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Evaluation of Wood Resistance to Artificial Weathering Factors Using Compressive Properties

Ocjena otpornosti drva na utjecaj umjetnih atmosferskih uvjeta mjerenjem tlačne čvrstoće

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ABSTRACT • *The purpose of the study was to determine the influence of artificial weathering on selected properties of wood. This paper presents the changes of incompressive strength of wood along fibers. The study involved wood of different density and anatomy - 17 species of tropical wood commercially available in Europe and Scots pine and European oak. The specimens were exposed to artificial weathering consisting of soaking wood in water, drying at 70 °C and exposure to UV radiation. Three-step aging cycle was repeated 140 times. In general, the tested wood species changed their compressive strength differently under the influence of artificial weathering. The process of artificial weathering caused a loss of strength of all tested wood species. The extent of changes depended on initial properties of wood (especially density) and anatomy. The changes were most pronounced at the beginning of the artificial weathering process.*

Key words: *tropical wood, Pinus, Quercus, artificial weathering, artificial aging*

SAŽETAK • *Cilj istraživanja bio je utvrditi utjecaj umjetnih atmosferskih uvjeta na promatrana svojstva drva. U radu je prikazana promjena tlačne čvrstoće drva uzduž vlakanaca. Istraživanje je provedeno na vrstama drva različite gustoće i anatomske građe – istraženo je 17 vrsta tropskog drva komercijalno dostupnoga u Europi te drvo običnog bora i europskog hrasta. Uzorci su bili izloženi umjetnim atmosferskim uvjetima: naizmjeničnom potapanju drva u vodi, sušenju na 70 °C i izlaganju UV zračenju. Ciklus koji se sastojao od ta tri postupka ponovljen je 140 puta. Općenito, promjena tlačne čvrstoća drva pod utjecajem umjetnih atmosferskih uvjeta za istraživane je vrste drva različita. Izlaganje umjetnim atmosferskim uvjetima prouzročilo je smanjenje tlačne čvrstoće svih istraživanih vrsta drva. Opseg promjena nakon izlaganja povezan je s početnim svojstvima drva (posebno s gustoćom) i anatomskom građom. Najveći intenzitet promjena zabilježen je na početku izlaganja umjetnim atmosferskim uvjetima.*

Ključne riječi: *tropsko drvo, Pinus, Quercus, umjetni atnosferski uvjeti, ubrzano starenje*

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1 INTRODUCTION
1. UVOD

The increasing demand for tropical wood products leads to expanded trade offers, and requires knowledge of the characteristics of exotic wood such as its physical, mechanical, technological properties and its resistance to external factors. Tropical wood species, having wide trunk diameters, attractive texture and high resistance to decay, are used in different industries e.g. furniture, timber, plywood, and outdoor applications such as garden furniture, fences, facades, terraces, etc. (Williams, 2005; Kilic and Niemz, 2012). The decisive element for the use of different wood species in the harsh outside environment is their durability. Natural durability of wood depends on work conditions (hazard classes and construction features), as well as on the type of wood. Variations of weather conditions and prolonged exposure to weathering elements cause the process called weathering.

Many researchers, involved in changes of wood properties caused by varying environmental conditions, describe the natural weathering of wood as a process of irreversible changes in the appearance and properties of a material as the effect of a long-term impact of weather: solar radiation, air and oxygen contained in it, changes in temperature and humidity, assuming no direct influence of biotic factors (Holz, 1981; Feist, 1990; Feistand Hon, 1984; Hon *et al*, 1986; Tolvaj and Faix, 1995; Colom *et al*, 2003; Williams, 1999, 2005). Wood weathering is a complex phenomenon (multifactorial) caused by solar radiation and by hydrolysis and leaching of wood components. Due to cyclical changes in humidity, swelling and shrinkage have a significant influence on changes in wood properties in the weathering process. Due to slowness and questionable repeatability of the process, it is difficult to examine wood weathering and its consequences. Substantial changes often appear in real terms after many years of using wood. For this reason, various methods of artificial weathering were developed in laboratories to simulate the natural effect of weather conditions and to determine changes occurring in wood in short time. These methods differ between themselves in order and intensity of effects of individual factors (eg. Temiz *et al.*, 2007; Evans *et al.*, 2008; Follrich *et al.*, 2011; Miklečić and Jirouš-Rajković, 2011). In addition, the fact should be taken into account that the size of samples used to determine the mechanical properties of artificially weathered wood is unrestricted, one published study - right for a type of test samples and artificial weathering – cannot be directly related to the results obtained in other trials.

Degradation phenomena have been reported in literature, e.g. Evans *et al.* (1996) studied the loss of mass and chemical changes occurring in wood *Pinus radiata* D. Don. during weathering. Evans *et al.* 2008, Bhat *et al.* (2010) tested wood and modified wood materials including its mechanical properties during weathering. Changes of physical properties were mainly tested (Oltean *et al.*, 2009; Schnabel *et al.*, 2009). Researches of tropical wood in this field are few. An example of the study of artificial weathering of tropical wood are tests made by Pastore *et al.*(2004) and Oltean *et al.* (2010) – change of appearance and color were tested.

In this paper, the effects of artificial weathering on compressive properties of several species of wood (assuming the absence of biotic interactions) were determined and compared to each other.The study includes seventeen species of wood from foreign forests (heartwood), commercially available in Europe. Parallel studies were performed on the control wood: pine *Pinus sylvestris* L. (individual sapwood and heartwood) and European oak *Quercus* sp. (heartwood). As the processs of weathering progressed, compression strength along fibers was determined.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Preparation of test specimens
2.1. Priprema uzoraka

Wood species selected for the research (Table 1) are a group of materials used for production of elements used in external conditions (such as elevation, terrace boards, garden furniture, etc.). This wood group represents different types of structures (coniferous, deciduous ring-pours and diffuse-pours) and differs in some details related to anatomy and density (Figure 1).

Samples of each wood species were collected from one board to obtain "identical sample". Thanks to

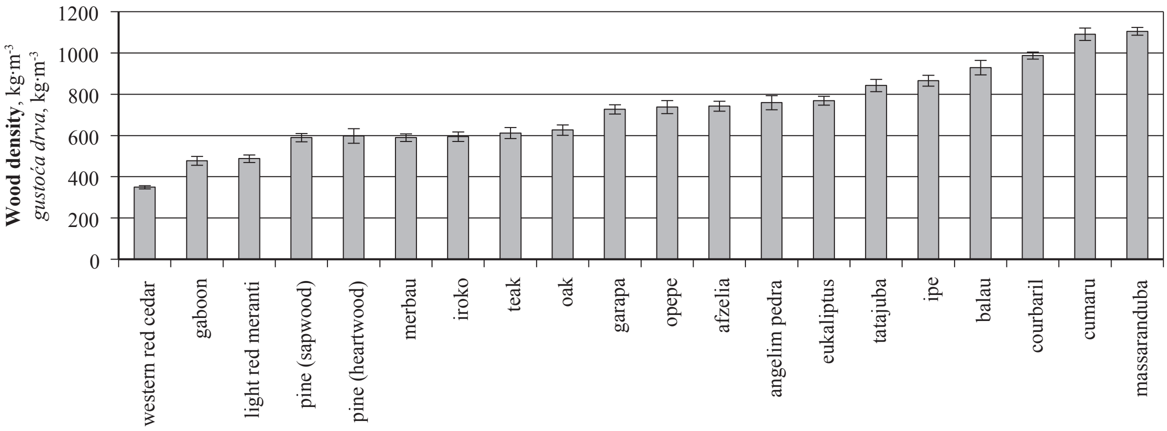

Figure 1 Comparison of average airdry wood density of species tested (for the whole batch of samples)
Slika 1. Usporedba prosječne gustoće uzoraka istraživanih vrsta drva (za cijelu seriju uzoraka)

Table 1 Research material
Tablica 1. Istraživani uzorci drva

Latin name / *Latinski naziv*	**Trade name and name according to PN-EN 13556 (2005)** / *Trgovački naziv i naziv prema PN-EN 13556 (2005)*	**Occurrence** *Stanište*	**Type of structure** *Vrsta anatomske građe*
Afzelia africana Smith ex Pers.	afzelia	Africa	deciduous diffuse-pours *listopadna difuzno-porozna*
Apuleia leiocarpa (Vog.) Macbride	garapa*	South America	
Aucoumea klaineana Pierre.	gaboon	Africa	
Bagassa guianensis Aubl.	tatajuba	South America	
Dipteryx odorata (Aubl.) Wild.	cumaru		
Eucalyptus sp.	eucalyptus	Asia	
Hymenea courbaril Linn.	courbaril	South America	
Hymenolobium sp.	angelim pedra		
Intsia bacori Prain. (*Intsia bijunga* Ktze.)	merbau	Asia	
Manilkara bidentata A. Chev.	massaranduba	South America	
Milicia excelsa (Welw.) C. C. Berg	iroko	Africa	
Nauclea diderrichii (Wild. & Th. Dur.) Merr.	opepe		
Pinus sylvestris L.	Scots pine	Europe	coniferous / *četinjača*
Quercus petraea Liebl., *Q. robur* L.	European oak		deciduous ring-pours *listopadna prstenasto-porozna*
Shorea sp., e.g. *S. acuminate* Dyer.	light red meranti	Asia	deciduous diffuse-pours *listopadna difuzno-porozna*
Shorea sp., e.g.. *S. laevis* Ridley	balau		
Tabebuia sp.	ipe	South America	
Tectona grandis L.	teak	Asia	deciduous ring-pours *listopadna prstenasto-porozna*
Thuja plicata D. Don	western red cedar	North America	Coniferous / *četinjača*

* *Apuleia leiocarpa* (Vog.) Macbride are not included in PN-EN 13556 (2005)

these samples, density was similar and the structure was kept in order to appearing changes in the weathering process, this being the main factor deciding on the examined properties. 30 groups of 6 samples were prepared from each wood species. Dimensions of samples were 15.0 x 15.0 x 22.5 mm (the last dimension along fibers). Each group was intended for the study of different stages of weathering. Before the determination of properties, each group was air conditioned at a temperature close to 20 °C (±2) and relative humidity (rH) around 60 % (±5).

2.2 Artificial weathering method
2.2. Izlaganje umjetnim atmosferskim uvjetima

The design of the artificial weathering cycle was based on literature (Matejak *et al*., 1983: Follrich, 2011). It took 30 hours to complete an artificial weathering cycle and it was divided into three steps (Figure 2). The first step was soaking speciemens in water at 20 °C (16 h). The conditions of the second step (8 h) were 70 °C and 5-10 % rH and the third step was performed at 30 °C and 20-25 rH (6 h) with irradiation with UV rays. Four fluorescent lamps100R's Lightech of 100 W each, and the spectrum 300 - 400 nm (90 % of the radiation spectrum is a wavelength of 340 -360 nm) were used for irradiating. 140 cycles of artificial weathering were conducted.

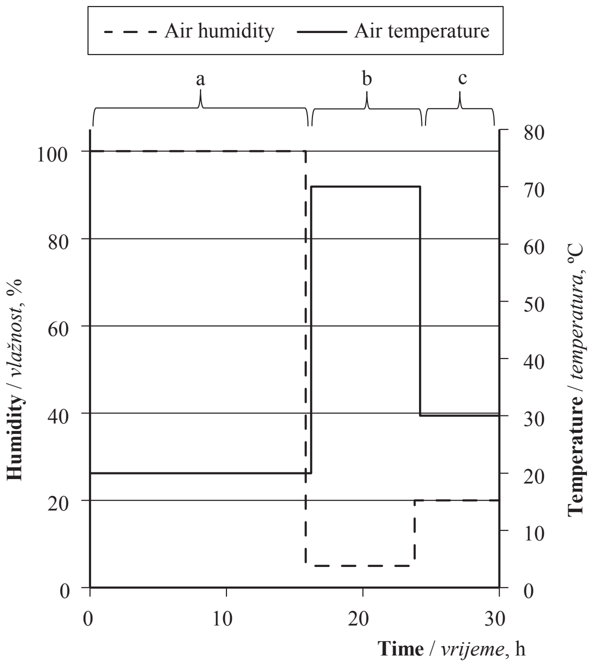

Figure 2 Changes in humidity and temperature during a full cycle of artificial weathering: a) soaking in water for 16 hours, b) drying at 70° C for 8 h, c) UV irradiation for 6 hours
Slika 2. Promjene vlažnosti i temperature tijekom jednog ciklusa umjetnih atmosferskih uvjeta

2.3 Mechanical testing
2.3. Određivanje tlačne čvrstoće

Examination of compressive strength of wood along fibers was performed before weathering, and then after 2, 4, 6, 8, 10, 12, 14, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 76, 84, 92, 100, 108, 116, 124, 132 and 140 cycles of artificial weathering. The compression test was performed according to PN-D 04102 (1979).

The use of slightly smaller dimensions of samples was a deviation from the mentioned norm. The deviation concerning the sample size occurred in view of the fact that no relation exists between the compressive strength along fibers and the size of samples when they are geometrically similar and when the section of the samples contained at least a couple of annual increments (Matejak *et al*., 1983). The aim of this treatment was to cause great changes in wood during the aging process. Examination of compressive strength of wood along fibers (*RC*) was carried out on the 10-ton universal testing machine. Constant speed of loading samples of 2 mm/min was used during the compression tests. For individual groups of samples, average values as well as standard deviations were calculated.

In order to illustrate the effect of artificial weathering of wood, the approximate percentage of decrease of compressive strength along fibers per one cycle of artificial weathering was determined by the formula:

$$\Delta RC = (RC_0-RC_n) \cdot (RC_0 \cdot n)^{-1} \cdot 100$$

where: ΔRC - percent decrease in compressive strength along fibers per one cycle of artificial weathering, RC_0 - compressive strength of wood along fibers before artificial weathering, RC_n - compressive strength of wood along fibers after n number of cycles of artificial weathering, n - number of artificial weathering cycles.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The study shows that the compressive strength of wood along fibers was reduced due to the artificial weathering process. The same direction of changes was observed for every tested wood species. By analyzing the average values of compressive strength along fibers, it has been observed that gaboon showed the greatest changes. 140 cycles of artificial aging process caused the loss of strength c. 35 % (from an initial value of 43 MPa to the final 28 MPa). Merbau also showed a large change - the change of c. 33 % occurred from 65 MPa to 43 MPa. Teak showed the greatest resistance to weathering stated by the smallest change in compressive strength along fibers. Strength of wood was falling from the initial value of 58 MPa to 48 MPa (reduction c. 18 %). Massaranduba showed a similar range of changes of compressive strength due to aging factors. 140 cycles of artificial weathering caused a loss of the compressive strength along fibers from the initial value of 92 MPa to 74 MPa (reduction c. 20 %). European oak, Scots pine (sapwood and heartwood) showed the rate of change of compressive strength along fibers similar to opepe and garapa (about 28 %). There was no difference in strength loss between Scots pine sapwood and heartwood. Both of them (heartwood and sapwood) were made from one board, which was the material of similar properties (similar density). It is important to emphasize European coniferous wood species, because sapwood is an important and often dominant part of trunk volume.

Based on the results, it can be assumed that, due to aging, the loss of compressive strength of wood along fibers is mainly caused by changes in wood structure. Cyclical changes in humidity and temperature caused strong stress (sorption and thermal) exceeding internal cohesion of wood. It resulted in cracks and significant loss of wood strength. There was also a mass loss due to leaching of a number of extractives from the cell walls and partial hydrolysis of hemicellulose and cellulose (relaxed frame of ligno-cellulosic, the disintegration of some long-chain tissue constituents of wood) in subsurface layers, which consequently led to the reduction of wood density. The main cause of deterioration of mechanical properties lies in cyclical changes of moisture conditions, whicih causes tissue destruction of wood (wood cracks). Wood cracks are the consequence of sorption stresses, which occur during rapid wetting and quick drying (Matejak *et al*., 1983; Feist, 1983, 1990; Feist and Hon, 1984; Williams, 1999, 2005). High frequency of changes in humidity causes cracking of wood - the larger amplitude and changes of frequency, the larger the damage. The cumulative impact of wood weathering factors leads to the damage of a wood structure, which is reflected in changes of its initial mechanical properties.

It is hard to indicate one particular factor that affects the extent of loss of compressive strength along fibers of tested wood species. This is probably the interaction of many factors with many interactions between them - this is a submicroscopic construction of wood (cell walls), microscopic (size, layout and contribution of individual structural elements - rays, parenchyma, fibers, vessels), macroscopic (width and layout of annual growth, the share of earlywood and latewood) and its chemical composition (types of extractives - resins, tannins, oils, minerals and other).

Gaboon is a wood with tangled texture - wood shows variations of cross grain. Deviation of wood fibers from the direction parallel to the longitudinal axis of the trunk causes an additional loss of strength. The loss of strength rises with increasing slope and cracks. Similarly, merbau has an irregular arrangement of fibers. Any deviation from fiber direction parallel to the direction of the destructive force causes the loss of strength (slope of 15° lowers the compressive strength of wood by 20 % - Kollmann and Côte, 1968). Additionally, in the case of merbau, a relatively large content of extractives negatively affects the change of strength (Grabner *et al*., 2005).

The change of the compressive strength along fibers of garapa and opepe, similar to European wood species of much lower density (Figure 1), can also be explained by a cross grain. Both opepe and garapa wood are characterized by variations of deflected fibers. In the case of teak, the smallest change in strength can be explained by limited changes in wood moisture due to artificial weathering. Acting hydrophobically, oily substances limited alternating swelling and shrinking, after soaking in water and drying, which led to weakening of wood structure through desorption cracks. The presence of oils in cumaru had no effect on changes in strength. Cumaru, merbau, gaboon and opepe show a cross grain. The consequence of irregular

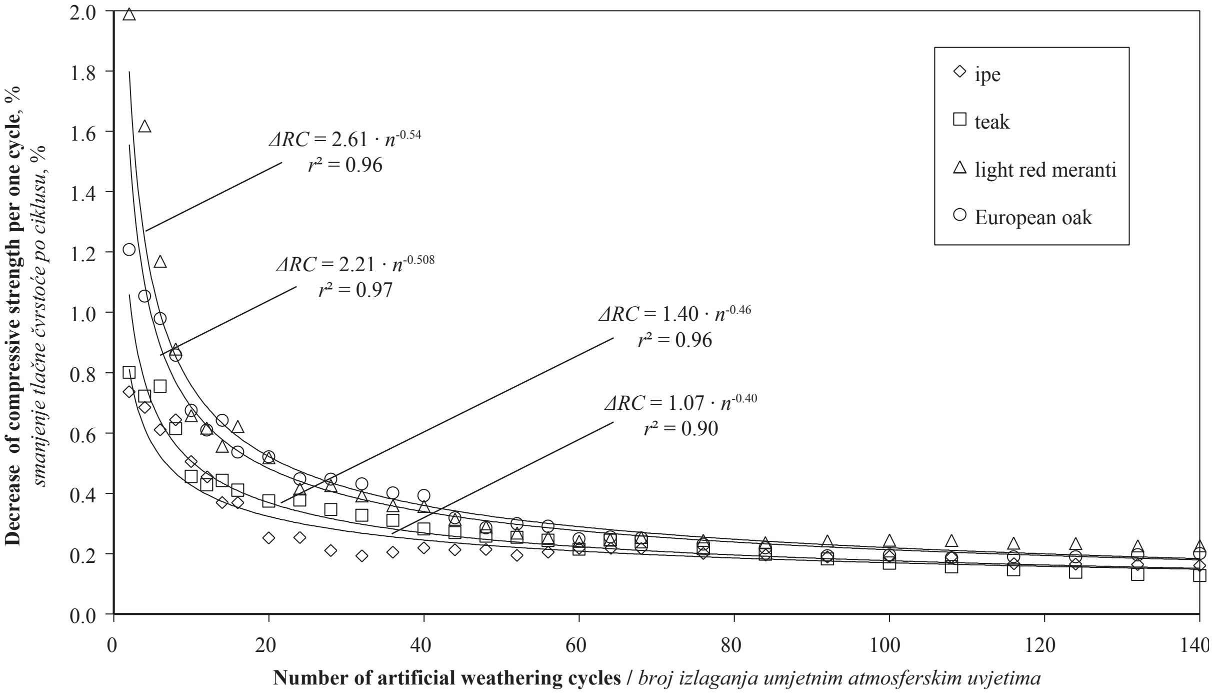

Figure 3 The dependence of decrease of compressive strength along fibers after one cycle of artificial weathering on the number cycles of artificial weathering for light red meranti, ipe, teak and European oak
Slika 3. Ovisnost smanjenja tlačne čvrstoće uzduž vlakanaca nakon jednog ciklusa izlaganja umjetnim atmosferskim uvjetima o broju ciklusa izlaganja drva svjetlocrvenog merantija, ipe, tika i europskog hrasta umjetnim atmosferskim uvjetima

structure is the reduction of the compression strength from 107 MPa to 78 MPa (approx. 27 %). The loss of compressive strength of other wood species ranged between 22 and 32 %, and without taking into account the extreme case of teak wood, the volume change decreases with the increase of wood density.

Irrespective of wood species, the results of testing compressive strength along fibers at different stages of artificial weathering process can be described by a straight line (a correlation coefficient above 0.91 in all cases) - Table 2. Regression analysis shows that the higher the density of wood is, the slope (gradient) value (*a*) decreases and the value of constatnt term (*b*) increases.

To illustrate the effect of artificial weathering of tested wood species, the approximate percent loss of the compressive strength along fibers per one cycle of aging (ΔRC) was determined. Irrespective of wood species, the character of changes was similar. Because of this, a few examples of the calculation of results are presented in Figure 3. The first cycles of artificial weathering process have the greatest influence on the loss of compressive strength. It could be due to the fact that the initial rapid changes in wood moisture caused the strongest stress sorption. As the number of conducted cycles of artificial aging rises, the loss of strength for one aging cycle is getting smaller and tends to a constant value (from about 45-50 cycles of the artificial aging process). Thus, the progressive aging changes in the strength of wood proceed more slowly.

Table 2 List of parameters of the equation ($RC_n = a \cdot RC_0 + b$) describing the change of compressive strength along fibers during artificial weathering
Tablica 2. Parametri jednadžbe ($RC_n = a \cdot RC_0 + b$) kojom se opisuju promjene tlačne čvrstoće uzduž vlakanaca tijekom izlaganja promatranih vrsta drva umjetnim atmosferskim uvjetima

Wood species *Vrsta drva*	RC_0	**Regression analysis** *Regresijska analiza*		
	MPa	*a**	*b**	*r**
western red cedar	35.50	-0.047	33.048	-0.93
gaboon	43.30	-0.042	40.388	-0.98
light red meranti	48.07	-0.091	45.677	-0.98
Scots pine (sapwood)	58.25	-0.102	55.889	-0.98
Scots pine (heartwood)	60.04	-0.103	57.920	-0.97
merbau	64.58	-0.120	60.070	-0.96
iroko	62.07	-0.096	60.220	-0.96
teak	58.10	-0.068	55.203	-0.91
European oak	46.12	-0.070	43.379	-0.95
garapa	67.77	-0.135	64.449	-0.98
opepe	74.17	-0.124	70.385	-0.96
afzelia	70.06	-0.127	65.347	-0.95
angelim pedra	71.06	-0.102	69.476	-0.98
eucalyptus	70.57	-0.125	67.657	-0.98
tatajuba	74.46	-0.110	69.373	-0.91
ipe	85.71	-0.132	83.472	-0.98
balau	97.15	-0.133	93.562	-0.97
courbaril	101.22	-0.143	97.349	-0.97
cumaru	107.72	-0.191	102.350	-0.95
massaranduba	92.43	-0.113	91.176	-0.98

* *a* – slope / *nagib*, *b* – constant term / *konstanta*, *r* – correlation coefficient / *koeficijent korelacije*

4 CONLUSION
4. ZAKLJUČAK

The presented results showed that the process of artificial weathering causes a reduction of the compressive strength along fibers of all tested wood species. The loss of the strength of wood was greater if wood was subjected to more artificial weathering cycles. Hydrophobic teak showed the greatest resistance to artificial weathering factors, expressed through the smallest decrease in the compressive strength along fibers. It is followed by massaranduba (the heaviest wood in the group). while gaboon and merbau showed the lowest resistance (loss of strength was partly the result of irregular arrangement of fibres). European wood species (oak and Scots pine) showed greater resistance to weathering factors as wood of similar density but of interlocked fibres.

At later stages of artificial weathering, the loss of compressive strength along fibers, after one cycle of artificial weathering. gets smaller and tends to a constant value - the highest intensity of change takes place at the beginning of the artificial weathering process. The rate (intensity) of changes depends on the initial density of wood.

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