Performance of modified wood in service – multi-sensor and multi-scale evaluation

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ABSTRACT

The performance of 120 selected façade materials provided by over 30 industrial and academic partners was evaluated during 12-month experimental campaign of natural weathering. A multi-sensor measurement chain for the acquisition of properties at different scales (molecular, microscopic, macroscopic) included both laboratory and on-site techniques. Investigated bio-materials were characterized before, during and after degradation by biotic and abiotic agents in order to provide experimental data to be used for better understanding of the bio-materials performance/degradation as a function of time and/or weather dose. Obtained data were utilized for the development series of numerical models simulating materials appearance changes along the service life of building facade. An original software simulating bio-materials' performance in any geographical location has been developed and is currently under integration with Building Information Modelling. It serves as a tool for demonstrating advantages of using bio-based materials when compared to other commonly utilized alternative resources. Results of the BIO4ever project provide solid technical and scientific knowledge, but also contribute to the public awareness by demonstrating the environmental benefits to be gained from the knowledgeable use of bio-based materials in buildings.

INTRODUCTION

Wood is a traditional material utilized for construction of buildings since beginning of civilisation. Its availability, relatively low maintenance cost and ease of processing, result in the common use as prevalent construction material for both interior and exterior applications. While possessing several advantages, such as aesthetic appeal and positive weight to load-bearing capacity ratio, unprotected wood suffers when exposed to the environmental conditions by changing its dimensions and appearance. The most susceptible parts are unprotected surfaces in outdoor environment, since these are directly subjected to ageing, weathering or decay.

Wood modification processes leads to the enhancement of desired properties by means of chemical, biological or physical agents. Wood properties are essentially determined by its chemical composition, therefore, several modification processes target specific changes of constitutive woody polymers at the molecular level. Nevertheless, some modification processes do not change the chemical composition of wood itself, but focus on the morphological or physical modification (Hill 2006). New developments in the field of wood modification offer assortment of innovative products with highly enhanced properties of natural timber. These include innovative bio-based composite materials, as well as more effective and environmental-friendly protective treatments, e.g. thermal treatment, densification, impregnation and chemical modifications. Similar revolutionary progress is observed with surface treatments including advanced coatings, or integration of nanotechnology developments in wood protection. Today's bio-based building materials, even if well characterized from the technical point of view, are often lacking of reliable models describing their performance during service life. This paper presents summary of the scientific results obtained within framework of BIO4ever project "Bio-materials for building envelope – expected performance, life cycle costing and controlled degradation".

EXPERIMENTAL

Experimental samples

Performance of 120 selected façade materials provided by over 30 industrial and academic partners from 17 countries was evaluated in several experimental configurations. The samples were classified in seven categories, according to the treatment applied: natural wood (or other bio-based material), composites, chemically modified, thermally modified, impregnated, coated and/or surface treatment and hybrid modified. The latest include combination of at least two different treatments (Table 1).

Table 1: Categories of bio-based facades materials tested within BIO4ever project

Modification process	Examples	Number of materials
natural	wood, bamboo	19
chemical	acetylation, furfurylation	5
composites	panels, bio-ceramics, tricoya, wood plastic composites	7
coating & surface treatments	different coatings, carbonized wood, nanocoatings	16
impregnation	DMDHEU, Knittex, Madurit, Fixapret	28
thermal modification	vacuum, saturated steam, oil heat treatment	20
hybrid modification	thermal treatment + coating, thermal treatment + impregnation, acetylation + coating etc.	25

An example of six radiata pine (*Pinus radiata* D.Don) samples representing different commercially available modification processes was selected for the demonstration. Weathering performance of these materials was compared with the not treated wood of scots pine (*Pinus sylvestris* L.), being usually considered as a reference material (Table 2).

Table 2: Description of experimental samples

Sample number	Wood species	Bulk treatment	Surface treatment	Product on the market
09	Radiata pine	thermal treatment + penetrating oil	-	yes
10	Radiata pine	thermal + silicate treatment	-	yes
30	Radiata pine	thermal treatment #1	coating	yes
31	Radiata pine	furfurylation	-	yes
34	Scots pine	-	-	yes
45	Radiata pine	thermal treatment#2	-	yes
51	Radiata pine	acetylation	-	yes

Selected modification processes included: acetylation, furfurylation, thermal treatment with various technologies and thermal treatment combined with impregnation and surface coating. Investigated treatments were classified as chemical, thermal and hybrid modification according to the categories presented in Table 1. All investigated modified materials are commercially available on the market.

Weathering tests

Natural weathering tests were performed in San Michele, Italy, (46°11’15’’N, 11°08’00’’E), in order to provide reference data for simulation of the bio-materials’ performance in a function of the exposure time. Samples were exposed on the vertical stands representing building façade. Stands were oriented to 4 cardinal directions. The weathering experiment was carried out for 12 months and the test is still ongoing. Presented results refer to the southern exposure of samples, with the experiment start in March 2017.

Materials characterization

High resolution photos (Nikon D5500 equipped with lenses Nikor AF-S 35mm) were regularly acquired in a monthly bases to capture the progress of the samples’ appearance change. Additionally, part of exposed samples (three replicas per cycle) was exchanged every 3 months and stored in a climatic chamber before characterization. Materials characterization included scanning with office scanner, as well as measurement of the colour (CIE L*, a*, b*), gloss, roughness (in two cardinal fibre directions), and spectroscopy in VIS, NIR and IR ranges with laboratory and portable spectrometers. The NIR bands were assigned according to Schwanninger *et al*. (2011a).

Table 2: Description of experimental samples

band number	Wavenumber (cm-1)	Wood component	Functional group
1	4198	holocellulose	CH
2	4280	cellulose	CH, CH_2
3	4339	holocellulose	CH
4	4404	cellulose, hemicellulose	CH, CH2, OH, CO
5	4620	cellulose, hemicellulose	OH, CH
6	4686	acetyl groups in hemicellulose	CH_3, C=C, C=O
7	4890	cellulose semi-crystalline and crystalline	OH, CH
8	5219	water	OH
9	5464	cellulose semi-crystalline and crystalline	C=O
10	5587	cellulose semi-crystalline and crystalline	CH
11	5658	unassigned	CH_2
12	5800	hemicellulose (furanose/pyranose)	CH
13	5883	hemicellulose	CH
14	5951	hemicellulose	CH_3
15	5980	lignin	CH
16	6009	hemicellulose	CH
17	6121	cellulose	OH
18	6287	cellulose crystalline	OH
19	6450	cellulose crystalline	OH
20	6722	cellulose semi-crystalline	OH
21	6785	cellulose	OH
22	7008	amorphous cellulose/water	OH
23	7300	hemicellulose	CH_3
24	7418	hemicellulose	CH_3

RESULTS AND DISCUSSION

Materials appearance

The intensity of weathering depends on timber species, architectural design solutions, function of product, finishing technology applied for wood protection, and on the specific local conditions. All experimental samples were prepared from radiate pine and exposed in same climatic conditions for identical period. Therefore, it can be stated that the difference in performance are modification process dependent. The appearance of investigated materials in the function of time is presented in Figure 1. It can be seen that some of the materials are relatively stable regarding colour and pattern changes. The material #10 become lighter after 3 months exposure period. However, according to the technical sheet provided by producers it was desired to "silver off" the surface due to weathering and then maintain that appearance unchanged during service life. Materials #31, #34, #45 and #51 contain noticeable mould discoloration on their surfaces. The visual assets in materials outlook were confronted with changes in colour coordinates. The lightness (*CIE L*) parameter was constant in materials with relatively stable colour (e.g. #09, #30). Even if the weathering test was performed for 12 months, none of investigated materials became grey, corresponding to the usual colour of wood long-term exposed to natural weathering. However, an increase of gloss parameters (especially across the fibres) was observed with the progress of the weathering process.

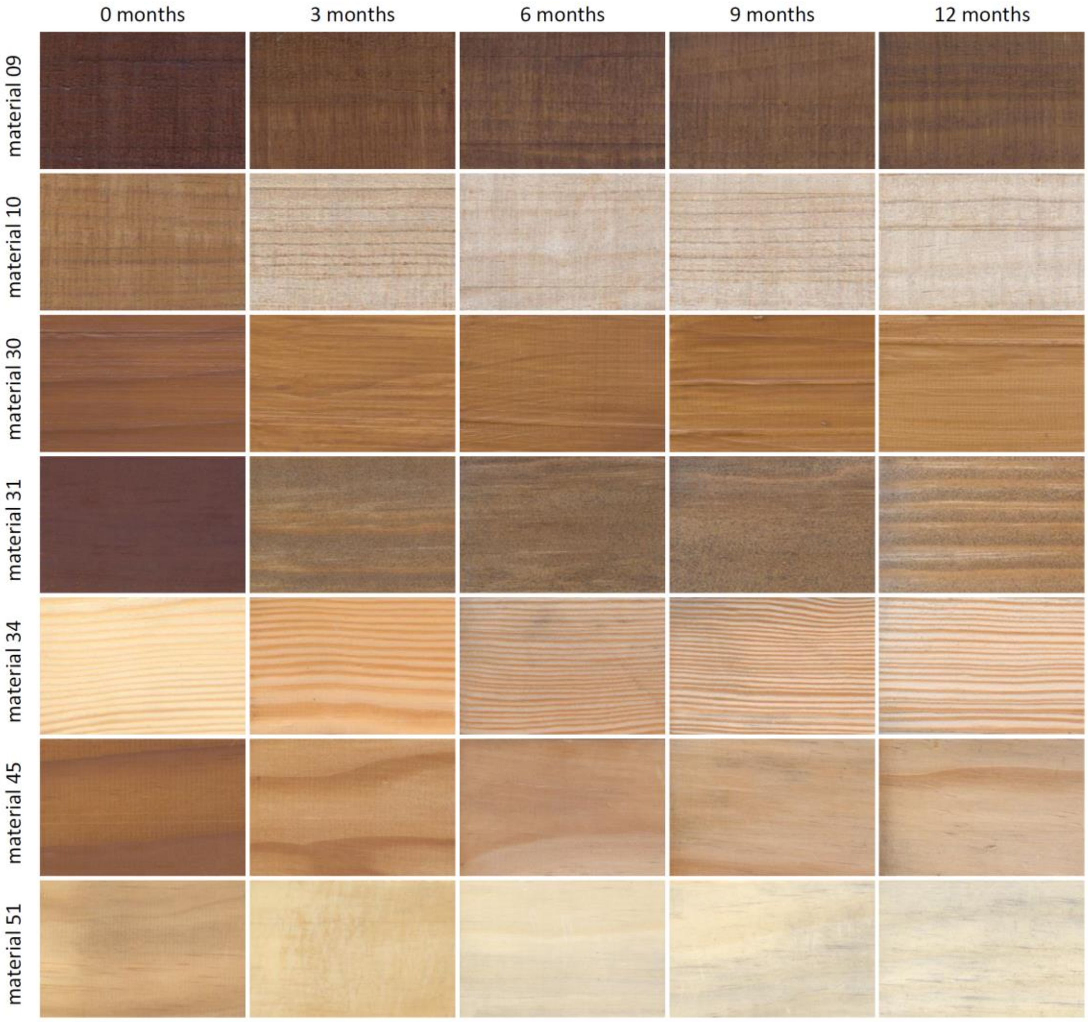

Figure 1: Change of samples appearance due to natural weathering in San Michele all'Adige (Italy)

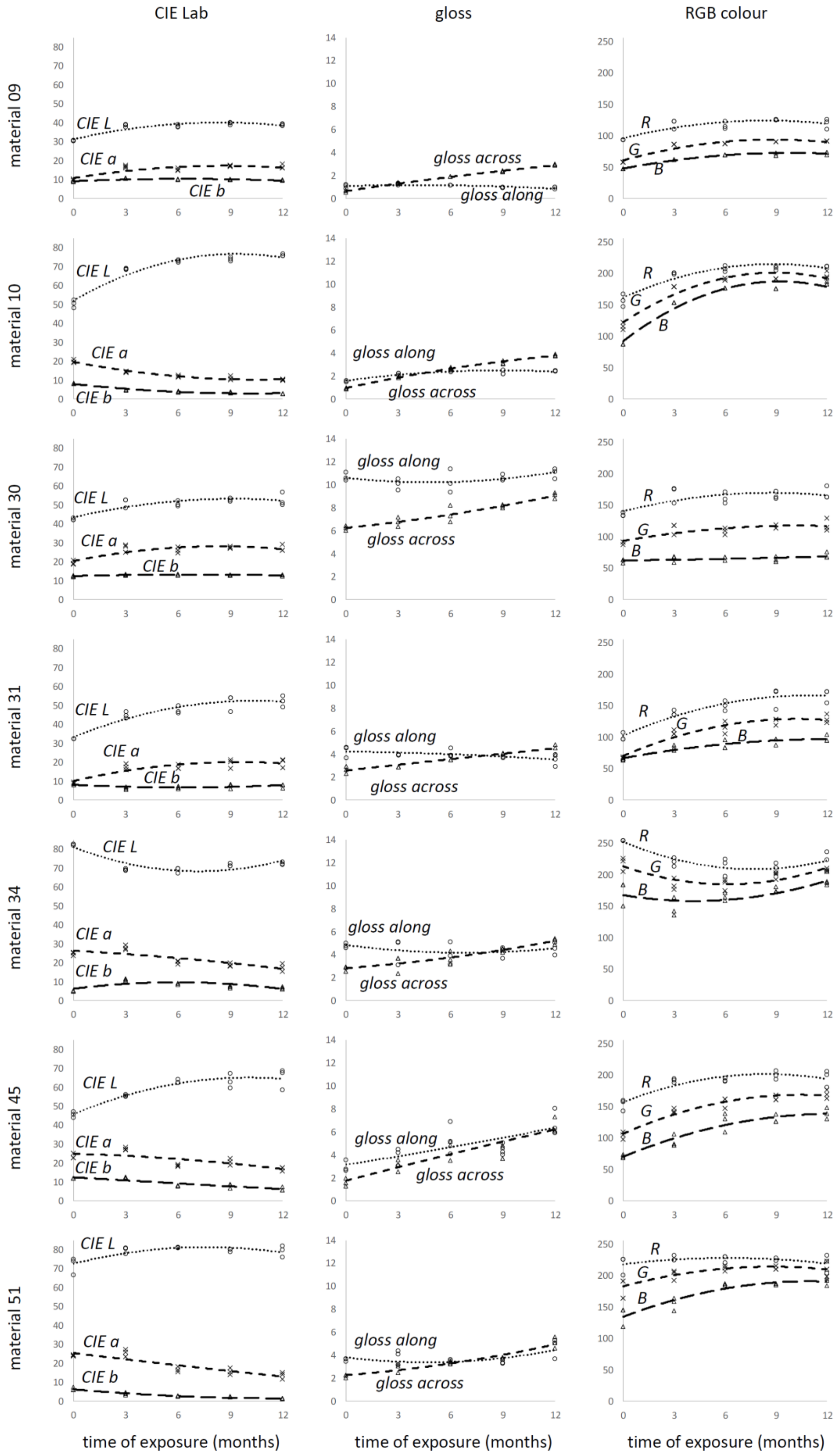

Figure 2: Change of CIE Lab, gloss and RGB parameters due to natural weathering

Chemical changes

NIR spectroscopy was used for non-destructive investigation of chemical composition of samples at different stages of their exposure. However, investigated materials being modified with several modification methods exhibit noticeable differences in their chemical composition already at the initial stage before any weathering. Consequently, differences in appearance of samples and their performance during service life are associated with their chemical composition. Figure 3 present the second derivative of NIR spectra, where functional groups related to key wood components as well as specific futures being results of wood modification are evidenced. The spectra of chemically modified wood (e.g. furfurylated or acetylated) are clearly varying from the other treatments. The highly branched and cross-linked furan polymers are chemically bonded with the wood chemical components as a result of furfurylation (Lande *et al*. 2008). Investigated furfurylated wood (pink spectrum, material #31) possessed spare peak at 6121cm^{-1} (17) not detected in other materials. Acetylation of wood results in a decrease of the number of hydroxyl groups as well as in the increase of the acetyl groups (Schwanninger *et al*. 2011b). In case of acetylated wood (material #51, black line on the Figure 3) shift of several peaks (e.g. 4, 8 or 12) toward higher wavenumbers occurred. Additional peaks 14, 16, 23 and 24, being assigned to CH_3 groups in acetyl ester groups in hemiceluloses, are clearly visible. Likewise, hydroxyl groups detected in the range 6000-7000 cm^{-1} are not evident due to reduction of their number caused by acetylation. Other processes (such as thermal modifications) affected the hemicellulose content, evidenced as a slight reducing of CH functional groups (spectral bands 12 and 13).

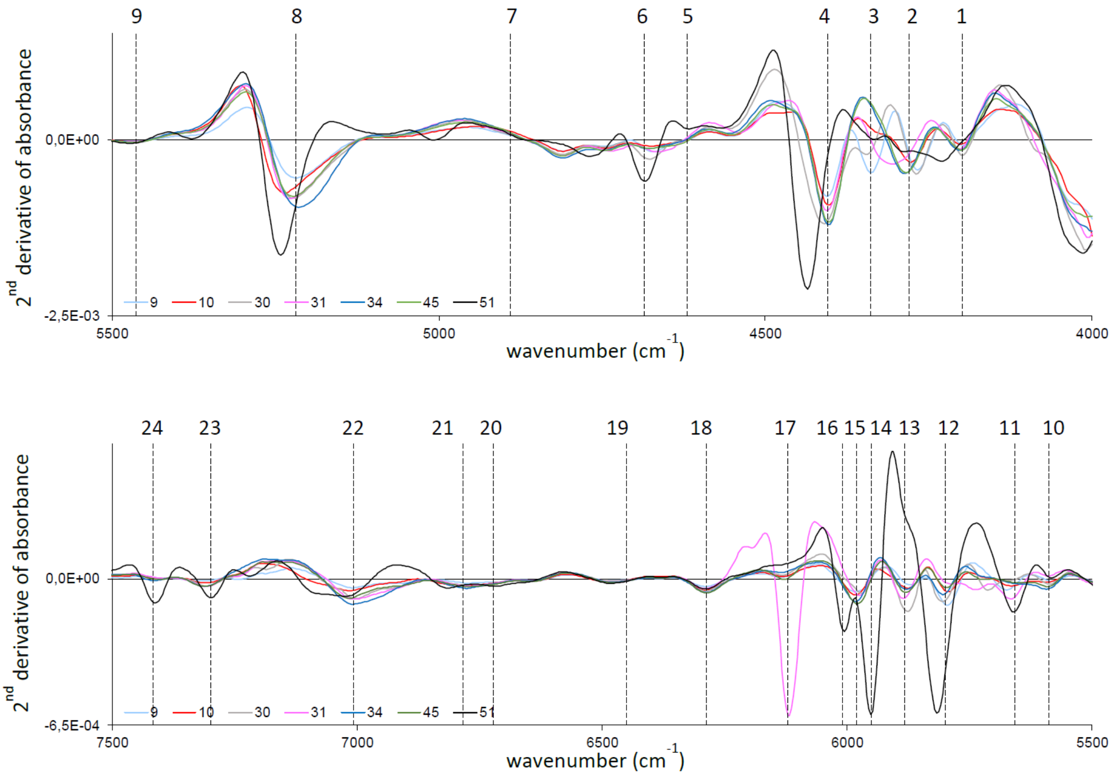

Figure 3: Second derivative of NIR absorbance spectra of investigated materials at their brand new stage

It is expected that natural weathering might affect the chemical composition of materials modified in different processes to various extends. It is due to materials' heterogeneity and variances in their response to the weathering mechanisms. Figure 4 presents a summary of such differences as recorded in the second derivative NIR spectra. In this case, subtraction of reference spectrum from the spectrum of 12 months exposed wood highlights the spectral differences. It is evident that mechanisms of degradation are different for materials after various treatments. Bands 4 and 8 assigned to carbohydrates and water respectively changed in all investigated materials. Even though, the shift of both peaks toward higher wavenumbers is noticed in material #51 (acetylated wood). The presence of positive peak 4 indicates degradation of the functional groups in cellulose and hemicellulose. The reference sample (material #34, pine wood) exhibits the highest changes (positive peaks) for bands: 1, 2, 4 and 8, what indicates decreasing of the functional groups quantity. The distinctive peak 17 observed in furfurylated wood is positive, (as well as bands 1, 3 and 4) what corresponds to the degradation of this component due to weathering. It is important to notice, that functional groups assigned to crystalline and semi-crystalline cellulose (bands: 7, 9, 10, 18, 19 and 20) did not degraded due to weathering in all investigated materials. Cellulose, being more resistant to weathering, became more abundant on the weathered wood surface. According to Kalnins and Feist (1993), the weathering leads to increases of hydroxyl concentration on the wood surface. It is confirmed by slight increase of band 22, assigned to the OH groups in amorphous cellulose. On the contrary, band 15 assigned to functional group of lignin was degraded for all investigated materials, but with different extends. Analysis of the specific degradation kinetics for particular functional groups of wood constituents allow deep understanding of the weathering mechanisms. It highlights week points of investigated materials that might be further improved by optimizing modification processes.

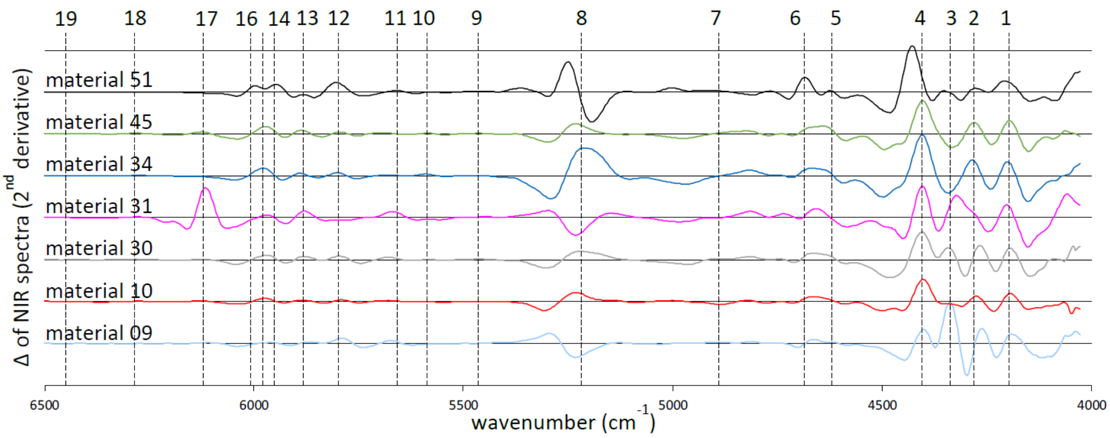

Figure 4: Change in NIR spectra due to 12 months of natural weathering

CONCLUSIONS

The main BIO4ever project output, beside of extensive data base of bio-based materials performance is an interactive software simulating the aesthetic performance of bio-materials integrated with LCA interactive calculation for maintenance operations. At this stage of the software development, all the available data regarding appearance change of each biomaterial in time (CIE Lab, RGB, gloss), weather dose map and specific building layout (UV surface map) are merged together allowing 3D model visualization (Sandak *et al*. 2018a). Time series of pictures that were acquired during exposure of tested materials, presented in Figure 1, are used for the interactive simulation of façades appearance. Software users will be able to choose a material from the database, select the building location and then simulate the structure look at the brand new stage and during its service life (Sandak *et al*. 2018b). The tool, dedicated for investors, architects, construction engineers, professional builders, suppliers and other relevant parties, including also final customers is now under extensive validation and integration with the BIM software.

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