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Evaluation of Weathering of Furfurylated Wood Decks after a 3-year Outdoor Exposure in Greece

Procjena utjecaja atmosferilija na drvene podove zaštićene furfuralom nakon tri godine izloženosti vanjskim uvjetima u Grčkoj

Original scientific paper • Izvorni znanstveni rad
Received – prispjelo: 10. 8. 2014.
Accepted – prihvaćeno: 20. 5. 2015.
*UDK: 630*833; 630*841.52*
doi:10.5552/drind.2015.1425

ABSTRACT • *Furfurylation is a modification process carried out in order to improve the biological resistance and dimensional stability of wood. In this research work, a three-year outdoor weathering test of furfurylated wood was performed using the following wood materials: a deck of furfurylated radiata pine (Pinus radiata), a deck of furfurylated maple (Acer spp.), a deck of furfurylated southern yellow pine (Pinus spp.), and a control deck of Ipê wood (Handroanthus spp.) that was used for comparative reasons. The decks, without any protection or finishing, were exposed for 36 months in Karditsa, Greece in order to evaluate some physical and structural properties of wood such as colour, staining, distortion, surface cracking and end splitting. All tested decks exhibited colour changes that were perceptible by the naked eye and much higher during the first twelve months of weathering. The three furfurylated wood decks showed smaller total colour changes as compared to those of Ipê control deck. In respect to surface cracking, furfurylated radiata pine deck generally showed minor surface cracks, while furfurylated maple deck presented the lowest degree of surface and end splitting. In overall, the furfurylated wood decks tested performed very well and showed no signs of black staining (except for the southern yellow pine deck) and no fungal or mould decay after three years of outdoor exposure.*

Key words: *furfurylated wood, wood decks, weathering test, Kebony wood*

SAŽETAK • *Furfuralizacija je postupak modifikacije koji se provodi kako bi se poboljšala biološka otpornost i dimenzionalna stabilnost drva. U ovom je istraživačkom radu provedeno trogodišnje izlaganje drva modificiranog furfuralom atmosferilijama na otvorenom, pri čemu su upotrijebljeni ovi drvni proizvodi: pod od furfuralom obrađenog drva bora (Pinus radiata), pod od furfuralom obrađenog drva javora (Acer spp.), pod od furfuralom obrađenog drva južnoga žutog bora (Pinus spp.) te kontrolni uzorak poda od ipe drva (Handroanthus spp.), koji je služio za usporedbu. Drveni podovi, bez ikakve zaštite ili površinske obrade, izloženi su 36 mjeseci u gradu Karditsi u Grčkoj kako bi se procijenila neka fizikalna i strukturna svojstva drva kao što su boja, obojenost, defor-*

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macije, površinske pukotine i cijepanje na čelima. Na svim ispitanim uzorcima zamijećena je promjena boje koja se vidi golim okom i mnogo je jača tijekom prvih dvanaest mjeseci izlaganja. Tri uzorka poda od drva modificiranog furfuralom pokazala su manje ukupne promjene boje u usporedbi s promjenama boje kontrolnog uzorka od ipe drva. Vezano za površinske pukotine, rezultati su pokazali da su na modificiranom drvu bora nastale vrlo male površinske pukotine, dok je na uzorcima od modificiranog drva javora uočeno najmanje površinskih pukotina i cijepanja drva na čelima uzoraka. Općenito, uzorci podova od furfuralom modificiranog drva pokazala su dobru otpornost na atmosferilije i na njima nije bilo znakova crnjenja (osim uzoraka od žutoga bora) a na uzorcima ni nakon tri godine izloženosti na otvorenome nisu primijećene ni gljivice ili plijesni.

Ključne riječi: *drvo modificirano furfuralom, drveni podovi, test izlaganja atmosferilijama, drvo Kebony*

1 INTRODUCTION
1. UVOD

During the recent years, wood modification has attracted increasing interest as an alternative method for improving the durability of wood without the use of toxic substances. According to Hill (2006): *"the modified wood should itself be non-toxic under service conditions and there should be no release of any toxic substances during service or at the end of service life"*. Wood constituents can be physically changed and their structure can be chemically modified. Both of these changes can lead to a more durable wood (Rowell, 1991). There is a number of ways to chemically modify the cell wall polymers and the most abundant reactivity regions are the hydroxyl groups. The hydroxyl groups in the wood polymers (cellulose, lignin, hemicelluloses) are the most reactive sites. Moreover, these are responsible for the dimensional instability through their hydrogen bonding to water. Chemical modification of wood by reacting hydroxyl groups with a covalently bounded less hydrophilic group leads to an increased dimensional stability (Rowell, 1991; Larsson-Brelid, 1998; Rowell, 2005; Hill, 2006). Presently, very little is known about the mode of action for modified wood, while some main hypotheses have been suggested by Hill (2006): *"a) the equilibrium moisture content is lowered in modified wood, and hence it is harder for fungi to get the moisture required for decay; b) there is a physical blocking of the entrance of decay fungi to micropores of the cell walls; and/or, c) inhibition of action of specific enzymes"*. Amongst other significant technologies, one important modification technology is that of wood furfurylation (Schneider, 1995; Westin, 1996; Lande *et al.*, 2004; Lande, 2008). Furfurylated wood is modified by furfuryl alcohol, which is a renewable chemical (Larsson-Brelid, 2013) derived from agricultural waste like sugarcane and corn. The modification with furfuryl alcohol is carried out by impregnating the wood structure with a polymerisable mixture of furfuryl alcohol and catalyst. After that the wood structure is heated to polymerise. The purpose of furfurylation is to improve the wood properties like resistance to decay and moisture (Lande *et al.*, 2004 and 2008). Early research on this type of wood modification was implemented by Alfred Stamm (1977), and in the early '90s it was continued by Schneider and Westin, who almost simultaneously developed similar catalytic systems for the furfurylation of wood (Schneider, 1995; Westin, 1996). They both used cyclic carboxylic anhydrides. Furfuryl alcohol molecules can, due to their high polarity, penetrate very well into the wood cell wall and polymerise in situ. This yields a permanent swelling of the wood cell walls. Wood furfurylation leads then to a high protection against biodegradation by fungi, bacteria and marine borers, while it increases the hardness, lowers the equilibrium moisture content, and improves largely the dimensional stability of wood. Furthermore, the leachates from furfurylated wood have negligible toxic effects (Pilgård *et al.*, 2010). Anti-shrinking/swelling efficiency has been reported to range from 30 % to 80 % depending upon chemical formulations and wood species used (Lande *et al.*, 2004). A moderate loading of furfuryl alcohol polymer into wood provides a biological resistance suitable for ground contact or marine use (Lande *et al.*, 2004; Westin and Alfredsen, 2007; Venås, 2008; Lande *et al.*, 2008). This modified wood has a dark brown colour, which is attractive, as it makes it look like the dark, expensive tropical hardwoods (Larsson-Brelid, 2013). Low loading gives sufficient biodegradation protection for above-ground exterior uses (Westin and Alfredsen, 2007). As reported by Lande *et al.* (2008), furfurylated wood has greater hardness and rupture properties as compared to untreated wood, while it is more brittle. In terms of weathering performance, Temiz *et al.* (2007) reported that furfurylated wood showed only slightly higher resistance to accelerated weathering than untreated wood.

Today, furfurylated wood is produced at a commercial scale by the manufacturing company Kebony AS in Norway (Larsson-Brelid, 2013). The process is based on a full cell (vacuum/pressure) impregnation with a solution followed by an intermediate vacuum drying step before steam curing and drying (post curing). The impregnation liquid is an aqueous solution containing mostly furfuryl alcohol, catalysts and buffering agents (Larsson-Brelid, 2013). Several outdoor tests have been performed up to date in order to demonstrate the high durability and biological resistance of furfurylated wood in exterior applications (Westin and Alfredsen, 2007; Venås, 2008; Lande *et al.*, 2008; Larsson-Brelid, 2013).

Therefore, the aim of this work was to evaluate some physical and structural properties of furfurylated wood decks, such as colour, staining, distortion, surface cracking and end-splitting, after a 36-month outdoor weathering test in a typical southern Europe climatic area like Greece.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Materials
2.1. Materijali

For the conduction of this work, the following wood materials were used: (i) one deck of furfurylated radiata pine *(Pinus radiata)*, (ii) one deck of furfurylated maple *(Acer spp.)*, (iii) one deck of southern yellow pine, SYP, *(Pinus spp.)*, and (iv) one deck of Ipê *(Tabebuia spp.)* as a control deck. The first three decks were prepared and delivered by Kebony AS (Norway), while Ipê deck was assembled by the Research Lab of Wood Science and Technology (WST) in Karditsa, Greece. All decks had surface dimensions of 80 cm x 120 cm and were made by planks having a 22 mm thickness; they were assembled together using stainless screws and having a 6 mm free width in between them. All wood planks used were without protection or finishing.

2.2 Methods
2.2. Metode

The wood decks having tangential surfaces were placed horizontally on polystyrene sheets in the terrace of WST to facilitate free distortion, and exposed outdoors for the period May 2011 to May 2014, at Karditsa, Greece. During the 36-month period (months 6, 12, 24 and 36), some physical and structural properties of the wood decks like colour, black staining, distortion, cracking and end-splitting, were monitored. Concerning colour determination, twelve colour measurement points were marked up on each deck (Fig. 1). Careful cleaning of the surfaces was made prior to each measurement. The determination of the colour coordinates was carried out by using a BYK-Gardner type colourimeter, having a circular measuring area with a diameter of 20 mm. Applying the CIELAB colour system, the colour parameters L^* (lightness), a^* (redness) and b^* (yellowness) as well as the total colour changes (ΔE^*) were determined in each weathering time interval (6th, 12th, 24th and 36th month). The total colour changes (ΔE^*), which were caused by weathering, were calculated using the following equation:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Where: ΔL^*, Δa^* and Δb^* are the changes of the colour coordinates L^*, a^* and b^* for the respective time intervals, compared to the initial non-weathered surfaces.

Evaluation of black staining was made by visual observation. All decks were carefully examined for any black stains or spots due to discolouration or negative effects of high moisture over long periods, or other reasons. The distortions in wood decks were measured (Fig. 3) with a dial gauge equipped with a straight stainless steel bar over the axes shown in Fig. 2 for each wooden plank. Initial control for distortions was made in all tested materials at the beginning of the work (May 2011). It is well known that distortions such as cupping are influenced by the shrinking-swelling anisotropy. However, furfurylated wood has been found to exhibit up to 60 % reduction in anisotropy (Lande *et al.*, 2004; Lande *et al.*, 2008).

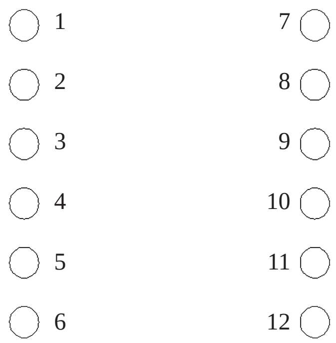

Figure 1 Colour measurement points on each of the testing decks (Note: the standard platform size of each deck was 80 cm x 120 cm; 5 planks in total; the mounting gap was ca. 3mm)
Slika 1. Točke mjerenja boje na svakom uzorku drvenog poda (napomena: standardna veličina uzorka ploče poda bila je 80 cm x 120 cm; ukupno je bilo pet ploča poda; praznina pri ugradnji bila je oko 3 mm)

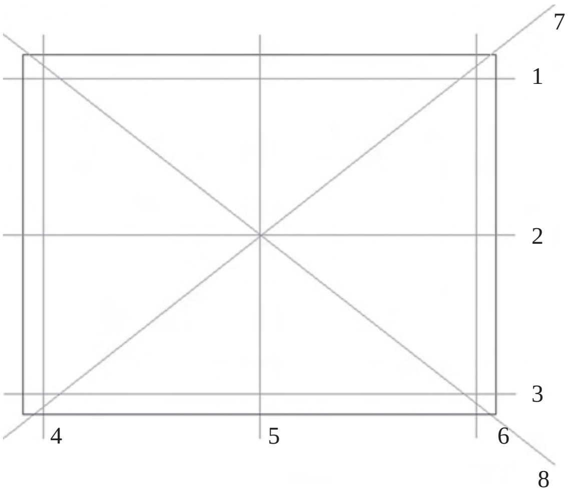

Figure 2 Distortion measurement axes
Slika 2. Osi mjerenja deformacije

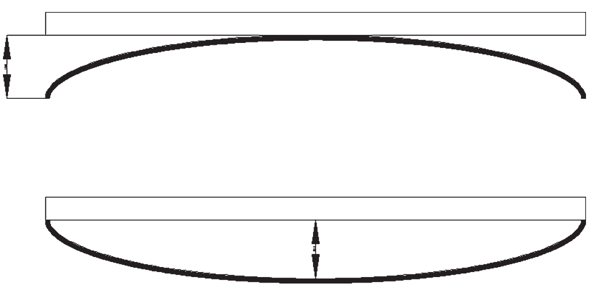

Figure 3 Determination of distortion as measured in a wood deck
Slika 3. Određivanje deformacije drvenih podova

In terms of surface cracking and end-splitting, initial control was made in all tested materials, and photographs were taken. All wood materials initially contained no cracks. For each time interval, the decks were observed carefully and respective photographs of the surface and edge cracks were taken. It should be noted that periodical measurements of the moisture content were made during the test by measuring the mass weight of each testing deck, with a conventional balance.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

All tested decks appeared to exhibit extensive greying effects on their surfaces after three consecutive years of outdoor weathering, while no signs of fungal decay or mould was observed in the decks. The mean values of the determined colour coordinates and total colour changes of the wood decks are shown in Table 1. Total colour changes (ΔE*) are plotted in Fig. 4. Lightness (*L**) changes are presented both in absolute values (Fig. 5), and in proportional changes (Fig. 6). The homogeneity of the colour changes, that is, the standard deviation changes of ΔE* values, is also presented in Fig. 7.

Concerning the changes in lightness, from Figs. 5 and 6, it can be concluded that after 36 months, the specimens tested showed increased *L** values due to the weathering effect. Ipê and furfurylated maple showed the largest lightness increases (28 % and 19 %, respectively) compared to the initial values, while furfurylated radiata pine and SYP samples showed the lowest increases (3 % each). Throughout the second weathering year, the changes in lightness were much smaller compared with those of the first year. All wood decks showed reductions in redness, but in positive values of the parameter *a** (redness factor).

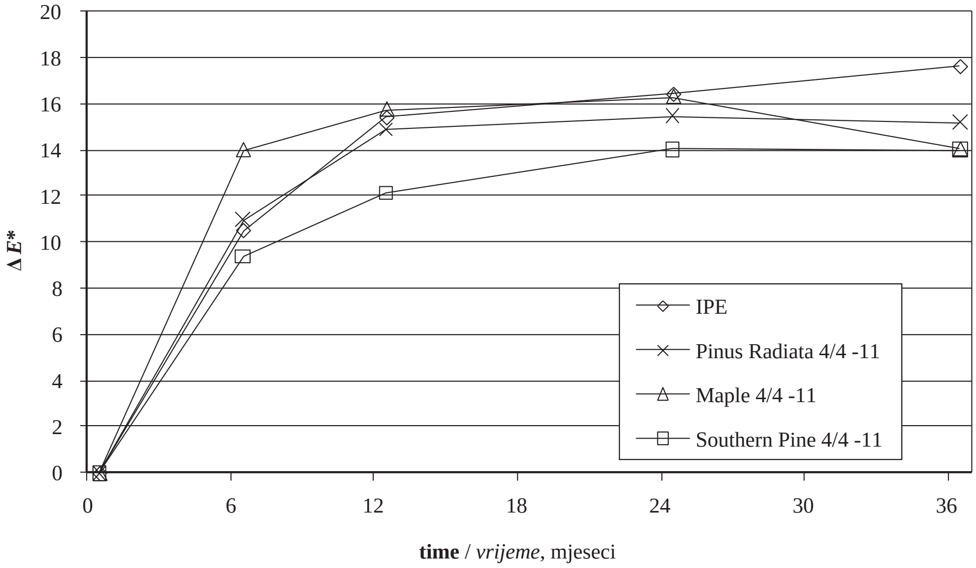

Figure 4 Total colour changes (Δ*E** value) of the wood decks throughout the weathering period
Slika 4. Ukupna promjena boje (vrijednost Δ*E**) drvenih podova tijekom razdoblja izlaganja atmosferskim utjecajima

Table 1 Mean values of the determined colour coordinates and total colour changes of furfurylated (FF) wood decks & control Ipê deck throughout the weathering period
Tablica 1. Srednje vrijednosti određenih koordinata boje i ukupne promjene boje furfuralom modificiranog drva i kontrolnog uzorka tijekom razdoblja izlaganja

Colour parameter *Parametar boje*	**Deck type** *Vrsta poda*	**Months of weathering (time intervals) /** *Mjeseci izlaganja*				
		0	6	12	24	36
Mean *L**	Ipê (control) / *kontrolni uzorak*	40.59	49.68	48.51	47.05	51.47
	FF Radiata pine / *FF borovina*	33.95	43.17	43.96	43.94	45.42
	FF Maple / *FF javorovina*	39.54	49.18	41.31	43.55	47.04
	FF Southern yellow pine / *FF žuta borovina*	30.42	37.21	38.28	39.67	40.86
Mean *a**	Ipê (control) / *kontrolni uzorak*	9.61	7.81	2.19	-1.15	1.71
	FF Radiata pine / *FF borovina*	9.01	6.76	2.01	1.39	2.27
	FF Maple / *FF javorovina*	9.80	5.60	1.89	1.59	2.66
	FF Southern yellow pine / *FF žuta borovina*	7.07	7.22	1.86	0.82	1.67
Mean *b**	Ipê (control) / *kontrolni uzorak*	16.47	12.98	7.20	8.03	6.50
	FF Radiata pine / *FF borovina*	15.23	11.63	7.52	6.96	8.88
	FF Maple / *FF javorovina*	19.05	11.44	6.34	6.26	10.09
	FF Southern yellow pine / *FF žuta borovina*	11.35	11.21	7.52	6.59	7.17
Mean Δ*E**	Ipê (control) / *kontrolni uzorak*	0	10.53	15.41	16.43	17.63
	FF Radiata pine / *FF borovina*	0	10.99	14.89	15.46	15.19
	FF Maple / *FF javorovina*	0	13.98	15.73	16.28	14.02
	FF Southern yellow pine / *FF žuta borovina*	0	9.37	12.12	14.05	14.00

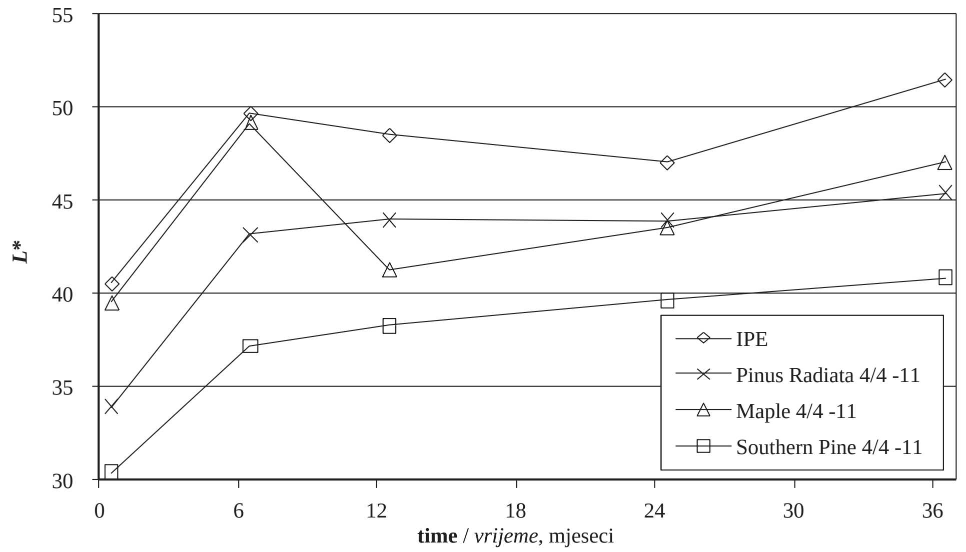

Figure 5 Absolute changes in lightness (L* value) of the wood decks throughout weathering
Slika 5. Apsolutna promjena svjetline (vrijednost *L**) drvenih podova tijekom razdoblja izlaganja atmosferskim utjecajima

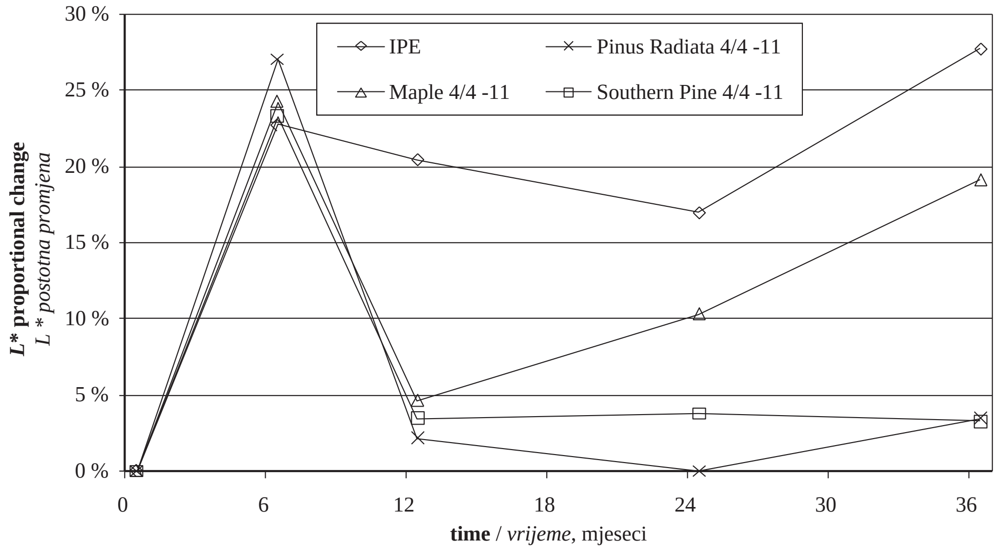

Figure 6 Proportional (%) changes in lightness (L* value) of the wood decks throughout weathering
Slika 6. Proporcionalna (%) promjena svjetline (vrijednost *L**) drvenih podova tijekom razdoblja izlaganja atmosferskim utjecajima

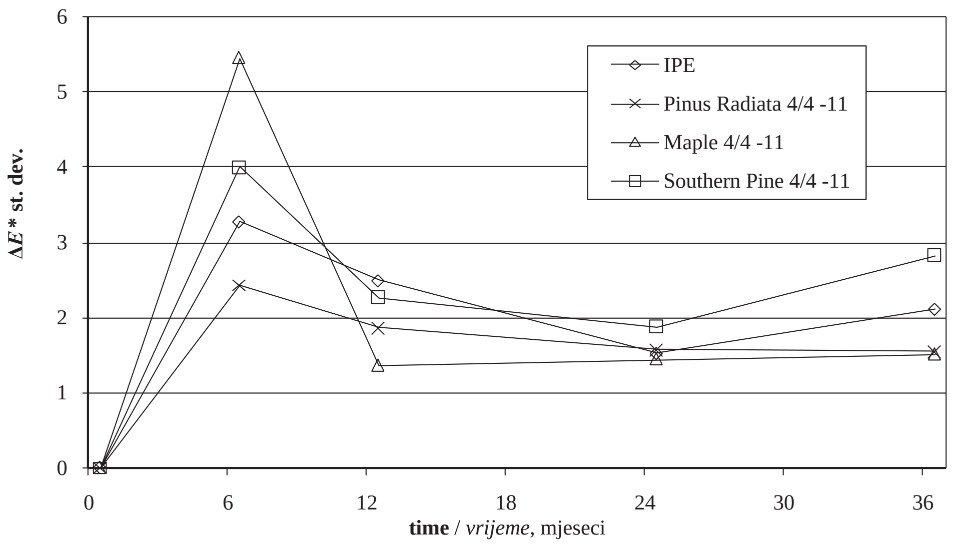

Figure 7 Standard deviation changes of Δ*E** values of the wood decks throughout weathering
Slika 7. Standardna devijacija ukupne promjene boje (vrijednost Δ*E**) drvenih podova tijekom razdoblja izlaganja atmosferskim utjecajima

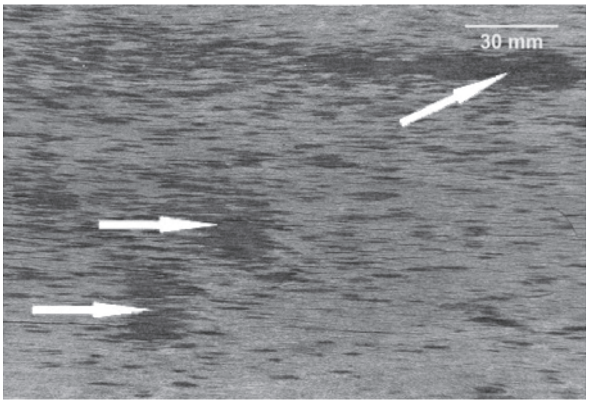

Figure 8 Some mild grey spots appearing in the furfurylated maple wood deck (at the end of 3rd year)
Slika 8. Neke blage sive pjege koje su se pojavile na podu od furfuralom modificiranog drva javora

Natural weathering induced reduction in yellowness in all of the decks; this was larger throughout the first year, but much smaller throughout the second and third weathering year. Concerning the total colour changes, after 36 months of weathering, all tested decks exhibited ΔE^* values in the range of 14.0 to 17.6; apparently, these colour changes were perceptible by the human eye. Furfurylated decks showed less total colour differences (14.0-15.2) as compared with the control deck (17.6). Among the furfurylated decks, the lowest total colour changes took place in SYP and maple decks (14.0 and 14.02, respectively) and the largest ones in radiata pine deck (15.19). As expected, the total colour changes were larger throughout the first year of weathering, and quite milder throughout the following two years of weathering.

In terms of the homogeneity of colour changes, furfurylated maple deck showed the most severe changes during the first six months of weathering and much lower ones during the next years. This could be attributed to the formation of some grey spots on the surface of furfurylated maple deck (Fig. 8). This may be attributed to the remaining chemicals from the treatment, and/or higher concentration of catalyst used.

Furthermore, furfurylated SYP deck showed some black staining spots (Fig. 11) in the surface during the third year of weathering.

It was observed that the approx. moisture content of wood decks ranged between 10-22 %, showing that the fibre saturation point (~30 %) never surpassed during the test. Consequently, it seems that the moisture content of wood has only a limited influence on the colour coordinates, if moisture content is below the fibre saturation point (Németh *et al.*, 2013).

The results from the distortion measurements are shown in Table 2. From that, it can be concluded that after 36 months of outdoor weathering, among all tested decks, the least distorted deck was that of furfurylated maple wood deck, followed by the furfurylated radiata pine wood deck. Noticeably, the most distorted deck was the Ipê control deck.

Table 2 Distortion absolute values (in mm) of all tested decks after the 36-month outdoor exposure (*Note: Comparison is made among the testing wood decks)*
Tablica 2. Apsolutne vrijednosti deformacije za sve uzorke drvenih podova nakon 36 mjeseci izlaganja na otvorenome (napomena: usporedba je napravljena između uzoraka u eksperimentu)

No	Control *Kontrolni uzorak*	Radiata pine *Borovina*	Maple *Javorovina*	Southern pine *Južna žuta borovina*
1	1.07	0.31	0.08	0.95
2	0.94	0.82	0.13	1.13
3	0.99	1.34	0.05	1.49
4	0.81	0.98	3.01	2.46
5	0.46	0.96	0.14	0.31
6	2.18	0.65	0.02	0.24
7	2.96	1.03	0.09	1.31
8	3.29	1.79	0.77	0.07

- Intense distortion / *intenzivna deformacija*

- Mild distortion / *blaga deformacija*

Figure 9 Radiata pine (Kebony) deck surface cracking appearance after 36 months of weathering
Slika 9. Površinske pukotine na uzorcima poda od drva bora nakon 36 mjeseci izlaganja utjecaju atmosferilija

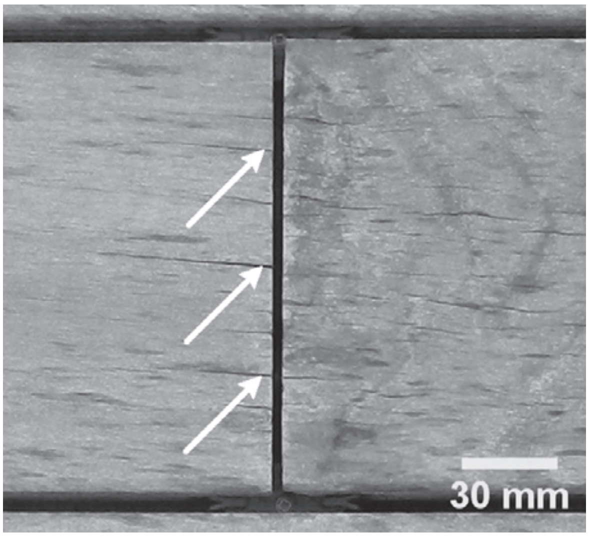

Figure 10 Maple (Kebony) deck surface cracking appearance after 36 months of weathering
Slika 10. Površinske pukotine na uzorcima poda od drva javora nakon 36 mjeseci izlaganja utjecaju atmosferilija

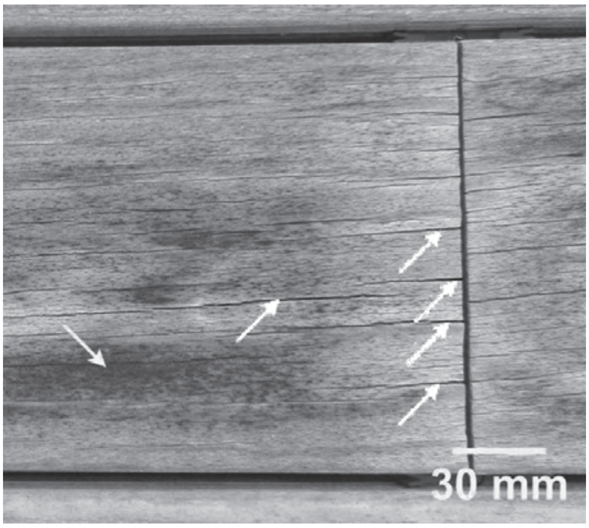

Figure 11 SYP (Kebony) deck surface cracking appearance *(red arrows)* and black staining spots *(yellow arrow)* after 36 months
Slika 11. Površinske pukotine (crvene strelice) i crne mrlje (žuta strelica) na uzorcima poda od drva žutoga bora nakon 36 mjeseci izlaganja utjecaju atmosferilija

Figure 12 Ipê wood deck prior to (up) and after 36 months of weathering (down)
Slika 12. Kontrolni uzorak prije (gore) i nakon razdoblja izlaganja (dolje)

After a thorough visual examination of the surface cracks, Ipê wood deck showed to have the fewest cracks on its surface, closely followed by furfurylated radiata pine deck (Fig. 9) which had only a few minor cracks. Mild was also the cracking appearance of the furfurylated maple wood deck (Fig. 10). Furfurylated SYP deck (Fig. 11) appeared to have a few surface cracks (8-9, in total) with a width of less than 1 mm; some black staining spots appeared sporadically on the surface (Fig. 11) of the furfurylated SYP deck.

After the three-year weathering period, the furfurylated wood decks were examined for end-splitting. It was observed that the furfurylated maple deck had the mildest edge effects (Fig. 14) with the smallest end-

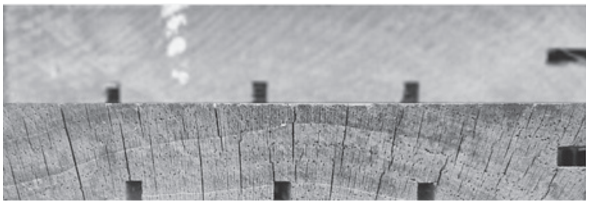

Figure 13 Furfurylated radiata pine wood deck prior to (up) and after 36 months of weathering (down)
Slika 13. Uzorak poda od furfuralom modificiranog drva bora prije (gore) i nakon 36 mjeseci izlaganja (dolje)

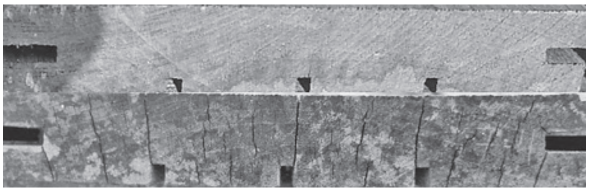

Figure 14 Furfurylated maple wood deck prior to (up) and after 36 months of weathering (down)
Slika 14. Uzorak poda od furfuralom modificiranog drva javora prije (gore) i nakon 36 mjeseci izlaganja (dolje)

Figure 15 Furfurylated SYP deck prior to (up) and after 36 months of weathering (down)
Slika 15. Uzorak poda od furfuralom modificiranog drva žutoga bora prije (gore) i nakon 36 mjeseci izlaganja (dolje)

splitting followed by the control Ipê deck and furfurylated radiata pine deck (Figs. 12 and 13, respectively).

4 CONCLUSIONS
4. ZAKLJUČAK

In this work, a three-year outdoor weathering test of furfurylated (Kebony) wood decks was carried out. The furfurylated radiata pine, southern yellow pine and maple wood decks tested were exposed outdoors for 36 months in Karditsa, Greece, and their physical and structural properties, namely, colour, staining, distortions, surface cracking and end-splitting were evaluated. The conclusions drawn in this work can be summarised as follows:

- All tested decks exhibited colour changes that were perceptible by the naked eye and were much higher during the first 12 weathering months and quite lower during the following ones.
- The furfurylated decks showed smaller total colour changes as compared to the control deck of Ipê wood.
- Concerning surface cracking, furfurylated radiata pine deck generally showed very minor surface cracks, while furfurylated maple deck presented the lowest degree of surface and edge cracking (end-splitting).
- In relation to distortions, the least distorted wood deck was that of furfurylated maple deck; whereas, the control Ipê deck was by far the most distorted wood deck.

In overall, all furfurylated wood decks tested, along with the control Ipê deck, behaved very well during this 36-month outdoor test, having no signs of fungal or mould decay after three years of exposure.

Acknowledgments – Zahvala

The authors would like to thank the lab assistants Mr. Gerasimos Bothos and Mr. Apostolos Katsigiannis for their technical assistance during this work.

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