sum w_i} \quad (1)$$

3. RESULTS AND DISCUSSION

Wood surface weathering is a very complex process affecting various surface properties at all scale levels. The evaluation of the progress of surface weathering is usually performed by means of an expert evaluation. Even if several guidelines and standards exist for assisting the evaluator, the grading procedure, is a subjective and person-dependent process. In this study three expert persons graded each sample, according to the six-point scale. The averaged results of such grading are presented in Fig. 2.

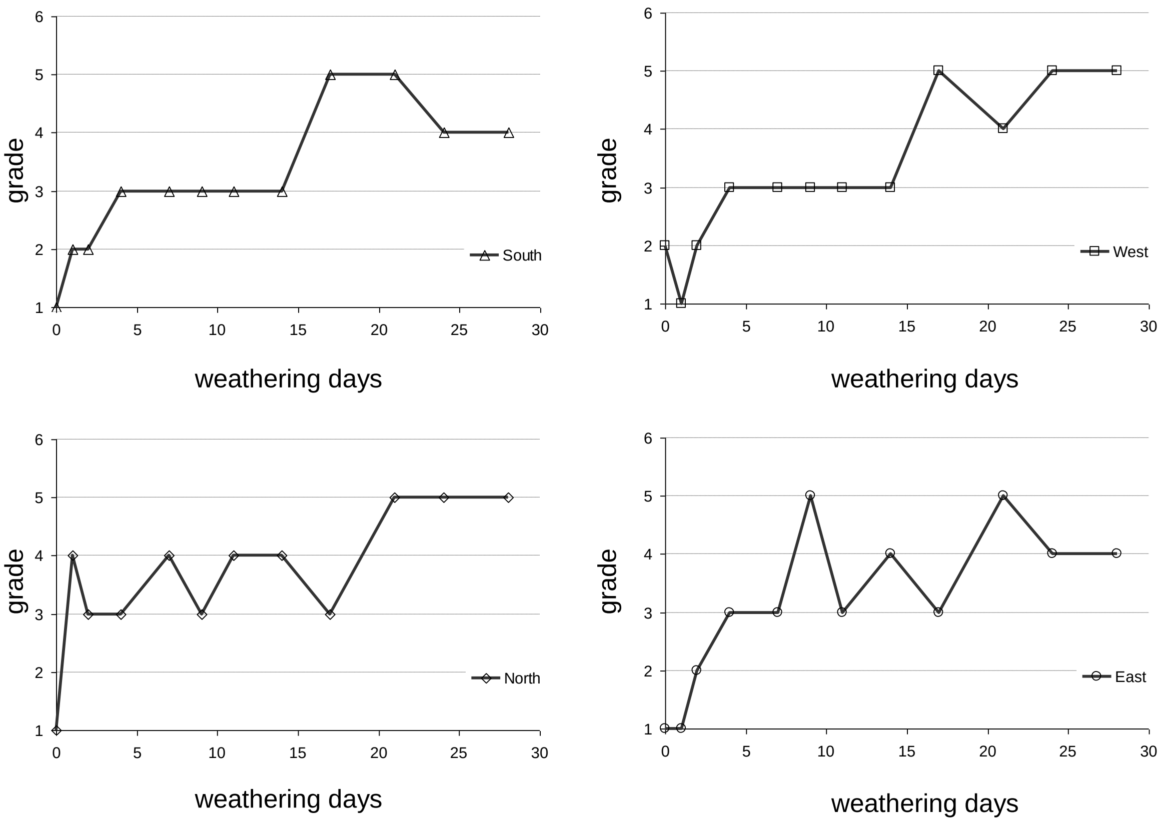

Figure 2. Expert person evaluation of the weathered surfaces quality of wood exposed to different directions

The data show a decline of the surface quality being the quality indicator along the exposure period. The perception of surface quality was varying as a function of the exposure site. Surprisingly the east and south exposures were estimated as relatively less degraded (score 4) comparing to northern and western exposures (score 5) at the end of weathering period. It can be noticed that the fluctuation of expert responses is relatively high, limiting the possibility to derive a trend analysis or any consistent conclusions.

Microscopic methods provide detailed information about surface morphology. Scanning electron microscopy (SEM) is considered to be a valuable tool for observing the microscopic anatomical details of degraded wood at down to cell wall scale, evaluating changes to the cell wall and presence of fungal activity (Hamed et al. 2012). According to Turkulin (2004) observations of the effects caused by photo degradation may provide information about the structural integrity of the wood surface and add understanding to the weathering process. The first sign of deterioration visible on the SEM images was the openings of bordered pits membranes in radial walls of early wood tracheids. With the progress of decomposition, cracks propagate through the cell wall, the surface was contaminated by dust and diagonally oriented micro-checks appeared. At the final stage (day 28) pits were completely eroded and fungal infestation (not previously seen by visual assessment) was observed. It was also noticed that western and northern exposure sites are slightly less affected by the weathering process (Fig. 3).

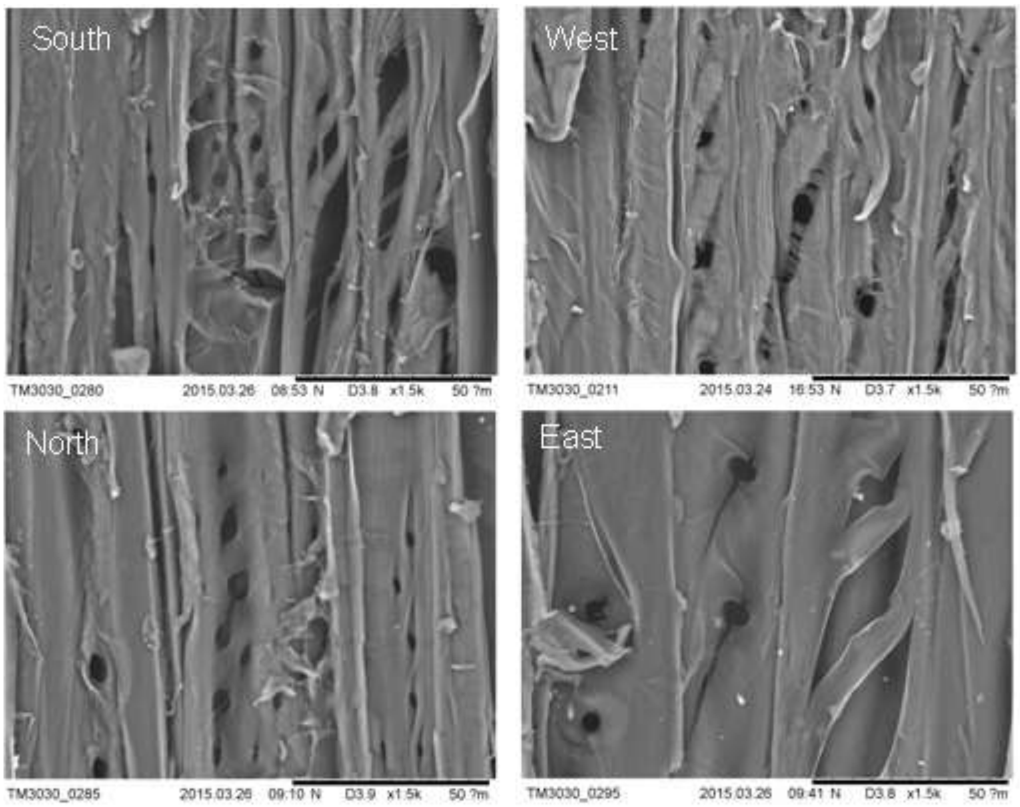

Figure 3. Late wood exposed for 28 days to different exposure sites

The alternative method to visual assessment is infrared spectroscopy since the infrared radiation reflected from the surface can be used for estimation of the physical-chemical structure of a surface (Sandak et al. 2016). Principal Component Analysis (PCA) was used in this study to analyse the spectra evaluation. PCA searches for unique properties of spectra and separates set of input data into groups of peculiar similarities allowing visualization of natural clustering of the data. The result from PCA performed on the NIR spectra of samples at the final stage of weathering is presented in Fig. 4. It can be clearly seen that spectra are clustering into various groups depending on exposure direction with exception of East and South which do not differentiate from each other. Such clustering is related to differences in the physical-chemical surface states, due to slightly varying weathering progress.

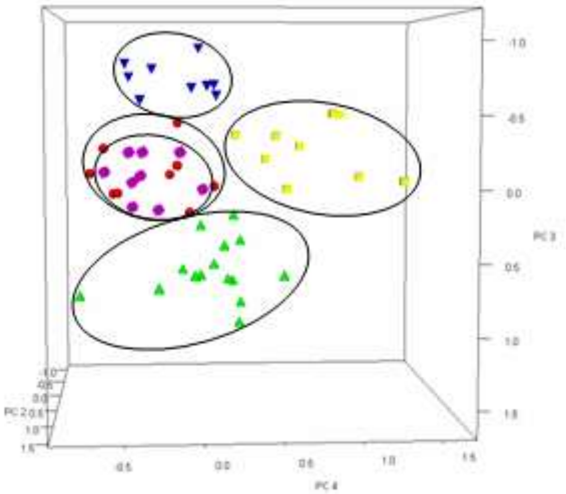

Figure 4. PCA of samples exposed for 21, 24 and 28 days against different directions:
● South ▼ West ■ North ■ East ▲ Reference

The alternative approach for quantification of the surface quality is based on the calculation of the weathering indicator W_{ind}, computed as in equation 1. W_{ind}, is an indicator suitable for presenting the combined effect of the investigated parameters. An example of the W_{ind} progress during weathering is shown in Figure 5. The colour parameters: lightness L*, colour-opponent dimensions: a*, b*, NIR absorbance at 5980cm^{-1} (band related to first overtone of CH stretching of lignin), MIR absorbance at 1505cm^{-1} (band related to aromatic ring of lignin) and PC1 computed from the NIR and MIR spectra were arbitrary selected for computation of the W_{ind} in all investigated samples. Parameters mentioned above were related to both sample appearance (colour) and chemical composition (selected lignin bands and calculated Principal Components). The importance of parameters was considered as equal, $w_i = 1$, with exception of parameters related to PC1 of NIR and MIR spectra and CIE b*, where $w_i = 0.5$. The indicator weight assignment was arbitrary choice of the expert person basing on the regularity of the signal. Similar trend to that of the subjective expert quality indicator can be noticed after plotting the W_{ind} (Fig. 5). Though, the scatter of values is highly reduced and follows logical trend of surface depreciation along the weathering time.

The concept to link spectroscopic to weather data was recently presented by Burud et al (2015). She firstly simulated the cumulated amount of solar radiation on a wooden surface exposed to four cardinal directions and correlated it with early wood spectra extracted from hyperspectral images. The Partial Least Squares (PLS) regression was used for development of the models. A high determination coefficient $R^2 = 0.798$ was obtained for validation data set indicating that the progress of degradation is clearly correlated to the solar radiation.

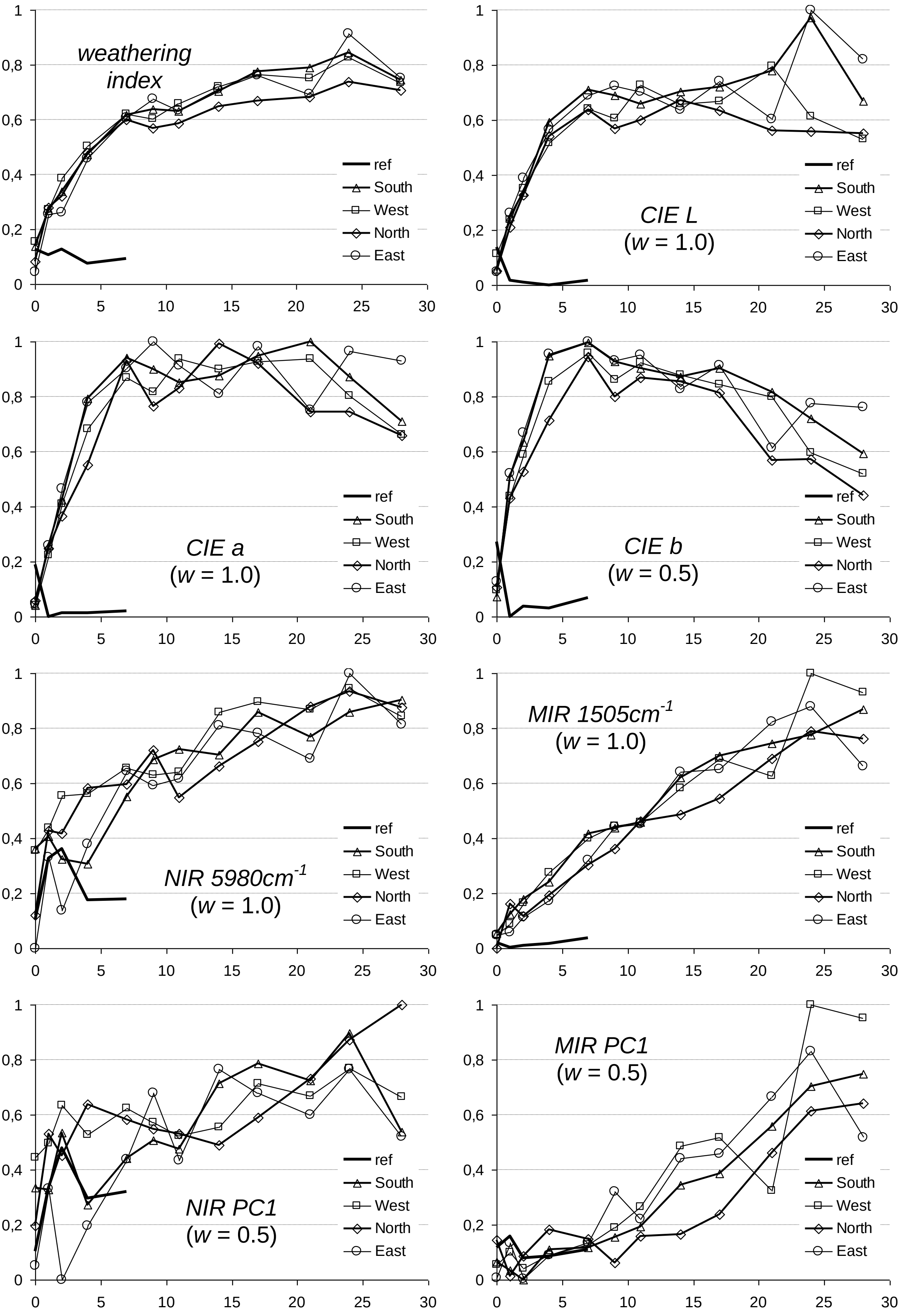

Figure 5. Progress of the weathering due to exposure duration (horizontal axis, days) and normalized components used for computation of weathering index w_{ind} (vertical axis). Note: *w* – weight or importance of the parameter

Similar approach was used in this study in order to link NIR spectra measured on thin samples. The results are presented on Fig. 6, which clearly show that also in this case the weathering progress is clearly correlated with cumulative solar radiation giving a R^2 = 0.839. However in order to develop more accurate models also wind driven rain should be taken into account as suggested by Ott et al. (2016).

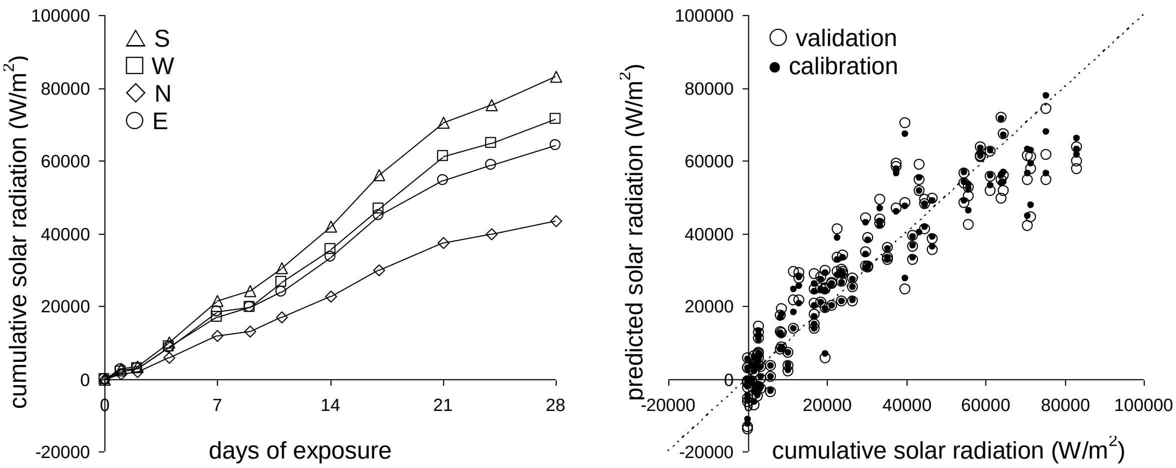

Figure 6. Cumulative solar radiation calculated for different exposure sites (left) and measured versus predicted cumulative solar radiation on the wood samples exposed in San Michele (right)

4. CONCLUSIONS

The role of the altering factors and knowledge on the weathering mechanisms are fundamental to assess the actual conditions of wooden members. Understanding of degradation processes is also essential for prediction of future performance and scheduling proper maintenance and conservation actions of wooden members. Multi-sensor data fusion was used here to merge the data acquired with various techniques and to compare it with visual assessment of the samples. Even if the weathering period was relatively short the influence of exposure direction seems to have an effect on the degradation intensity. There is a clear relationship between cumulated solar radiation and spectroscopic data.

Results of this research will be used for future determination of the weather-dose response model that can be essential to predict the future performance of timber façades elements.

4. ACKNOWLEDGMENT

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