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Effects of aging on wood: a literature review

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Abstract Knowledge of wood aging and the property changes of aged wood compared with recent wood are crucial for conservation of wooden cultural heritage objects and historic buildings constructed of wood and also for the reuse of old construction wood. Therefore, a thorough literature review is presented about the different aspects of wood aging to provide a database for further investigations. One focus lies on the different kinds of aging: natural aging under aerobic and anaerobic storage conditions in contrast to accelerated aging under heat treatment. Further, influencing factors like wood treatment and long-term loading on the aging process are discussed. Property changes of naturally aged wood that has been stored under aerobic conditions are also researched. The resulting chemical, physical, and mechanical changes are thus discussed as well as any changes in color.

Introduction

Wood has served humanity in many different functions since ancient times (e.g., constructions, tools, furniture, energy), and it is still valued as one of our most important raw materials. Therefore, a wide range of wood properties have been investigated and documented up to the present (cf. Wagenführ 2007); however, these properties have mostly been derived from tests on recent wood samples, yet the aging process of wood and the properties of aged wood have been so far scarcely

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investigated. Furthermore, knowledge of the properties of aged wood is not only important for the conservation of wooden heritage and historic wood constructions, but it must also be considered when recycling wood. Thereby, chemical, physical, and mechanical property changes are of great interest. To this aim, a thorough literature study is presented on the different aspects of wood aging with focus on sound, naturally aged wood stored in dry air. The review is based on studies carried out during the PhD of Kránitz (2015).

The literature study is split into two parts. The first part deals with the different kinds of aging. Therein, natural aging under aerobic and anaerobic storage conditions as well as accelerated aging under heat treatment is discussed, and the influences of wood treatment and long-term loading on the aging process are investigated. The second part deals with the property changes of naturally aged wood and concerns its chemistry, color, and hygroscopic and mechanical behaviors.

Due to difficulty of specimen matching, the aging effect is not always easy to clarify. In many cases, only small quantities of sound, aged wood are available for research purposes. In addition, the history of the investigated material is usually not known in detail (e.g., storage conditions which play a crucial role in the aging process). Normally, no information about the original properties of the investigated material is available. Therefore, results for aged wood are commonly compared to values of recent material with different growing conditions (climate, exposition, forest stand, etc.) and properties (density, annual ring width, microfibril angle, etc.) which complicate the comparison. This should be kept in mind when interpreting the results.

The biotic degradation of old wood, which is not a theme of this study, is another important and great research field within the topic of wood aging. A detailed introduction concerning the properties of aged and archeological wood, including biologically deteriorated wood and its conservation, can be found in Rowell and Barbour (1990) and Unger et al. (2001).

Aging of wood

Natural aging

Definition

Aging is understood as the irreversible change of physical, chemical, and mechanical properties of a material during extended storage or usage. Deterioration therefore may occur because of climatic and environmental factors, but also through wood-destroying organisms (insects, fungi, bacteria, and marine borers) (Unger et al. 2001). The changes in physical and mechanical properties of wood due to aging originate from changes in the microstructure and in effect from chemical changes in the components. Since storage conditions determine what kind of chemical processes may occur, it is obvious that they have a significant effect on the aging process. In the case of wood, aerobic and anaerobic conditions have to be identified (Fengel 1991).

Aerobic aging

Wood is most stable when stored indoors in dry air. Due to favorable conditions (low temperature and UV radiation, and no contact with liquid water), the effect of aging on its structure appears to be minimal, even for archeological wood up to an age of 4400 years, as long as no insect or fungi attacks have occurred (Nilsson and Daniel 1990).

Wood located outdoors is exposed to direct sunlight and undergoes chemical degradation caused by UV radiation. According to Norrstrom (1969) in Kuo and Hu (1991), lignin contributes 80–95 %, carbohydrates 5–20 %, and extractives about 2 % to the total UV absorption coefficient of wood. Thus, lignin is the cell wall component most sensitive to UV light. It was also shown that lignin transfers the UV light to cellulose resulting in degradation of cellulose (Yoshimoto 1972). Besides photodegradation, surface thermal degradation also has to be taken into account, as the surface temperature of outdoor-irradiated wood can reach 60–90 °C depending on its color (Tolvaj and Molnár 2008). Furthermore, erosion of wood by means of wind and rain occurs (Unger et al. 2001), allowing photodegraded substances to be easily washed out (Nemeth 1998). Wood exposed to weathering is also subjected to mechanical stresses due to fluctuations in temperature and humidity (Borgin et al. 1975b). These combined effects lead to decomposition of the surface layers and result in a chequered, gray surface in the long term (Unger et al. 2001).

Anaerobic aging and fossilization

Anaerobic conditions emerge when the wood is buried in the ground or submerged in water. In the case of buried wood, a relatively rapid removal of amorphous or paracrystalline cellulose occurs, and a slower conversion of crystalline to non-crystalline cellulose takes place as well (Chowdhury et al. 1967). In a very slow fossilization process, the cell wall substance is transformed into highly condensed compounds (coalification) or is substituted by minerals (silification) (Fengel 1991). The degradation may be influenced by ground water leaching and the acid–base and oxidizing–reducing characteristics of this water (Florian 1990).

Extended storage in water causes swelling of the secondary cell walls and slow hydrolyzation of the carbohydrates, resulting in the loosening of the fibrillar texture, which may be supported by soft rot fungi and tunnelling bacteria (low amounts of oxygen are necessary) and erosion bacteria (in nearly or completely anoxic environments). Further degradation occurs as the crystalline structure of the cellulose is broken down. The residual lignin skeleton may maintain the original shape while in water, however, drying of the material results in cell collapse. Consequently, waterlogged wood undergoes extreme shrinkage and tends to split, warp, and crumble when moved to ambient air (Hoffmann and Jones 1990; Björdal 2012; Pedersen et al. 2013).

Accelerated aging and heat treatment

Different artificial aging methods, which were mostly designed to simulate the conditions of outdoor weathering or photodegradation processes indoors, were developed to investigate the property changes of naturally aged wood (e.g., Chang and Chang 2001; Follrich et al. 2011; cf. also chapter 3.2.). One suitable method for accelerated aging, which concerns the whole wood including the inner parts, is thermal treatment (Matsuo et al. 2011; Ganne-Chédeville et al. 2012; Froidevaux and Navi 2013).

Generally, heat treatment is applied to grade up the wood properties in the field of dimensional stability (Yildiz 2002; Popper et al. 2005; Li et al. 2011) and decay resistance (Weiland and Guyonnet 2003; Hakkou et al. 2006) as well as color changes (Bekhta and Niemz 2003; Brischke et al. 2007). However, it was shown that strength properties decrease as a result of thermal treatment (Bekhta and Niemz 2003; Poncsák et al. 2006; Pfriem et al. 2010). These alterations are a result of chemical changes due to high temperatures (Rowell et al. 2009). Thereby, aging processes can be compared with a mild thermal treatment. Whereas most industrialized heat treatment processes involve temperatures between 150 and 260 °C, thus, mild temperatures in the range of about 100 to 150 °C were used for accelerated aging (Sandberg et al. 2013).

The most important effect of heat treatment on the chemical properties of wood is the degradation of hemicelluloses, which has been reported by many authors (Tjeerdsma et al. 1998; Yildiz et al. 2006; Gonzalez-Pena et al. 2009; Niemz et al. 2010). This might be responsible for color changes (Bourgois et al. 1991) and for improved decay resistance (Hakkou et al. 2006) and correlates with reduced strength as well (Niemz et al. 2010). As the hydroxyl group content of hemicelluloses decreases, wood becomes less hydrophilic, resulting in lower equilibrium moisture content (EMC) and better dimensional stability (Tjeerdsma et al. 1998; Weiland and Guyonnet 2003). The weight loss observed during thermal treatment (Tjeerdsma et al. 1998) is probably also caused by degradation of hemicelluloses (Gonzalez-Pena et al. 2009). Thereby, the degradation of wood strongly depends on temperature, moisture conditions, and treatment time (Stamm 1956).

Although the apparent lignin content increases, structural changes were reported, indicating that some deterioration took place (Tjeersdma and Militz 2005; Gonzalez-Pena et al. 2009; Niemz et al. 2010). Cellulose alters only slightly, and its crystalline structure remains intact even at high temperatures (Yildiz et al. 2006). However, some degradation in the amorphous regions occurs, consequently decreasing the accessibility of hydroxyl groups and resulting in higher crystallinity of cellulose (Nakao et al. 1989; Wikberg and Maunu 2004). These changes together with the increased porosity and average pore diameter reported by Pfriem et al. (2009) contribute to the decreasing EMC (Bekhta and Niemz 2006; Esteves and Pereira 2009; Niemz et al. 2010).

In addition, artificial drying at higher temperatures already influences the wood properties. Chemical changes arise mainly at temperatures above 100 °C, while negative drying effects are negligible below 71 °C (Winandy 1996). Bending, impact bending, and tensile strength of spruce wood are not affected by drying even

at 80 °C (Oltean et al. 2011), and no changes in the static strength properties were observed up to drying temperatures of 110 °C (Teischinger 1992b). However, fracture toughness was found to decrease by drying at temperatures as low as 50 °C, with the effect being more pronounced above 100 °C. For specimens subjected to high-temperature (100–110 °C) drying, the decrease in fracture toughness was accompanied by severe microstructural damage (Teischinger 1992b; Stanzl-Tschegg et al. 1994). Other properties, like EMC, swelling and shrinkage, and color, may be influenced as well. For more literature, see Teischinger (1991, 1992a).

In many cases, the property changes of heat treatment are different to those of natural aging. According to Noguchi et al. (2012), aged samples of Japanese red pine showed lower damping and higher sound velocity than recent wood, while thermal treatment increased damping. This qualitative difference might result from differences in the moisture content (MC) of wood during natural aging and thermal treatment, since MC is known to have a significant effect on the aging process (Erhardt et al. 2000; Chen et al. 2012; Sonderegger et al. 2014). Investigations by Fourier transform infrared spectroscopy (FTIR) and UV resonance Raman spectroscopy on spruce wood showed signs of hemicellulose degradation of naturally aged wood, while hydrothermal treatment up to 160 °C caused mainly alterations in lignin (Ganne-Chédeville et al. 2012). Despite these differences, knowledge of artificially aged wood can contribute to the characterization and understanding of the natural aging process, even if it cannot be perfectly simulated.

Further influencing factors on aged wood

Wood preservatives

In investigations on aged wood that has served in practice, the possibility of a preservation treatment must be considered. Until the sixteenth century, materials like tar, pitch, plant oils, wood distillation products, smoke, and mercury and arsenic compounds were applied to protect wood (Clausnitzer 1990), some of them as early as around 4000 BC (Lohwag 1967). In addition to the former, distillation products of coal, various waterborne salts, fluorine and boron, and other organic compounds were in use, particularly since the seventeenth century (Clausnitzer 1990). From the end of the nineteenth century, chemical wood protection has been undergoing extensive development. Today's preservation practices are introduced in, for example, Ross (2010).

However, the application of chemicals does not only influence its durability. Materials penetrating wood can also modify its chemical composition and thus influence the results of a chemical analysis even when they are not bound chemically to the wood substance. Preservatives containing salts may change the hygroscopic behavior of wood (Niemz 1993). Mechanical properties may also be influenced, mainly due to temperature effects occurring during the treatment (Ross 2010). Surface treatment usually penetrates only the outer layers of the wood and thus has no direct influence on the inner parts. However, finishing can act as a water barrier by hindering sorption processes.

Effects of long-term loading

Most objects made of wood are subjected to external loading during their service to a greater or lesser extent. Long-term or repeated loading can lead to permanent changes in the material, even when no fracture occurs, and thus the damage cannot be seen with the naked eye. Therefore, the rheological behavior of wood and the load history of the material have to be taken into account when investigating the effect of aging on the mechanical properties. For examples and summaries of the voluminous literature on this topic, see Holzer et al. (1989) and Smith et al. (2003).

The most critical of the long-term loading factors are the magnitude and types of stress, the rate and duration of load, MC and temperature, and the material characteristics (Bodig and Jayne 1993). Several models (e.g., Madison curve, Barrett and Foschi models, and Foschi and Yao model) enable calculating the duration of load (DOL) effect (Wood 1951; Barrett and Foschi 1978, Foschi and Yao 1986). Thereby, the height of the load crucially affects the rate of ultimate strength reduction during aging, which has to reach a certain stress threshold (e.g., for the Foschi and Yao model, 0.53 % of the short-term ultimate strength has to be attained), below which no DOL effect is measured (Fridley et al. 1996b). Furthermore, in dynamic (cyclic) load, the influence is time-dependent and change of wood moisture increases the DOL effect (see, e.g., Reichel 2015). For example, two studies report no changes and therefore no DOL effect on the mechanical performance of structural roof timber elements after a service time of 85 and 600 years, respectively (Deppe and Rühl 1993; Fridley et al. 1996a, b). In contrast, structural members of wooden towers showed microstructural damage similar to compression failures of standing trees caused by storms and thus a diminished impact bending strength and Young's modulus after only 30 years of service due to long-term load with punctually high stresses caused by wind and additionally periodic shrinking stresses (Kollmann and Schmidt 1962).

Properties of naturally aged wood

Chemistry

Due to the different structures of the main chemical wood components (cellulose, hemicelluloses, and lignin), the characteristic degradation processes as well as their sensitivity to degradation differ remarkably. As cellulose has an extremely ordered and high degree of intermolecular association within the fibrils, it exhibits a low solubility in most solvents and a relatively strong resistance to hydrolysis. Hemicelluloses, on account of their less ordered structure, have higher solubility and are more readily hydrated. Ether and carbon–carbon bonds make lignin resistant to hydrolysis, but it is susceptible to oxidizing reagents (Hedges 1990; Fengel 1991).

In the following, diverse studies on the chemistry of aged wood are presented. Table 1 gives an overview of the results. According to Holz (1981), no significant differences of the investigated lignin, cellulose, pentosane, and ash content were found between spruce wood estimated to be about 180 years old and recent

Table 1 Change of wood properties during aging

Species (Scientific name / Trade name)	Age [year]	Lignin	(Holo)cellulose	Hemicellulose	Crystallinity	Extractives	Ash	EMC	Swelling	Bending strength	Compression strength	Tensile strength	Shear strength	Young's modulus	Impact bending strength	Hardness	Reference
Softwoods:																	
Abies alba Mill. / Silver fir	n.a.							↓									Lang (2004)
	300-800	↑	↓				↑										Tomassetti et al. (1990)
Chamaecyparis obtusa Endl. / Hinoki	300-1300		↓		↑	↑		↓	↓	~	~		↓	~	↓	~	Kohara and Okamoto (1955)
	500-1600							↓						↑			Kawai et al. (2008)
	1250		↓	↓	-												Yonenobu and Tsuchikawa (2003), Tsuchikawa et al. (2005)
	1400				-			↓									Inagaki et al. (2008)
	<1600							↓		-/↓[R]				-			Yokoyama et al. (2009)
Juniperus phoenicea L. / Phoenician juniper	4100-4400	↓	↑		↓		↑										Van Zyl et al. (1973), Borgin et al. (1975a)
Larix decidua Mill. / European larch	300-800	↑	↓				↑										Tomassetti et al. (1990)
Picea abies [L.] Karst. / Norway spruce	60(-180?)	-	-	-			-		-								Holz (1981)
	100							↓									Kurtoglu (1983)
	115-290													↑			Kranitz et al. (2014)
	300								↑	↑	↑	↑			↓		Schulz et al. (1984)
	200-500	↓		↓		↓											Ganne-Chédeville et al. (2012)
	300-800	↑	↓				↑										Tomassetti et al. (1990)
	n.a.										↓				↓		Baron (2009)
	n.a.							↓						↓	↓		Lang (2004)
Pinus densiflora Siebold et Zucc. / Japanese red pine	270				-								-				Ando et al. (2006)
	300													↑			Noguchi et al. (2012)
	170-500		↓		↑									↓			Saito et al. (2008)
Pinus pinea L. / Stone pine	4100-4400	↓	↑		↓		↑										Van Zyl et al. (1973), Borgin et al. (1975a)
Pinus strobus L. / Eastern white pine	140									↓	↑	↓	↑	↓		↑	Attar-Hassan (1976)
Pinus sylvestris L. / Scots pine	205				↓			↑									García Esteban et al. (2006)
	150-400									-	-						Rug and Seemann (1989)
	300-400			↓	↓			-	-					-			Erhardt et al. (1996)
	600										-						Deppe and Ruhl (1993)
Hardwoods:																	
Tilia cordata Mill. / Small-leaved lime	150-270			↓	↑												Popescu et al. (2007)
Acacia nilotica (L.) Willd. Ex Delile	4100-4400	↓	↑		↓		↑										Van Zyl et al. (1973), Borgin et al. (1975a)
Quercus sp. / Oak	60-260				↑												Gawron et al. (2012)
Pterocarpus sp.	500	↑	↓							↓	-			↓			Narayanamurti et al. (1961)
Tectona grandis L. fil / Teak	1800										↑						Narayanamurti et al. (1958)
	2200		↓	↓													Chowdhury et al. (1967)
Zelkova serrata Makino / Keyaki	240-650		↓		↓	↑		↓	↓	↓	↓		↓	↓	↓	↓	Kohara and Okamoto (1955)

Legend: ↑: increase, ↓: decrease, - : no change, ~ : increase (for the first 100 years) and decrease (afterward), R: radial

Summary of literature data. ↑: increase, ↓: decrease, –: no change, ~: Increase (for the first 100 years) and decrease (afterward), R: radial

reference samples. Equally, García Esteban et al. (2006) noted no chemical discrepancies (analyzed by FTIR) in the cell wall of 205-year-old Scots pine compared with recent wood; however, crystallinity was found to be lower in the former. For older softwoods (300- to 800-year-old fir, spruce, and larch wood), Tomassetti et al. (1990) determined, by means of thermogravimetric (TG) analysis, an increase in the lignin and ash portions and a decrease in the cellulose part with increasing wood age, and Erhardt et al. (1996) observed some degradation of the hemicellulose (hydrolysis of xylan) and a decrease in the amount of crystalline material in 300- to 400-year-old Scots pine. In contrast, the crystallinity of the investigated Japanese softwoods hinoki (300–1400 years) and Japanese red pine (170–500 years) remained more or less constant (Yonenobu and Tsuchikawa 2003;

Tsuchikawa et al. 2005; Ando et al. 2006; Inagaki et al. 2008; Saito et al. 2008) or were slightly higher (Japanese red pine (Saito et al. 2008)) with an increase in these characteristics found in hinoki for the first 100 years followed by a decrease (Kohara and Okamoto 1955). Analogue to other softwoods, the amount of "cellulosic materials" decreases in the two Japanese softwoods (Kohara and Okamoto 1955; Saito et al. 2008). Furthermore, for hinoki, a loss of the amorphous regions of cellulose was stated for the aged wood (Tsuchikawa et al. 2005; Yonenobu and Tsuchikawa 2003), also the hemicellulose degrades (furanose and pyranose) and a looser arrangement of the microfibrils takes place (Tsuchikawa et al. 2005), whereas the soluble constituents increase (Kohara and Okamoto 1955).

Regarding European hardwoods, hemicelluloses degraded (hydrolyzes of xylan) and levoglucosan content increased in 150- to 180-year-old lime wood from painting supports. The latter indicates an increase in the more ordered part of the cellulose macromolecule (Popescu et al. 2007). Also for oak, an increase in the cellulose crystallinity index was shown with aging (Gawron et al. 2012). Regarding Japanese and Asian hardwoods, the amount of cellulose and crystallinity decreased, whereas soluble constituents increased in 240- to 650-year-old keyaki wood (Kohara and Okamoto 1955). For 500-year-old *Pterocarpus* wood gathered from an altar, cellulose content was found to be lower than usual values in recent wood, while lignin content was higher (Narayanamurti et al. 1961), and for a 2200-year-old teak sample, a significant difference in birefringence and a decrease in the cellulose and pentosan content were reported (Chowdhury et al. 1967).

Specific changes of the chemical components were apparent in 4100- to 4400-year-old *Juniperus phoenicea*, *Pinus pinea*, and *Acacia nilotica* samples found in pyramids in Egypt. Besides an increase in ash content, the analysis revealed higher holocellulose and lower lignin content for the aged samples than for recent wood. Considering the higher-carbonyl-group content found for the aged samples, the authors assume that oxidation of the lignin had taken place, which had degraded the macromolecules to smaller (soluble) units. Also, a reduction in birefringence was measured, which indicates a reduction in the amount of crystalline cellulose (Van Zyl et al. 1973; Borgin et al. 1975a, b).

Color

The color of wood depends on its basic chemical composition (Hon et al. 1985), and thus discolorations should be a result of alterations in the chemical components. Photodegradation is an important factor causing color changes in wood under natural conditions. The depth of penetration and the initiated chemical changes depend on the wavelength of the irradiation (Kataoka et al. 2007), and thus the effects of different light spectra are not the same. When wood is exposed to direct sunlight, severe damages are induced by UV radiation (Tolvaj and Faix 1995; Papp et al. 2005). In the case of objects stored indoors, the sunlight spectrum is mostly filtered by window glass, resulting in a reduced UV radiation intensity. Furthermore, artificial light sources are present as well. Thereby, accelerated lightfastness testing, for example, with a UVA 351 lamp, suitably simulates indoor color changes (Chang and Chang 2001). While photodegradation of wood is considered a superficial

process due to limited penetration of light into wood (Kataoka et al. 2007; Kataoka 2008), thermal oxidation may affect the whole cross section. However, color changes by natural aging and by heat treatment are similar, due to oxidation processes in both cases (Matsuo et al. 2011). The intensity of the color change is high at the onset of aging and decreases with elapsed time (Kohara 1955; Oltean et al. 2008; Miklecic et al. 2011, 2012). For example, aged spruce, fir, oak, and hinoki wood show a decrease in lightness and an increase in chromaticity similar to a low heat treatment (Bekhta and Niemz 2003; Brischke et al. 2007; Matsuo et al. 2011; Sonderegger et al. 2015).

Hygroscopic behavior

Considering that most problems with wooden cultural heritage objects occur due to swelling and shrinkage of wood, information about the hygroscopic behavior of aged wood is very important. Unfortunately, only a few and partly inconsistent references regarding the swelling of aged wood could be found (cf. Table 1). A decrease in the swelling coefficients was reported on hinoki and keyaki wood, aged up to 1300 and 650 years, respectively (Kohara and Okamoto 1955). In contrast, an increase in swelling in a 300-year-old spruce beam was observed (Schulz et al. 1984), which, however, can be explained by the clearly higher density of the aged wood (cf. Sonderegger et al. 2008). No significant differences in swelling were reported on spruce specimens aged 60–180 years (Holz 1981), and no changes could be proven for Scots pine aged 300–400 years either (Erhardt et al. 1996).

More studies are available considering the sorption isotherms and EMC (Table 1). Sorption curves of aged spruce and fir specimens are slightly shifted to lower EMC values (Kurtoglu 1983; Lang 2004). Also, the EMC of hinoki and keyaki decreases with increasing wood age (Kohara and Okamoto 1955; Inagaki et al. 2008; Kawai et al. 2008; Yokoyama et al. 2009). In contrast, no difference or only a slight decrease was observed in the EMC of aged wood of various species (Buck 1952), and no significant changes or even an increase in the sorption curves are reported for aged Scots pine compared with recent wood (Erhardt et al. 1996; García Esteban et al. 2006). Thereby, a decrease in adsorption sites in hemicelluloses or amorphous cellulose may contribute to lower EMC values (Inagaki et al. 2008), whereas decreasing crystallinity induces contrary effects (García Esteban et al. 2006). The decrease in adsorption sites could be confirmed by CO_2 adsorption tests (Horvath and Kawazoe 1983) of 1300-year-old hinoki wood. The pore volume of aged wood is reduced due to a decrease in the number of micropores (<0.6 nm), which results in stabilization of the microstructure (Kojiro et al. 2008). Equally for liquid water uptake, the total amount of water taken up by 1500-year-old teak samples was considerably lower due to a clear decrease in their hygroscopicity (Narayanamurti et al. 1958).

Mechanical behavior

Knowledge of the mechanical properties of aged wood not only is important for the conservation of wooden heritage but must also be considered when recycling wood.

In Table 1, a short overview of studies on the topic presented in the following is given.

Most studies on the mechanical behavior of wood deal only with a few selected properties. Compression strength has been relatively often investigated, primarily by condition assessment of aged wood structures. Measurements on constructions of softwoods like spruce, fir, or Scots pine do not show any changes in the compression strength for at least up to 400 years of age (Ehlbeck and Görlacher 1988, 1993; Rug and Seemann 1989; Deppe and Rühl 1993; Nier 1994; Weimar 2000; Lang 2004; Lißner and Rug 2005). Investigations on Eastern white pine, aged 140 years, Scots pine, aged 260–480 years, and 300-year-old spruce roof elements even show an increase in the compression strength (Attar-Hassan 1976; Schulz et al. 1984; Witomski et al. 2014), but the strength of hinoki decreases after about 100 years (Kohara and Okamoto 1955). For hardwood, compression strength is unaltered for 500-year-old *Pterocarpus* (Narayanamurti et al. 1961), whereas 1800-year-old teak shows an increase (Narayanamurti et al. 1958) and keyaki, aged up to 650 years, decreases in strength compared with recent wood (Kohara and Okamoto 1955). The hardness of aged wood shows similar tendencies to compression strength (Kohara and Okamoto 1955; Attar-Hassan 1976).

Determination of bending strength and Young's modulus in the longitudinal direction is also frequently established when investigating aged wood. Several studies on softwoods used in construction did not show any differences between bending strength of recent and aged wood up to 400 years (Ehlbeck and Görlacher 1988, 1993; Rug and Seemann 1989; Nier 1994; Horie 2002; Baron 2009), or they indicate that the strength of aged wood even increases (Schulz et al. 1984). Values for aged hinoki wood from historical buildings, which were density corrected, are similar to those of recent wood even up to 1600 years (Yokoyama et al. 2009), whereas uncorrected values show a decrease after about 100 years (Kohara and Okamoto 1955). A decrease in strength is also found for Eastern white pine (Attar-Hassan 1976).

A decrease in static bending Young's modulus was observed for aged spruce and Eastern white pine (Attar-Hassan 1976; Lang 2004), but by means of ultrasound tests, an increase in dynamic Young's modulus was measured (Attar-Hassan 1976; Kránitz et al. 2014). For aged Scots pine, no significant change or otherwise a decrease in Young's modulus were found, depending on the author (Erhardt et al. 1996; Lang 2004). No deterioration regarding Young's modulus was observed in Jeso spruce and Sakhalin fir (Horie 2002). Inconsistent results are reported for aged Japanese red pine and hinoki wood with an increase in Young's modulus (Kawai et al. 2008; Noguchi et al. 2012), no change (Yokoyama et al. 2009) or a decrease (Saito et al. 2008), or an increase for the first 100 years followed by a decrease (Kohara and Okamoto 1955).

For hardwood, a decrease in bending strength and Young's modulus was observed both for 500-year-old *Pterocarpus* specimens (Narayanamurti et al. 1961) and for keyaki wood aged up to 650 years (Kohara and Okamoto 1955).

In the radial direction, a decrease of about 25 % in rupture strength was observed on 200- to 500-year-old spruce specimens by microtensile tests, but no differences in Young's modulus were found (Froidevaux et al. 2012). Also for hinoki wood

aged up to 1580 years, bending strength and breaking strain in the radial direction were significantly lower compared with recent samples (Yokoyama et al. 2009).

Investigations on tensile strength are contradictory. Whereas an increase in strength for 300-year-old spruce wood is reported (Schulz et al. 1984), 140-year-old Eastern white pine shows a decrease compared with recent wood (Attar-Hassan 1976).

Wood might become more brittle with aging (Attar-Hassan 1976; Kawai et al. 2008). Many authors report a decrease in the absorbed energy in the (impact) bending test for aged wood (Kohara and Okamoto 1955; Schulz et al. 1984; Weimar 2000; Lang 2004; Baron 2009; Yokoyama et al. 2009). Samples investigated in these studies served in constructions for 300–1600 years and consist mainly of softwoods with the hardwood keyaki as the only exception. Inspections of the fracture surfaces reveal a higher proportion of brittle fractures for aged wood than for recent wood (Weimar 2000; Lang 2004). However, for a short service time of 30–80 years, no difference in the impact bending strength of two Japanese softwoods was observed (Horie 2002).

Regarding shear strength, the values of aged Eastern white pine increased and that of hinoki and keyaki wood decreased with age (Attar-Hassan 1976; Kohara and Okamoto 1955), but no difference between the shear strength of 270-year-old Japanese red pine and recent wood could be detected. However, acoustic emission analysis during the shearing tests showed more brittleness of the aged wood. A relatively long and stable progress of microcracking was found before the final fracture, with the fracture surfaces appearing more uneven and complex on the microscopic level. Also, besides intra-wall failure, trans-wall failures, which were initiated mainly from the bordered pits, occur in the case of aged wood (Ando et al. 2006).

Under dry conditions, 200- to 500-year-old spruce wood tends to creep and relax more than recent wood, but no significant differences occur in wet climates. Creep recovery and relative mechano-sorptive strain are similar for aged wood to recent wood, but the irreversible part is clearly greater (Froidevaux et al. 2012).

Conclusion

The literature study provided an insight into the aging process and the different kinds of aging. In addition, the property changes of aged wood were discussed. The topic has been investigated worldwide, many of them originating from Japan. It was shown that in addition to environmental influences the species of the wood also has a high influence on the property changes of aged wood. In many cases, aging of wood can be compared with the effect of a low thermal treatment in the range of about 100 to 150 °C which is used to simulate accelerated aging.

Despite often contradictory trends concerning wood aging, which may be influenced by the difficulty in specimen matching, conditions during aging, or different test methods, some general statements can be deduced from the analyzed literature data (cf. Table 1). Concerning the property changes, generally, the hemicellulose content decreased with increasing age, whereas the ash content

increased. Also in most of the cases, the EMC slightly decreased with increasing age. On the other hand, inconsistent results were found for crystallinity, holocellulose and amorphous cellulose, lignin and extractives, and swelling and shrinkage. The wood darkened with increasing age, and the color tended toward higher chromaticity values. Whereas no, or inconsistent, trends were found in many cases for the mechanical properties parallel to the grain, and therefore, the influence of aging was very low, the increased brittleness of aged wood induced reduced strength properties perpendicular to the grain (bending, tension) as well as reduced impact bending strength and lower strain (especially plastic strain).

Preferably, this comprehensive information about wood aging contributes to a better understanding of its influencing factors and aids in the proper conservation of wooden cultural heritage objects and also encourages a greater extent of reuse of aged wood.

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References

Ando K, Yoshihiko H, Sugihara M, Hirao S, Sasaki Y (2006) Microscopic processes of shearing fracture of old wood, examined using the acoustic emission technique. J Wood Sci 52:483–489

Attar-Hassan G (1976) The effect of ageing on the mechanical properties of Eastern white pine. Bull Assoc Preserv Technol 8(3):64–73

Baron T (2009) Untersuchungen an ungeschädigten und durch Pilzbefall geschädigten Nadelholzbauteilen mit ausgewählten Prüfverfahren (Investigations with selected test methods on undamaged softwood constructions and constructions damaged through fungal decay). (In German) Dissertation, Technische Universität Dresden

Barrett JD, Foschi RO (1978) Duration of load and probability of failure in wood. Part I. Modeling creep rupture. Can J Civil Eng 5(4):505–514

Bekhta P, Niemz P (2003) Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung 57:539–546

Bekhta P, Niemz P (2006) Effect of high temperature on physical and mechanical properties of spruce wood. In: Kurjatko S, Kudela J, Lagana R (eds) Wood structure and properties '06. Arbora publishers, Zvolen, p 508

Björdal CG (2012) Microbial degradation of waterlogged archaeological wood. J Cult Herit 13(3S):118–122

Bodig J, Jayne BA (1993) Mechanics of wood and wood composites. Krieger Publishing Company, Malabar

Borgin K, Faix O, Schweers W (1975a) The effect of aging on lignins of wood. Wood Sci Technol 9:207–211

Borgin K, Parameswaran N, Liese W (1975b) The effect of aging on the ultrastructure of wood. Wood Sci Technol 9:87–98

Bourgois J, Janin G, Guyonnet R (1991) La mesure de couleur: une méthode d'étude et d'optimisation des transformations chimiques du bois thermolysé (The color measurement: A fast method to study and optimize the chemical transformations undergone in the thermally treated wood). Holzforschung 45:377–382

Brischke C, Welzbacher CR, Brandt K, Rapp AO (2007) Quality control of thermally modified timber: interrelationship between heat treatment intensities and CIE L*a*b* color data on homogenized wood samples. Holzforschung 61:19–22

Buck RD (1952) A note on the effect of age on the hygroscopic behavior of wood. Stud Conserv 1(1):39–44

Chang HT, Chang ST (2001) Correlation between softwood discoloration induced by accelerated lightfastness testing and by indoor exposure. Polym Degrad Stabil 72:361–365

Chen Y, Fan YM, Gao JM, Stark NM (2012) The effect of heat treatment on the chemical and color change of black locust (*Robinia pseudoacacia*) wood flour. Bioresources 7:1157–1170

Chowdhury KA, Preston RD, White RK (1967) Structural changes in some ancient Indian timbers. Proc Roy Soc B 168:148–157

Clausnitzer K-D (1990) Historischer Holzschutz: Zur Geschichte der Holzschutzmaßnahmen von der Steinzeit bis in das 20. Jahrhundert (Historical wood preservation: As to the history of wood preservation procedures from Stone Age to the twentieth century). Ökobuch Verlag, Staufen bei Freiburg

Deppe H-J, Rühl H (1993) Evaluation of historical construction timber. 1. Density and compression strength. Holz Roh Werkst 51:379–383 **(in German)**

Ehlbeck J, Görlacher R (1988) Erste Ergebnisse von Festigkeitsuntersuchungen an altem Konstruktionsholz (First results from investigations of strength on wood from old constructions). In: Wenzel F (ed) Erhalten historisch bedeutsamer Bauwerke. SFB 315 Universität Karlsruhe, Jahrbuch 1987, Ernst & Sohn, Berlin, pp 235–247

Ehlbeck J, Görlacher R (1993) Probleme bei der Beurteilung der Tragfähigkeit von altem Konstruktionsholz (Problems with the evaluation of timber bearing capacity in old constructions). In: Schmidt H (ed) Erhalten historisch bedeutsamer Bauwerke. SFB 315 Universität Karlsruhe, Sonderband 1990: Erhaltungskonzepte, Ernst & Sohn, Berlin, pp 201–208

Erhardt D, Mecklenburg MF, Tumosa CS, Olstad TM (1996) New versus old wood: differences and similarities in physical, mechanical, and chemical properties. In: Bridgeland J (ed) International council of museums-committee for conservation 11th triennial meeting. James & James, London, pp 903–910

Erhardt D, Tumosa C, Mecklenburg M (2000) Chemical and physical changes in naturally and accelerated aged cellulose. In: Cardamone JM, Baker MT (eds) Historic textiles, papers, and polymers in Museums. American Chemical Society, Washington, pp 23–37

Esteves BM, Pereira HM (2009) Wood modification by heat treatment: a review. Bioresources 4:370–404

Fengel D (1991) Aging and fossilization of wood and its components. Wood Sci Technol 25:153–177

Florian M-LE (1990) Scope and history of archaeological wood. In: Rowell RM, Barbour RJ (eds) Archaeological wood: properties, chemistry, and preservation. Advances in Chemistry Series 225, American Chemical Society, Washington, DC, pp 3–32

Follrich J, Teischinger A, Müller U (2011) Artificial ageing of softwood joints and its effect on internal bond strength with special consideration of flat-to-end grain joints. Eur J Wood Prod 69:597–604

Foschi RO, Yao FZ (1986) Another look at three duration of load models. In: Proceedings of the 19th meeting, international council for research and innovation in building and construction, working commission W18—timber structures, CIB-W18, Florence, Italy

Fridley KJ, Mitchell JB, Hunt MO, Senft JF (1996a) Effect of 85 years of service on mechanical properties of timber roof members. Part 1: experimental observations. For Prod J 46(5):72–78

Fridley KJ, Mitchell JB, Hunt MO, Senft JF (1996b) Effect of 85 years of service on mechanical properties of timber roof members. Part 2: cumulative damage analysis. For Prod J 46(6):85–90

Froidevaux J, Navi P (2013) Aging law of spruce wood. Wood Mat Sci Eng 8(1):46–52

Froidevaux J, Volkmer T, Ganne-Chédeville C, Gril J, Navi P (2012) Viscoelastic behavior of aged and non-aged spruce wood in the radial direction. Wood Mat Sci Eng 7(1):1–12

Ganne-Chédeville C, Jääskeläinen A-S, Froidevaux J, Hughes M, Navi P (2012) Natural and artificial ageing of spruce wood as observed by FTIR-ATR and UVRR spectroscopy. Holzforschung 66:163–170

García Esteban L, García Fernández F, Guindeo A, Palacios P, Gril J (2006) Comparison of the hygroscopic behaviour of 205-year-old and recently cut juvenile wood from *Pinus sylvestris* L. Ann For Sci 63:309–317

Gawron J, Szczesna M, Zielenkiewicz T, Golofit T (2012) Cellulose crystallinity index examination in oak wood originated from antique woodwork. Drewno 55(188):109–114

Gonzalez-Pena MM, Curling SF, Hale MDC (2009) On the effect of heat on the chemical composition and dimensions of thermally-modified wood. Polym Degrad Stabil 94:2184–2193

Hakkou M, Petrissans M, Gerardin P, Zoulalian A (2006) Investigations of the reasons for fungal durability of heat-treated beech wood. Polym Degrad Stabil 91:393–397

Hedges JI (1990) The chemistry of archaeological wood. In: Rowell RM, Barbour RJ (eds) Archaeological wood: properties, chemistry, and preservation. Advances in Chemistry Series 225, American Chemical Society, Washington, pp 111–140

Hoffmann P, Jones MA (1990) Structure and degradation process for waterlogged archaeological wood. In: Rowell RM, Barbour RJ (eds) Archaeological wood: properties, chemistry, and preservation. Advances in Chemistry Series, American Chemical Society 225, Washington, pp 35–65

Holz D (1981) Zum Alterungsverhalten des Werkstoffes Holz – einige Ansichten, Untersuchungen, Ergebnisse (Aging of wood—some aspects, investigations, results). Holztechnologie 22:80–85

Holzer SM, Loferski JR, Dillard DA (1989) A review of creep in wood: concepts relevant to develop long-term behavior predictions for wood structures. Wood Fiber Sci 21:376–392

Hon DNS, Chang ST, Feist WC (1985) Protection of wood surfaces against photooxidation. J Appl Polym Sci 30:1429–1448

Horie H (2002) Strength deterioration of recycled lumber collected from demolished wooden buildings in Hokkaido. Mokuzai Gakkaishi 48:280–287

Horvath G, Kawazoe K (1983) Method for the calculation of effective pore-size distribution in molecular-sieve carbon. J Chem Eng Jpn 16:470–475

Inagaki T, Yonenobu H, Tsuchikawa S (2008) Near-infrared spectroscopic monitoring of the water adsorption/desorption process in modern and archaeological wood. Appl Spectrosc 62:860–865

Kataoka Y (2008) Photodegradation of wood and depth profile analysis. Mokuzai Gakkaishi 54:165–173

Kataoka Y, Kiguchi M, Williams RS, Evans PD (2007) Violet light causes photodegradation of wood beyond the zone affected by ultraviolet radiation. Holzforschung 61:23–27

Kawai S, Yokoyama M, Matsuo M, Sugiyama J (2008) Research on the aging of wood in RISH. In: Gril J (ed) Wood science for preservation of cultural heritage: mechanical and biological factors. Braga, Portugal, pp 52–56

Kohara J (1955) Studies on the permanence of wood (X): colorimetry on the old timbers by the trichromatic colorimeter. J Jpn For Soc 37(2):63–66

Kohara J, Okamoto H (1955) Studies of Japanese old timbers. Sci Rep Saikyo Univ 7(1a):9–20

Kojiro K, Furuta Y, Ohkoshi M, Ishimaru Y, Yokoyama M, Sugiyama J, Kawai S, Mitsutani T, Ozaki H, Sakamoto M, Imamura M (2008) Changes in micropores in dry wood with elapsed time in the environment. J Wood Sci 54:515–519

Kollmann F, Schmidt E (1962) Structural derangement and loss in strength of permanently stressed coniferous wood (in German). Holz Roh Werkst 20:333–338

Kránitz K (2015) Effect of natural aging on wood. Dissertation, ETH Zurich

Kránitz K, Deublein M, Niemz P (2014) Determination of dynamic elastic moduli and shear moduli of aged wood by means of ultrasonic devices. Mater Struct 47:925–936

Kuo ML, Hu NH (1991) Ultrastructural changes of photodegradation of wood surfaces exposed to UV. Holzforschung 45:347–353

Kurtoglu A (1983) The properties of sorption of old spruce timber. Holzforsch Holzverw 35(6):125–126

Lang A (2004) Charakterisierung des Altholzaufkommens in Deutschland (Characterisation of the waste wood situation in Germany). Dissertation, Universität Hamburg

Li X, Cai Z, Mou Q, Wu Y, Liu Y (2011) Effects of heat treatment on some physical properties of Douglas fir (*Pseudotsuga menziesii*) wood. Adv Mat Res 197–198:90–95

Lißner K, Rug W (2005) Ergänzung bzw. Präzisierung der für die Nachweisführung zur Stand- und Tragsicherheit sowie Gebrauchstauglichkeit von Holzkonstruktionen in der Altbausubstanz maßgebenden Abschnitte der DIN 1052. Bauforschung, T 3068, Fraunhofer IRB Verlag, Stuttgart

Lohwag K (1967) Zeittafel zur Geschichte des Holzschutzes (Chronological table of the history of wood preservation). Int Holzmarkt 58(16/17):45–54

Matsuo M, Yokoyama M, Umemura K, Sugiyama J, Kawai S, Gril J, Kubodera S, Mitsutani T, Ozaki H, Sakamoto M, Imamura M (2011) Aging of wood: analysis of color changes during natural aging and heat treatment. Holzforschung 65:361–368

Miklecic J, Jirous-Rajkovic V, Antonovic A, Spanic N (2011) Discoloration of thermally modified wood during simulated indoor sunlight exposure. Bioresources 6:434–446

Miklecic J, Kasa A, Jirous-Rajkovic V (2012) Colour changes of modified oak wood in indoor environment. Eur J Wood Prod 70:385–387

Nakao T, Tanaka C, Takahashi A, Okano T, Nishimura H (1989) Long-term changes in degree of crystallinity of wood cellulose. Holzforschung 43:419–420

Narayanamurti D, Ghosh SS, Prasad BN, George J (1958) Note on examination of an old timber specimen. Holz Roh Werkst 16:245–247

Narayanamurti D, Prasad BN, Verma GM (1961) Examination of old timbers—part III: old Pterocarpus specimen from Tirupathi. Holz Roh Werkst 19(2):47–50

Nemeth K (1998) A faanyag degradációja (Degradation of wood). Mezőgazdasági Szaktudás Kiadó, Budapest
Niemz P (1993) Physik des Holzes und der Holzwerkstoffe (Physics of solid wood and wooden materials). DRW, Leinfelden-Echterdingen
Niemz P, Hofmann T, Rétfalvi T (2010) Investigation of chemical changes in the structure of thermally modified wood. MADERAS: Ciencia y Tecnología 12(2):69–78
Nier J (1994) Experimentelle Festigkeitsuntersuchungen an alten Bauhölzern und daraus abgeleitete Erkenntnisse zur Tragfähigkeitsbeurteilung (Experimental investigations of strength on old construction timber and therefrom deduced knowledge for bearing capacity estimation). Dissertation, Technische Hochschule Leipzig
Nilsson T, Daniel G (1990) Structure and the aging process of dry archaeological wood. In: Rowell RM, Barbour RJ (eds) Archaeological wood: properties, chemistry, and preservation. Advances in Chemistry Series 225, American Chemical Society, Washington, pp 67–86
Noguchi T, Obataya E, Ando K (2012) Effects of aging on the vibrational properties of wood. J Cult Herit 13(3S):21–25
Norrstrom H (1969) Light absorbing properties of pulp and pulp components, 1. Method. Sven Papperstidn 72(2):25
Oltean L, Teischinger A, Hansmann C (2008) Wood surface discolouration due to simulated indoor sunlight exposure. Holz Roh Werkst 66:51–56
Oltean L, Teischinger A, Hansmann C (2011) Influence of low and moderate temperature kiln drying schedules on specific mechanical properties of Norway spruce wood. Eur J Wood Prod 69:451–457
Papp G, Barta E, Preklet E, Tolvaj L, Berkesi O, Nagy T, Szatmári S (2005) Changes in DRIFT spectra of wood irradiated by UV laser as a function of energy. J Photochem Photobiol A 173:137–142
Pedersen NB, Björdal CG, Jensen P, Felby C (2013) Bacterial degradation of archaeological wood in anoxic waterlogged environments. In: Harding SE (ed) Stability of complex carbohydrate structures: biofuels, foods, vaccines and shipwrecks. The Royal Society of Chemistry, Cambridge, pp 160–187
Pfriem A, Zauer M, Wagenführ A (2009) Alteration of the pore structure of spruce (*Picea abies* (L.) Karst.) and maple (*Acer pseudoplatanus* L.) due to thermal treatment as determined by helium pycnometry and mercury intrusion porosimetry. Holzforschung 63:94–98
Pfriem A, Buchelt B, Zauer M, Wagenführ A (2010) Comparative analysis of thermally modified and native spruce loaded perpendicular to the grain. Eur J Wood Prod 68:267–270
Poncsák S, Kocaefe D, Bouazara M, Pichette A (2006) Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). Wood Sci Technol 40:647–663
Popescu C-M, Dobele G, Rossinskaja G, Dizhbite T, Vasile C (2007) Degradation of lime wood painting supports: evaluation of changes in the structure of aged lime wood by different physico-chemical methods. J Anal Appl Pyrol 79:71–77
Popper R, Niemz P, Eberle G (2005) Investigations on the sorption and swelling properties of thermally treated wood. Holz Roh Werkst 63:135–148
Reichel S (2015) Modellierung und Simulation hygro-mechanisch beanspruchter Strukturen aus Holz im Kurz- und Langzeitbereich (Modelling and simulation of the short-term and long-term material behaviour of hygro-mechanically loaded wooden structures). Dissertation, TU Dresden
Ross JC (ed) (2010) Wood handbook: wood as an engineering material. Forest Products Laboratory, Madison
Rowell RM, Barbour RJ (1990) Archaeological wood: Properties, chemistry, and preservation. Advances in Chemistry Series 225, American Chemical Society, Washington
Rowell RM, Ibach RE, McSweeny J, Nilsson T (2009) Understanding decay resistance, dimensional stability and strength changes in heat-treated and acetylated wood. Wood Mat Sci Eng 4(1–2):14–22
Rug W, Seemann A (1989) Ermittlung von Festigkeitswerten an alten Holzkonstruktionen (Determination of strength values on old wood constructions). Holztechnologie 30:69–73
Saito Y, Shida S, Ohta M, Yamamoto H, Tai T, Ohmura W, Makihara H, Noshiro S, Goto O (2008) Deterioration character of aged timbers: insect damage and material aging of rafters in a historic building of Fukushoji-temple. Mokuzai Gakkaishi 54:255–262
Sandberg D, Haller P, Navi P (2013) Thermo-hydro and thermo-hydro-mechanical wood processing: an opportunity for future environmentally friendly wood products. Wood Mat Sci Eng 8:64–88
Schulz H, von Aufsess H, Verron T (1984) Eigenschaften eines Fichtenbalkens aus altem Dachstuhl (Properties of a spruce beam after 300 years in roof construction). Holz Roh Werkst 42:109
Smith I, Landis E, Gong M (2003) Fracture and fatigue in wood. John Wiley & Sons Ltd, Chichester

Sonderegger W, Alter P, Niemz P (2008) Investigations on selected properties of tonal wood of spruce from Grisons. Holz Roh Werkst 66:345–354
Sonderegger W, Mannes D, Kaestner A, Hovind J, Lehmann E (2014) On-line monitoring of hygroscopicity and dimensional changes of wood during thermal modification by means of neutron imaging methods. Holzforschung. doi:10.1515/hf-2014-0008
Sonderegger W, Kránitz K, Bues C-T, Niemz P (2015) Aging effects on physical and mechanical properties of spruce, fir and oak wood. J Cult Herit. doi:10.1016/j.culher.2015.02.002
Stamm AJ (1956) Thermal degradation of wood and cellulose. Ind Eng Chem 48:413–417
Stanzl-Tschegg SE, Tschegg EK, Teischinger A (1994) Fracture energy of spruce wood after different drying procedures. Wood Fiber Sci 26:467–478
Teischinger A (1991) Der Einfluss des Trocknungsverfahrens auf ausgewählte Holzkennwerte, Teil 1 (Influence of drying process on selected wood properties, part 1). Holzforsch Holzverw 43(1):20–22
Teischinger A (1992a) Der Einfluss des Trocknungsverfahrens auf ausgewählte Holzkennwerte, Teil 2 (Influence of drying process on selected wood properties, part 2). Holzforsch Holzverw 44(5):83–86
Teischinger A (1992b) Effect of different drying temperatures on selected physical wood properties. In: Vanek M (ed) 3rd IUFRO international wood drying conference, Vienna, pp 211–216
Tjeerdsma BF, Boonstra M, Pizzi A, Tekely P, Militz H (1998) Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Holz Roh Werkst 56:149–153
Tjeersdma BF, Militz H (2005) Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. Holz Roh Werkst 63:102–111
Tolvaj L, Faix O (1995) Artificial aging of wood monitored by DRIFT spectroscopy and CIE L*a*b* color measurements. 1. Effect of UV light. Holzforschung 49:397–404
Tolvaj L, Molnár S (2008) Photodegradation and thermal degradation of outdoor wood. In: Gril J (ed) Wood science for preservation of cultural heritage: mechanical and biological factors. Braga, Portugal, pp 67–72
Tomassetti M, Campanella L, Tomellini R (1990) Thermogravimetric analysis of ancient and fresh woods. Thermochim Acta 170:51–65
Tsuchikawa S, Yonenobu H, Siesler HW (2005) Near-infrared spectroscopic observation of the ageing process in archaeological wood using a deuterium exchange method. Analyst 130:379–384
Unger A, Schniewind AP, Unger W (2001) Conservation of wood artifacts. Springer, Berlin
Van Zyl JD, Van Wyk WJ, Heunis CM (1973) The effect of aging on the mechanical and chemical properties of wood. IUFRO-5 meeting: wood in the service of man. Pretoria 2:1069–1080
Wagenführ R (2007) Holzatlas (Wood atlas), 6th edn. Fachbuchverlag, Leipzig
Weiland JJ, Guyonnet R (2003) Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holz Roh Werkst 61:216–220
Weimar H (2000) Aspekte der stofflichen Charakterisierung von Altholz (Aspects of the material characterisation of aged wood). Diploma thesis, Universität Hamburg
Wikberg H, Maunu SL (2004) Characterisation of thermally modified hard- and softwoods by C-13 CPMAS NMR. Carbohyd Polym 58:461–466
Winandy JE (1996) Effects of treatment, incising, and drying on mechanical properties of timber. In: Ritter MA, Duwadi SR, Lee PDH (eds) National conference on wood transportation structures—new wood treatments. USDA Forest Service, Forest Products Laboratory, Madison, pp 371–378
Witomski P, Krajewski A, Kozakiewicz P (2014) Selected mechanical properties of Scots pine wood from antique churches of Central Poland. Eur J Wood Prod 72:293–296
Wood, LW (1951) Relation of strength of wood to duration of loads. Report no 1916, USDA Forest Service, Forest Products Laboratory, Madison WI
Yildiz S (2002) Physical, mechanical, technological and chemical properties of beech and spruce wood treated by heating. Karadeniz Technical University, Trabzon
Yildiz S, Gezer ED, Yildiz UC (2006) Mechanical and chemical behavior of spruce wood modified by heat. Build Environ 41:1762–1766
Yokoyama M, Gril J, Matsuo M, Yano H, Sugiyama J, Clair B, Kubodera S, Mitsutani T, Sakamoto M, Ozaki H, Imamura M, Kawai S (2009) Mechanical characteristics of aged Hinoki wood from Japanese historical buildings. CR Phys 10:601–611
Yonenobu H, Tsuchikawa S (2003) Near-infrared spectroscopic comparison of antique and modern wood. Appl Spectrosc 57:1451–1453
Yoshimoto T (1972) Photochemical analysis of wood and related substances. J Jpn Wood Res Soc 18:45–49