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STUDY OF COLOUR CHANGE DUE TO ACCELERATED SUNLIGHT EXPOSURE IN CONSOLIDATED WOOD SAMPLES

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ABSTRACT

The aim of this work has been to determine potential colour changes in poplar (*Populus* spp.) and walnut (*Juglans regia* L.) samples caused by the use of some commercial wood-structure consolidants, including various acrylic, epoxy and aliphatic compounds that are widely employed for restoration applications. Experiments involved the application of these products on undeteriorated samples and on samples deteriorated via multiple freeze-thaw cycles, followed by artificial ageing in a Solar Box chamber equipped with a 280 nm UV filter. Colour was measured before and after the deterioration and before and after the artificial ageing by means of a reflectance spectrophotometer. The results are interpreted based on wood typology, level of deterioration, and consolidant characteristics.

KEYWORDS: Wood, *Populus* spp., *Juglans regia* L., consolidation, accelerated ageing, colour changes.

INTRODUCTION

Wood colour changes have been investigated by several authors to evaluate the effectiveness of chemical or thermal treatments as preservation methods against outdoor weathering/exposure (Aydin et al. 2003, Biscontin et al. 2009, Charrier et al. 2002, Cutrubinis et al. 2008, Esteves et al. 2008, Gunduz et al. 2009, Matsuo et al. 2010, Mitsui and Tolvaj 2005, Oltean et al. 2010, Sharratt et al. 2009, Temiz et al. 2005, Umemura et al. 2008). Because colour darkens with the increase of treatment times and temperatures, some authors have suggested that it can be used as an indicator of the degree of modification and mechanical property losses (Bekhta and Niemz

2003, Bourgois et al. 1991, Derbyshire et al. 1995).

The aesthetic beauty of wood is obvious, as seen in its extensive use for veneers, floorings, frames and furniture. In cultural heritage wood has been widely used since ancient times, both as a structural building component and as a material for panels, statues, furniture, etc. (Agresti et al. 2010). Like other objects of art, wood artefacts often require structural consolidation (Unger et al. 2001). Wood consolidation is achieved by treating a porous wood surface with a penetrating liquid that invades all parts of the wood, eventually acting as a strengthener. Wood consolidation can add much-needed strength to deteriorated wood objects, defective structural members and decaying furniture. The choice of the most appropriate consolidant is not easy when the objects to be restored have historical, artistic and ethno-anthropological value. In these cases the choice of consolidant material is often influenced by economic and aesthetic issues, whereas toxicity for the operators and harm to the environment may not be considered. To date, no standard methodology has been developed for the treatment of wooden objects in cultural heritage. Colour is certainly one of the most important parameters that have to be considered during the treatment of wood artefacts, as discussed in a recent international congress held in Bressanone (Italy) (Biscontin et al. 2009, Genco et al. 2009). Moreover colour change method is the most sensitive to determine the extent of photodegradation of consolidated wood exposed to ultraviolet and visible radiation (Sharratt et al. 2009), although other indicators such as strength loss (Derbyshire et al. 1995) and weight changes can also be used (Evans 1998). Nevertheless, the chemical and toxicity characteristics of a chosen consolidant also have to be considered (Lionetto and Frigione 2009, Råberg et al. 2005, Scultz et al. 2007). The measurement of wood colour is not easy due to surface variability, as discussed by several authors (Butler et al. 2001, Della Patria and Omarini 2009, Dirckx et al. 1992, George et al. 2005, Liu and Furuno 2002, Lo Monaco et al. 2011, Lukmandaru et al. 2009, Schnabel et al. 2009). For this reason data have been collected from different areas of each sample to quantify and account for this variability.

In the present paper the effectiveness of some commercial consolidants has been tested, with results discussed in relation to changes in wood colour. The consolidants have been applied to both deteriorated, by means of freeze/thaw cycles, and undeteriorated wood samples. Walnut (*Juglans regia* L.) and poplar (*Populus* spp.) woods have been selected for study due to their widespread use in Italy for constructing statues, furniture, flooring and painted panels.

Six different consolidant products have been tested: Paraloid B72, an acrylic polymer widely used in conservation of cultural heritage (Borgioli and Cremonesi 2005a, Castelli et al. 2003, Chapman and Mason 2003, Donato and Agozzino 2004); two epoxy resins (EPO155 and Templum EPO TOP) used especially as structural consolidants (Borgioli and Cremonesi 2005b, Down 1984, 1986, Bordoni et al. 2004); Regalrez 1126, a low molecular weight aliphatic resin (Borgioli and Cremonesi 2005c, Castelli et al. 2002, Crisci et al. 2010, De La Rie and McGlinchey 1990, Leonard 1990, McGlinchey 1990); and two novel synthetic consolidants (Linfoil and Linfosolid) that are based on natural sources (Genco et al. 2009, Lionetto and Frigione 2009, Lo Monaco et al. 2011). The photo-ageing and consolidating properties of Paraloid B72 have been investigated by many authors (Chiantore and Lazzari 2001, Crisci et al. 2010, Ding et al. 2008, Down et al. 1996, Melo et al. 1999, Munnikendam 1973, Podany et al. 2001, Schniewind and Kronkright 1984, Wang and Schniewind 1985, Yang et al. 2007), due to its wide use in the conservation of cultural heritage, and thus it can be considered as a reference material for the study of the other consolidants. In spite of past research, only limited study has been conducted on colour changes of wood surfaces treated with Paraloid B-72 or the other consolidating products (Biscontin et al. 2009, Crisci et al. 2010, Cutrubinis et al. 2008, Genco et al. 2009, Lo Monaco et al. 2011, Temiz et al. 2005, Umemura et al. 2008).

In this paper colour changes will be discussed in relation to wood modifications, consolidant effect and wood/consolidant system behaviour.

MATERIAL AND METHODS

Artificial deterioration of the wood samples

Wood samples were constructed using 50 mm thick, 40 cm wide, and 4 m long commercial boards of walnut and poplar (Castelgiorgio, Italy). The boards were cut to obtain 50x50x400 mm.

The 50x50x400 mm wood samples were first boiled for 4 hours, to completely saturate the cell walls, and then frozen at -20°C for 24 hours. This step was repeated 5 times. The wood was then cut to obtain 20x20x30 mm samples. These samples were then subjected to 5 freeze/thaw cycles, consisting of immersion in liquid nitrogen for 5 minutes every 4 hours. This procedure caused the collapse of the wood tissues that provide the mechanical support, and resulted in cracking along fiber direction. The artificial deterioration procedure aimed to leave unaltered the density of the wood samples.

Consolidants

The consolidant characteristics and the methods used for their application are summarized in Tab. 1, as reported by the manufacturers Geal S.r.l. (Pistoia, Italy) and CTS (Altavilla Vicentina - VI, Italy).

Tab. 1: Trade names, chemical characteristics and application methods of the consolidants. Linfosolv is a solvent system made of a mixture of refined paraffinic aliphatic derivatives and extracts from citrus.

Consolidant (trade name)	Chemical characteristics	Applied mixture	Application method
EPO 155	Epoxy resin with low viscosity	EPO155 monomer with K156 hardener (2:1 weight ratio)	Under vacuum impregnation for 40 minutes
Templum EPO TOP	Cyclo aliphatic epoxy resin,density 1.12 $kg.l^{-1}$	Templum monomer and hardener based on cyclo aliphatic amines (1:0.7 weight ratio)	Under vacuum impregnation for 45 minutes
Regalrez 1126	Aliphatic resin with low molecular weight, density 0.97 $kg.l^{-1}$	10 % weigth ratio solution in white spirit	Under vacuum impregnation for 24 hours
Paraloid B72	Acrylic resin, ethyl methacrylate (EMA)/methyl acrylate (MA) copolymer	5 % weight ratio solution in acetone	Under vacuum impregnation for 24 hours
Linfoil	Mixture of vegetable oils, resins and waxes in aliphatic solvent	1:1 volume ratio in Linfosolv	Under vacuum impregnation for 24 hours
Linfosolid	Concentrated acrylic polymers in a solvent mixture	2:1 volume ratio in Linfosolv	Under vacuum impregnation for 24 hours

Accelerated ageing treatment

The accelerating ageing of the wood samples was performed in a Model 1500E Solar Box (Erichsen Instruments). The system is equipped with a UV filter that cuts off the spectrum at 280 nm. Consolidated and unconsolidated examples of deteriorated and undeteriorated samples were exposed for a week at 550 $W.m^{-2}$ and 55°C.

Colour monitoring

After exposure for a given length of time the samples were removed from the Solar Box chamber and the colour was measured using an X-Rite CA22 reflectance spectrophotometer

(See Tab. 2 for instrument characteristics). The CIELAB colour system was used where L* describes the lightness while a* and b* describe the chromatic coordinates on the green-red and blue-yellow axes, respectively. Full reflectance data from 400 to 700 nm were also measured and reported.

The differences in lightness (ΔL^*), chromatic coordinates (Δa^* and Δb^*), and total colour (ΔE^*) were then calculated using these parameters according to Normal 14/83 (1993) and EN 15886 (2010). The total colour difference, ΔE^*, between two measurements ($L^*_1a^*_1b^*_1$ and $L^*_2a^*_2b^*_2$) is the geometrical distance between their positions in CIELAB colour space.

Tab. 2: Characteristics of the colour measuring instrument.

Instrument	**CA22**
Manufacturer	X-Rite
Colour scale	CIEL*a*b*and CIE L*C*h
Illuminant	D65
Standard observer	10°
Geometry of measurement	45°/0°
Spectral range	400-700
Spectral resolution	10 nm
Measurement diameter/area	4 mm

It is calculated using the following equation :

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

To guarantee that successive measurements are made in the same area, a photo of each sample was taken at the beginning of the experiment and chosen measure points were marked on the printed photographs.

Colour measurements were performed after 24 hours and after one week (168 hours) of Solar Box exposure. Four areas were chosen for each sample and, following Normal 14/83 (1993), 3 measurements were taken for each point.

Statistical analysis

The validity of the collected data was checked using multiple tests within Statistica (2007) software package. For the colorimetric analysis this included the Kolmogorov-Smirnov test for data normality and the Levene test for variance homogeneity; two way ANOVA analysis (completely randomized design) have also been applied (α=0.05). Sample lightness (L*) and chromatic coordinates (a* and b*) were tested before and after deterioration, before and after consolidation process, before and after accelerated ageing. Twelve measurements were used for each test.

RESULTS AND DISCUSSION

Deteriorated samples

The wood samples that were deteriorated by the freeze/thaw and liquid nitrogen cycles exhibit great colour variations (Tab. 3). In particular, lightness (L*) values decrease markedly, in agreement with sapwood darkening of various wood species deteriorated via heating (Charrier et al. 2002).

Tab. 3: Lightness, chromatic coordinates and total colour differences after the deterioration process.

		L^*_1	a^*_1	b^*_1	L^*_2	a^*_2	b^*_2	ΔL^*	Δa^*	Δb^*	ΔE^*
Poplar	Average	78.41	2.49	20.19	66.72	4.18	21.73	-11.69	1.69	1.54	11.91
	std dev	4.54	0.74	1.66	4.22	0.60	1.40				
Walnut	Average	59.77	4.96	17.49	43.97	5.11	15.82	-15.81	0.15	-1.67	15.89
	std dev	7.06	1.21	2.66	4.90	0.57	1.79				

Darkening intensity was found by these authors to depend both on wood species and the experimental conditions of the treatment. Wood colours after deterioration tended towards yellow to brown due to photo-oxidation of lignin and wood extractives, with the resultant formation of coloured, quinine-like components (Charrier et al. 2002). Coloured byproducts produced during degradation of hemicelluloses might also contribute to colour changes (Kocaefe et al. 2008).

Consolidated samples

After deterioration process the wood samples were consolidated using the selected products according to the procedures described in Tab. 2. Consolidants were also applied to undeteriorated samples.

The present work builds on results of a previous study by our group (Genco et al. 2009) that found that lightness generally decreased in consolidated samples, with the lowest ΔL^* and ΔE^* values observed for undeteriorated walnut and poplar samples consolidated with Regalrez 1126. In that paper the authors found that acrylic and aliphatic resins have good penetration but poor consolidation, whereas epoxy resins give good consolidation but undergo considerable colour variations (Genco et al. 2009).

Based on these previous results, further experimental tests were performed to evaluate colour changes caused by accelerated ageing procedure. Both consolidated and unconsolidated, deteriorated and undeteriorated, wood samples were aged in the Solar Box chamber. Colour differences expressed as ΔL^*, Δa^*, Δb^* and ΔE^* are reported in Tabs. 4-7. Reflectance spectra of unconsolidated samples and of Linfoil treated woods are shown in Figs. 1-2.

Colour measurements were carried out after 24 h and 168 h (one week), as described below. The former time span was chosen because experimental tests have shown that large colour variations can occur during the first 24 h of exposure in both accelerated simulated and natural weathering regimes (Sharratt et al. 2009, Oltean et al. 2010).

Solar Box exposure (24 h)

After 24 h of exposure in the Solar Box, deteriorated samples of unconsolidated poplar wood were found to have a ΔE^* value greater than that of undeteriorated ones due principally to an increase in the value of b^* (Tab. 4). This can be caused by a chemical modification of the wood compounds that give rise to the main colour changes (i.e. yellowing).

In contrast, undeteriorated samples of unconsolidated walnut wood exhibit ΔE^* values after 24 h of exposure that are higher than those of deteriorated ones, due to an increase in b^* (Δb^*=4.50, Tab. 5). It is possible to hypothesize that colour changes could depend on extractives that are abundant in walnut wood. The deterioration process probably caused both the loss of extractives and their modification, resulting in the deteriorated samples exhibiting a lower colour variation.

Poplar wood samples consolidated with epoxy resins exhibit high ΔE^* values due mainly to lightness variations (consolidant whitening, Tab. 4).

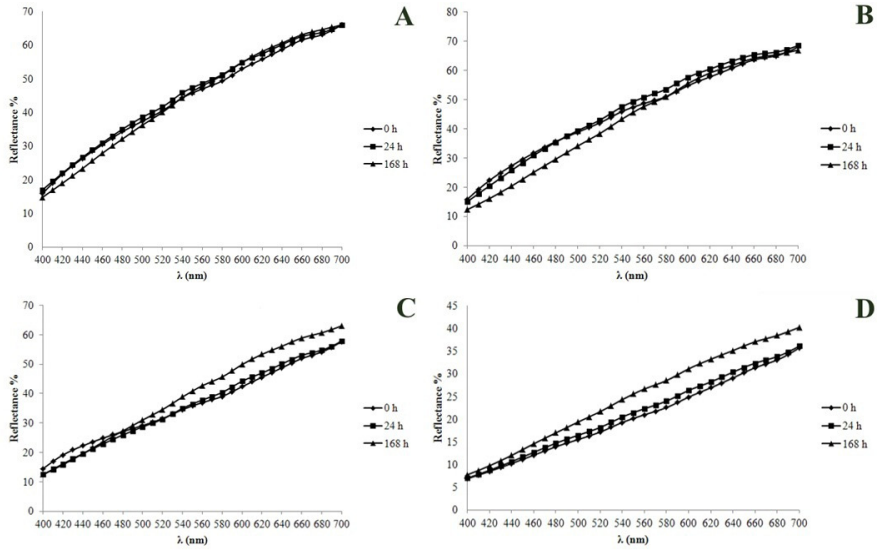

Fig. 1: Reflectance spectra of unconsolidated wood samples: A – undeteriorated poplar, B – deteriorated poplar, C – undeteriorated walnut, D – deteriorated walnut.

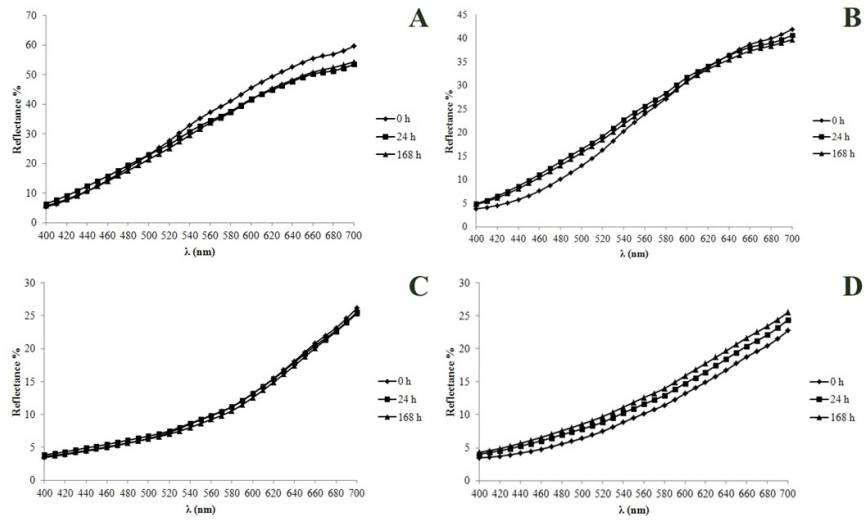

Fig. 2: Reflectance spectra of Linfoil consolidated wood samples: A – undeteriorated poplar, B – deteriorated poplar, C – undeteriorated walnut, D – deteriorated walnut.

Linfoil-treated samples also show high ΔE* values, however these are due to a decrease in b* values (consolidant browning). In contrast, Paraloid B72-, Regalrez 1126-, and Linfosolid-treated samples yielded low ΔE* values (ΔE*<3, apart from Regalrez 1126-treated deteriorated samples for which ΔE*=3.31). ΔE*=3 is considered as the limit of colour changes detectable by the human eye (Hon and Minemura 2001, Hon and Shiraishi 2001, Oltean et al. 2010).

Tab. 4: Lightness, chromatic coordinates, and total colour differences before and after the artificial ageing (24 h) on the undeteriorated and deteriorated poplar wood samples (both unconsolidated and consolidated).

	UNDETERIORATED SAMPLES				DETERIORATED SAMPLES			
	ΔL*	Δa*	Δb*	ΔE*	ΔL*	Δa*	Δb*	ΔE*
Unconsolidated samples	1.01	-0.12	0.82	1.31	1.10	0.06	3.30	3.48
EPO 155	4.71	-1.17	-3.27	5.85	4.71	-1.96	-3.51	6.19
Templum	4.59	-0.85	-1.82	5.01	4.61	-0,70	-1.99	5.07
Regalrez 1126	-0.10	0.28	1.80	1.82	0.63	0.12	3.25	3.31
Paraloid B72	-1.12	0.32	2.39	2.66	0.48	-0.17	1.50	1.58
Linfoil	-1.76	-0.92	-6.70	6.99	2.09	-3.07	-6.92	7.86
Linfosolid	0.18	0.07	1.58	1.59	0.60	0.00	1.23	1.37

Tab. 5: Lightness, chromatic coordinates, and total colour differences before and after the artificial ageing (24 h) on the undeteriorated and deteriorated walnut wood samples (both unconsolidated and consolidated).

	UNDETERIORATED SAMPLES				DETERIORATED SAMPLES			
	ΔL*	Δa*	Δb*	ΔE*	ΔL*	Δa*	Δb*	ΔE*
Unconsolidated samples	0.41	0.12	4.50	4.52	1.27	-0.23	0.68	1.46
EPO 155	-0.03	-0.49	-0.67	0.83	2.64	-0.13	0.81	2.76
Templum	0.89	-0.62	-0.16	1.09	2.71	-0.61	0.35	2.80
Regalrez 1126	-3.11	0.40	0.46	3.17	2,32	-0.32	1.02	2.55
Paraloid B72	-2.54	0.28	0.17	2.56	1.99	-0.07	1.15	2.30
Linfoil	0.20	-0.35	-1.79	1.83	2.38	-0.61	-1.23	2.75
Linfosolid	-3.51	0.53	1.10	3.72	1.91	-0.19	0.24	1.94

Regarding Paraloid B72, Regalrez 1126 and Linfosolid consolidated and deteriorated samples ΔE* values depend mainly on b* increases, so colour changes can be attributed to poplar wood. In regards to consolidated walnut samples, ΔE* values after 24 h of exposure are always low and near the perception limit of the human eye: only Regalrez 1126 (ΔE*=3.17) and Linfosolv- (ΔE*=3.72) treated undeteriorated samples gave slightly higher values.

Solar Box exposure (168 h)

After 168 h (a week) in the Solar Box, unconsolidated poplar wood samples show a ΔE* trend that is similar to that obtained after 24 h (Tab. 6). The high ΔE* values for the unconsolidated samples are mainly due to variations in b*. As such, poplar wood undergoes a clear yellowing under the artificial ageing process due to photodegradation of its constituents, as discussed by several authors (Aydin et al. 2003, Derbyshire et al. 1995, Dirckx et al. 1992, Mitsui and Tolvaj 2005, Schnabel et al. 2009, Sharratt et al. 2009, Temiz et al. 2005, Umemura et al. 2008). This yellowing increases with the deterioration of the unconsolidated samples and with the exposure time in Solar Box (Sharratt et al. 2009).

In regards to the consolidated poplar wood samples, data in Tab. 6 show high, though fluctuating, ΔE* values for all consolidants. In fact, compared to 24 h values, ΔE* sometimes increases after one week while other times it decreases. It can thus be hypothesized that both wood and consolidant undergo colour variations.

Epoxy resins have a low penetration depth and form a surface film that partially prevents wood colour variations, meaning that ΔE* values are mainly affected by colour changes of the consolidant (whitening). However after 168 h in the Solar Box wood colour variations also become important, especially for Templum-treated samples (Δb*=6.51 for undeteriorated samples, see Tab. 6).

Tab. 6: Lightness, chromatic coordinates, and total colour differences before and after the artificial ageing (168 h) on the undeteriorated and deteriorated poplar wood samples (both unconsolidated and consolidated).

	UNDETERIORATED SAMPLES				DETERIORATED SAMPLES			
	ΔL*	Δa*	Δb*	ΔE*	ΔL*	Δa*	Δb*	ΔE*
Unconsolidated samples	0.36	0.81	4.45	4.54	-1.23	1.98	8.24	8.56
EPO 155	3.88	-1.73	1.39	4.47	5.97	-2.97	-0.10	6.66
Templum	4.36	-0.15	6.51	7.83	3.43	-0.30	3.54	4.93
Regalrez 1126	-2.09	2.39	8.11	8.71	-2.94	2.31	9.90	10.58
Paraloid B72	-2.30	2.30	9.63	10.17	2.36	0.70	5.60	6.12
Linfoil	-2.40	0.26	-3.86	4.56	1.33	-2.82	-6.49	7.20
Linfosolid	-3.48	2.55	9.81	10.72	-0.14	1.78	7.35	7.56

Regalrez 1126 has a good penetration into wood samples but does not form a surface protection (Genco et al. 2009), meaning that colour variations in the samples treated with this aliphatic resin are mainly due to changes in the poplar wood itself. This result is also in agreement with the high chemical stability of Regalrez 1126 to photo-oxidation (Crisci et al. 2010).

Linfoil-consolidated samples exhibit high colour variations, mainly due to a decrease in b* (browning). It has been demonstrated that Linfoil has a good penetration (Genco et al. 2009) into poplar wood samples; in this case colour variation mainly depends on consolidant modification.

Poplar wood samples treated with Linfosolid and Paraloid B72 show a similar behaviour: colour variations are mainly due to an increase in b* (yellowing). These two consolidants have a quite low penetration (Genco et al. 2009) into both as regards poplar and walnut wood. In these cases colour changes mainly depend on the wood itself.

Unconsolidated walnut wood samples show elevated ΔE* values after 168 h in the Solar Box (Tab. 7). Undeteriorated samples undergo higher colour variations (mainly due to b* increases) than deteriorated ones (mainly due to L* increases). As already discussed it is probable that wood colour changes in walnut might depend on extractives. This is because the extractives have been both partially removed and chemically modified by the deterioration process and, as a consequence, deteriorated samples undergo less colour variations.

Tab. 7: Lightness, chromatic coordinates, and total colour differences before and after the artificial ageing (168 h) on the undeteriorated and deteriorated walnut wood samples (both unconsolidated and consolidated).

	UNDETERIORATED SAMPLES				DETERIORATED SAMPLES			
	ΔL*	Δa*	Δb*	ΔE*	ΔL*	Δa*	Δb*	ΔE*
Unconsolidated samples	3.46	0.43	8.86	9.52	5.30	-0.55	3.07	6.14
EPO 155	-0.96	-0.21	1.35	1.67	6.31	-0.37	3.09	7.04
Templum	0.04	0.04	2.05	2.05	7.84	-0.85	3.85	8.77
Regalrez 1126	-5.72	1.31	1.86	6.15	6.30	0.03	4.10	7.52
Paraloid B72	-2.50	1.23	3.18	4.22	6.59	0.21	5.07	8.32
Linfoil	-0.74	0.13	-1.62	1.79	4.00	-0.77	-0.64	4.12
Linfosolid	-3.17	1.16	2.79	4.38	5.47	0.14	4.97	7.39

Undeteriorated walnut wood samples treated with consolidant products generally have quite low ΔE* values (Tab. 7), with the exception of the high value of 6.15 being observed for undeteriorated samples treated with Regalrez 1126. It may be proposed that consolidants have a protective action towards walnut wood extractives, with the exception of Regalrez 1126 which has demonstrated a poor affinity for this wood species (Genco et al. 2009). This statement is

supported by previous research which found that EPO 155, and especially Linfoid, have a good affinity with walnut wood (Genco et al. 2009), with the lowest ΔE* values being obtained for these two consolidants both with undeteriorated and deteriorated samples. Deteriorated and consolidated walnut samples show higher ΔE* values, probably due to both consolidant product and wood colour changes (Tab. 7). Variations in L* mainly affect total colour differences, while L* values always increase for deteriorated samples treated with consolidants.

Colour changes reported using reflectance data

Figs. 1 and 2 show the changing reflectance spectra of unconsolidated and Linfoil treated wood samples during the 168 h of exposure. We chose to discuss the behaviour of Linfoil because it demonstrated a good consolidant especially for walnut samples (Genco et al. 2009) and also for other woods containing extractives (Lo Monaco et al. 2011).

The reflectance spectra of unconsolidated poplar samples are shown in Figs. 1A-B. A decrease of reflectance is visible in the blue region of the spectrum, more evident after 168 h and for deteriorated samples. This change corresponds to a decrease in blue shades and correlates to an increase of yellow/red colour.

The reflectance spectra of unconsolidated walnut are shown in Figs. 1C-D. An increase of reflectance can be observed for both undeteriorated and deteriorated samples, especially in the yellow-red. This corresponds to a yellowing of the wood surface. A little decrease of reflectance in the blue, can also be observed for undeteriorated walnut.

The reflectance spectra of Linfoil treated poplar are shown in Figs. 2A-B. The undeteriorated samples exhibit a decrease in the yellow-red region of the spectrum whereas the deteriorated ones undergo an increase of reflectance in the blue. This corresponds to a darkening and browning of undeteriorated samples, in accordance also with the decrease of L* and b* (Tab. 6).

The reflectance spectra of Linfoil treated walnut exhibit little variation throughout the exposure period, particularly for undeteriorated samples (Figs. 2C-D). Deteriorated samples undergo a general and constant reflectance increase in the entire visible region (Fig. 2D), corresponding to a surface whitening, in accordance also with the increase of L* obtained for deteriorated samples (Tab. 7).

Statistical analysis results

A two way ANOVA analysis illustrates that both poplar and walnut undergo significant changes before and after the deterioration process and before and after the artificial ageing of the unconsolidated and consolidated samples (24 and 168 h). Only the chromatic coordinate "b" shows no significant difference in the samples after the deterioration process.

CONCLUSIONS

One of the most important criteria for wood used in cultural heritage is its visual appearance. Colour and colour stability can be considered the main features of this appearance, and thus these parameters must be considered when choosing the most appropriate product for wood restoration and consolidation. In the present study, traditional and novel organic products have been applied to both deteriorated and undeteriorated wood samples to monitor for changes in wood colour and to determine the effect of deterioration on the consolidation process.

Generally speaking, no constant trend was observed in the present work due to the interplay between these variables. Regarding colour changes due to the deterioration process, a general lightness decrease was observed in accordance with literature data (Charrier et al. 2002).

A different behaviour of the unconsolidated wood samples was observed following the artificial ageing: deteriorated poplar samples exhibited ΔE* values greater than those of undeteriorated ones, whereas deteriorated walnut samples showed ΔE* values lower than those of undeteriorated ones. This is probably due to the presence of extractives in walnut wood that underwent modifications during the deterioration process.

Colour changes in consolidated samples varied according to wood and consolidant typology. Walnut samples exhibited a clearly different behaviour before and after the deterioration process due to the loss and chemical modification of extractives. The application of consolidants on undeteriorated samples caused little colour variations compared to unconsolidated ones. It has been proposed that consolidants could have a protective action towards walnut wood extractives. Linfoil- and EPO 155-treated walnut samples exhibited the lowest ΔE* values.

The colour changes in consolidated poplar wood samples are inconsistent and thus generalisations are very difficult. One possible explanation for this variability is that both wood and consolidant underwent colour variations. Colour changes of unconsolidated wood samples were mainly due to increases in b* (yellowing). The ΔE* values of Regalrez 1126-, Paraloid B72- and Linfosolid-treated samples also depended mainly on increases in b*: in these cases colour changes can be attributed to poplar wood.

Linfoil-treated samples always showed a decrease in b*, due to consolidant browning. Finally, colour changes of poplar samples consolidated with the epoxy resins were the result of both increases in L* and b* variations (b* decreased after 24 h and increased after a week, except for deteriorated samples treated with EPO 155). Consolidant whitening is likely the main phenomenon after 24 h, whereas wood colour changes are probably important over longer exposure times (as seen in the measurements after 168 h).

In conclusion, this research illustrates that several parameters are involved in colour changes of consolidated wood samples and that an "ideal" consolidant for all species does not exist.

Linfoil was found to be a good consolidant for walnut wood samples, probably because its colour variations compensate for wood colour changes due to extractives. Consolidated poplar samples showed more complex and fluctuating results depending on both wood and consolidants. Linfoil and EPO 155 gave good results after a week on undeteriorated samples. Paraloid B72 and Templum treated samples exhibited the lowest ΔE* values for the deteriorated woods.

Further experimental tests will be necessary to better understand the influence of the several parameters that affect colour changes.

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