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REVIEW ARTICLE

A review of the long-term effects of humidity on the mechanical properties of wood and wood-based products

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Abstract
Wood is an indispensable building material for modern structures. As a kind of biological material, it is more likely than other materials to be affected by the environment. It has been shown that the effect of long-term exposure to humidity will accelerate the decrease in mechanical properties and long-term strength of wood and wood-based products. The most commonly used methods for studying the deterioration of the mechanical properties of wood and wood-based products under the action of long-term humidity exposure are artificially accelerated aging and outdoor exposure. Many scholars have studied various artificially accelerated aging tests, which can accelerate the aging of wood and wood-based products and save substantial time. However, the results of outdoor exposure tests can be better correlated with the aging of the materials in the actual environment. Scholars have established a relationship between artificially accelerated aging tests and the results of outdoor exposure tests and have studied the results of outdoor exposure tests under different climatic conditions. This paper not only reviews the artificially accelerated aging tests used for wood and wood-based products in the past twenty years, but also summarizes their characteristics and application scope. In addition, the relationship between the outdoor exposure tests and the artificially accelerated aging tests is reviewed. At the end of the paper, the challenges and prospects for the future works are put forward.

1 Introduction

In recent years, modern wood structures have gradually entered the public consciousness because of their environmental protection characteristics, good heat preservation and energy savings, good seismic performance and short construction cycle. As an assembled architectural form, modern wood structures have a history of more than 100 years. Modern wood structure mainly includes pure wood (log) structure, glued wood (glulam, cross laminated timber (CLT), laminated veneer lumber (LVL), etc.) structure and mixed-wood structures (steel-wood mixed, concrete-wood mixed, etc.). As biological materials, wood and wood-based products are an indispensable part of modern wood buildings and are more vulnerable to environmental influences. Here, wood refers to wood members made by simply processed logs and wood-based products including glulam, CLT, LVL, plywood, particleboard, fiberboard, oriented strand board (OSB), etc. In particular, long-term exposure to humidity changes will not only accelerate the deformation of wood and wood-based products, but also lead to the decline in mechanical properties and long-term strength of the materials. It may affect the bearing capacity and stability of the overall structure.

To study the durability and long-term strength of wood and wood-based products under changes in the external environment, scholars have evaluated the long-term mechanical properties of wood and wood-based products with changes in humidity. To quantify the humidity effects, some efforts have been made to develop predictive models for assessing the moisture diffusion in wood. At the first stage, some scholars have studied the influence of humidity on wood and wood-based products at the microscopic level (Greil et al. 1998; Ilaria and Benedetto 2001). With the development of finite element software, scholars homogenized wood microstructure and conducted multi-scale modeling according to continuum micromechanics to study and predict water transport distribution in wood (Eitelberger and Hofstetter 2011; Eitelberger et al. 2011a, b, 2012; Gamstedt

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et al. 2013). On the basis of numerical simulation, scholars have proposed the cumulative damage model and the creep model of wood under changing humidity. Some researchers (Gerhards and Link 1987; Barrett and Foschi 1987; Fridley et al. 1992) laid the foundation for the study of wood cumulative damage model and creep model, followed by a series of studies on wood creep (Hanhijärvi 1995, 2000a, b; Pavel et al. 2015; Qin and Yang 2018; Huang 2016; Huc 2019). With the enrichment of the test data, scholars further studied the effects of different sizes and temperatures on creep (Peng et al. 2017; Chang and Lam 2018; Hsieh and Chang 2018; Chiniforush et al. 2019), moisture-induced stress (Frandsen 2007; Fortino et al. 2009; Angst-Nicollier 2012; Angst-Nicollier and Malo 2013; Salinas et al. 2020), and constitutive models (Hassani et al. 2015). The effects of creep induced by both load and humidity on the long-term performance of wood members have also been analyzed (Massaro and Malo 2019). The effects of long-term humidity on creep, moisture distribution and decay of glulam have also been studied by numerical simulation and aging tests (Zhou et al. 2010; Li et al. 2016, 2018; Lee et al. 2019; Fortino et al. 2019).

Artificially accelerated aging tests and outdoor exposure tests are usually used to study the long-term strength of wood and wood-based products. Artificially accelerated aging tests include boiling, wet and thermal aging and dry–wet cycle aging tests. The most commonly used is dry-wet cycle aging test. As artificially accelerated aging tests are achievable in laboratory conditions within a reasonable amount of time, many countries have formulated a standard method of artificially accelerated aging to study the long-term mechanical properties of wood-based products (River 1994; Li et al. 2016; Mohammad et al. 2017; Way et al. 2018; Varanda et al. 2019). Some scholars have studied the influences of aging on the physical and mechanical properties of wood by comparing the wood members of historical and new structures (Bekhta and Niemz 2003; Poncsák et al. 2006; Pfriem et al. 2010; Sandberg et al. 2013; Sonderegger et al. 2015; Kránitz et al. 2016). At the same time, researchers have also tested and analyzed the steps of different aging tests and the effects on the test piece (Kojima and Suzuki 2011a).

Although artificially accelerated aging tests accelerate the aging of wood and wood-based products, they cannot precisely replicate the aging of wood members in the actual environment. Therefore, many scholars have carried out outdoor exposure tests to study the durability of wood and wood products. Brischke and his collaborators have studied the effects of different outdoor exposure conditions, section size and degradation typology on the durability of wood (Brischke and Rapp 2008a, b; Brischke and Meyer-Veltrup 2015, 2016; Meyer-Veltrup et al. 2017a). In addition to the above studies independently addressing the effects of humidity, some studies have also considered the effects of external loads on wood members (Meyer-Veltrup et al. 2017b). There are also some cases of long-term monitoring of existing outdoor wood structures to evaluate their durability and service life (Niklewski 2018; Treu et al. 2019). It is noted that the outdoor exposure tests require a long period of time and are easily limited by the region. Some researchers have investigated the relationship between artificially accelerated aging and outdoor exposure tests and evaluated the application scope and aging degree of different aging tests. (Scheffer 1979; Alexopoulos 1992; Hasegawa 1996; Kojima et al. 2011; Kojima and Suzuki 2011b; Korai et al. 2014). The correlations between different climatic factors and properties of wood and wood-based products were analyzed (Korai et al. 2015, 2017; Korai and Watanabe 2015; Niklewski et al. 2016).

This paper reviews the humidity effects on the degradation of wood and wood-based products. Various standard and non-standard accelerated aging tests have been summarized. Comparison studies between different tests have been carried out. Typology of outdoor exposure tests has been presented. Correlation studies on outdoor exposure and artificially accelerated aging have been summarized. The influences of different climatic factors on outdoor exposure tests have been discussed. It is noted that there are various kinds of wood-based products and this paper mainly focuses on glulam and wood-based panels including plywood, particleboard, fiberboard, and OSB. The database summarized in the paper is aiming to provide a comprehensive understanding of the field. Based on the findings from this review, recommendations are proposed for future works.

2 Humidity effects on degradation of wood and wood-based products

2.1 Effects of humidity on wood

2.1.1 Degradation of wood under the action of humidity

Wood is a kind of orthotropic and porous material, as shown in Fig. 1 (Greil et al. 1998; Liu 2008). It is composed of numerous tubular cells in close alignment observed under the microscope. Most of the cells are arranged in longitudinal direction, while less of them are arranged in transverse direction. Each cell consists of a cell wall and a cell cavity, and the cell wall is composed of a fine fiber bundle. The thicker the cell wall is, the smaller the cell cavity is. The thicker the cell wall, the greater the density and strength of the wood is. However, at the same time, the deformation is also greater.

The transport of water in wood is characterized by three phases. Below the fibre saturation point (FSP), about 28–30% moisture content, there is diffusion of water vapor in lumens, diffusion of bound water in wood cell walls and

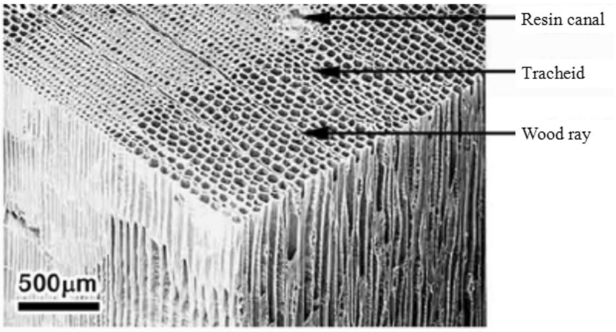


Fig. 1 Microstructure of wood

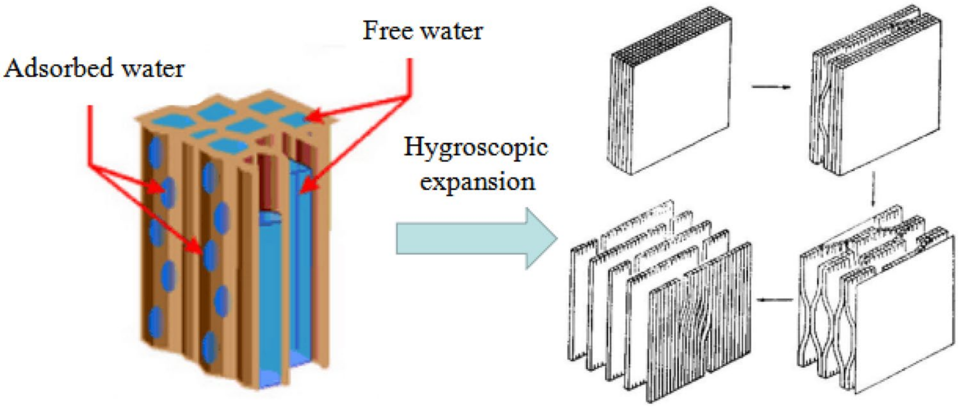
sorption between the two phases. Above the FSP, there is free water diffusion in lumens (Frandsen 2007). However, a change in humidity in the external environment usually affects the adsorbed water, as shown in Fig. 2, the water absorption and the expansion of the cell wall, and vice versa. Due to the periodic changes of temperature and humidity throughout the year, the cell wall is repeatedly contracted and expanded. The moisture gradients due to constrained shrinkage and swelling induce stresses that may cause cracks.

2.1.2 Humidity effect on durability of wood

Environmental factors affect the long-term strength of wood. The effect of long-term humidity change is very prominent, especially in humid and hot areas where the atmospheric water content is very high. The changing environmental humidity will reduce the long-term strength of wood under load, increase creep effects, and lead to excessive deformation, cracks or early damage. Gerhard and Link (1987) was of the opinion that the effect of time on the long-term strength of the component should not be neglected at any stress level; therefore, the damage accumulation model was established for the first time based on the lifetime damage of the wood member. Subsequently, Barrett and Foschi (1987) from Canada established a long-term strength model of wood members based on the Gerhard model. The effect of cyclic humidity on the long-term strength of wood members was studied, and the influence of continuous loads on the strength of the wood member was analyzed by using the strain energy method (Fridley et al. 1992). Hanhijärvi (2000a) also considered the effects of humidity, creep and stress levels, and established a long-term failure model for wood beams, which greatly promoted the analysis of wood continuous load effects by numerical simulation. At the same time, Hanhijärvi (2000b) also studied the influence of water content and stress level on the long-term strength of wood structures. Experimental studies and numerical simulations have been carried out. The previous creep model of wood was finally improved. The improved model considers the creep of mechanical adsorption and can be used to predict the mechanical properties of wood structures in an environment of changing humidity Qin and Yang (2018) proposed a multivariate cumulative damage model and a prediction model suitable for analyzing the strength degradation of ancient Tibetan wood building components.

In recent years, based on Hanhijärvi's studies, two-dimensional and three-dimensional moisture induced stress models and orthotropic constitutive models considering mechanical adsorption have been studied (Frandsen 2007; Hassani et al. 2015; Salinas et al. 2020). Fortino et al. (2009) developed a 3D orthotropic-viscoelastic-mechanosorptive model for wood, and it was further developed by many other authors later and currently. Because humidity and temperature generally affect each other, researchers have carried out tests on wood creep under different temperature conditions, and combined them with numerical simulation to study the influence of temperature and humidity on wood creep (Ekevad and Axelsson 2012; Pavel et al. 2015; Peng et al. 2017; Chang and Lam 2018; Chiniforush et al. 2019). Considering that the wood members are in a changing environment of long-term load and moisture, scholars have studied the creep

Fig. 2 Moisture absorption and expansion process of wood (Zhang 2012; Huacuijiaju 2018)



behavior of wood members in the changing environmental conditions (Massaro and Malo 2019). Huang (2016) studied the ultimate adsorption creep of poplar under different loads and humidity cycles. The results show that there is an increased load effect on creep under changes in cyclic moisture, which usually leads to the rapid increase in viscoelastic creep in the first humidification stage, resulting in recovery of deformation. Since wood members have different strength grades, Angst-Nicollier (2012) studied the influence of cross section geometry and screw reinforcement on moisture-induced stress.

The change in external humidity will cause fungal decay, thus accelerating the deterioration of wood members. Scholars have carried out a series of studies on fungal decay caused by moisture. Brischke's group studied the factors of decay affecting the service life of wood members and explored the influencing trend of temperature and humidity on wood decay (Brischke 2007; Brischke and Rapp 2008a, b; Meyer-Veltrup and Brischke 2015; Meyer-Veltrup et al. 2016; Brischke et al. 2019). Wood decay model and outdoor wood members decay model were established (Brischke and Rapp 2010; Isaksson et al. 2012).

As has been documented, some parameters can also influence the effect of moisture in wood, including climate type, size of wood cross section and type of protective coating (Jonsson 2004; Ekevad et al. 2011; Ekevad and Axelsson 2012; Knorz et al. 2016; Sepulveda-Villarroel et al. 2016). Fragiacomo et al. (2011) studied the influence of climate type, wood cross section size, protective layer type and other main parameters on moisture-induced stress. Brischke and Lampen (2014) studied the change in moisture content on native, modified, and preservative treated wood, and analyzed the influence of different protective treatments on wood.

2.2 Effect of humidity on wood-based products

2.2.1 Degradation of wood-based products under the action of humidity

Because solid wood cannot meet all the needs of modern wood structures, adhesives for structures were produced in 1942, and laminates are assembled together to form glulam. The emergence of adhesives has promoted the rapid development of the glulam production industry such that the application scope of glulam structures has been extended to outdoor open-air environments without concerns over the problem of glue joint degumming. Since then, the application scope of glulam structures has been further expanded. The adhesive is a kind of polymer that is also affected by changes in humidity. In the manufacturing process today, while the strength of the adhesive is higher than the strength of a metal sheet, the force between the adhesive molecule and the surface of the adhesive material is weakened by water molecules damaging the hydrogen bond at the interface. Therefore, in an environment of changing humidity, the degradation of the adhesive strength will also have a serious effect on the wood-based products.

The manufacturing technology used to produce wood-based panels is different from that used for glulam. The contact area between the wood-based panel and the adhesive is larger and deeper, so the influence of the adhesive on the quality of the wood-based panel is greater. When the humidity changes, the wood and the adhesive absorb or desorb water to produce expansion or shrinkage, and the difference in the wet expansion coefficients produces wet stress in the wood-based panel. There are three kinds of failure of the gluing interface caused by wet stress. The first is that the stress caused by the change in humidity leads to fatigue failure of the adhesive layer and the interface; the second is the hydrolysis of the adhesive layer due to the action of moisture on the adhesive layer and its interface with wood; and the third is a decrease in adhesion strength due to the effect of moisture on the interface.

2.2.2 Effect of humidity on durability of wood-based products

Both the fabrication process of wood-based products and the anisotropy of the wood itself will lead to unbalanced stress–strain conditions between different laminates and between the outer and inner sections of laminates, which will cause excessive deformation of wood-based products, affecting the service life. The reason for this is that the material is sensitive to humidity and temperature. Therefore, it is very important to master the mechanical behavior and deformation of wood-based products in humid and hot environment. In the last 15 years, many achievements have been made in the research of multi-phase methods of wood-based products. Among them, there is a large development of multi-phase methods for moisture transport in wood-based products (where the unknowns are all the water phases below the FSP) compared to the more traditional single-phase methods (where the only unknown is the moisture content). The effect of humidity change on wood-based products is reflected not only in the dry shrinkage and swelling of wood but also in changes in the strength of the adhesive. Durability is an important index for evaluating structural glue.

Scholars have done a lot of research on multi-phase methods of wood-based products. At the same time, the application of finite element method to the mechanical properties of wood-based products was reviewed in detail (Ochoa and Reddy 1992; De Borst et al. 2012; Reddy 2014; Caliri et al. 2016). Because the macroscopic material properties of wood-based products depend on their microscopic behavior, many scholars have established methods to analyze the micromechanics of materials. From micro to macro level, the effects of humidity and temperature on wood-based products were described (Rammerstorfer and Böhm 2014). These methods usually homogenize the material and then study it from different aspects (Drago and Pindera 2007; Böhm 2016; Zaoui 2002). Considering the moisture diffusion, moisture expansion and mechanical contributions in an isotropic way, Blanchet et al. (2005) used finite element software to calculate the hygro-mechanical distortion at changing surrounding humidity. Subsequently, the mechanical interaction of glueline, interphase and adherent in wood-based products with changing environment moisture was further studied (Gindl et al. 2005; Serrano and Enquist 2005; Konnerth and Gindl 2006, 2008; Konnerth et al. 2006a, b). Joffre et al. (2014) proposed a suitable method to consider moisture/stiffness relations on microscale. Wood and wood-based products were modeled by relating the elastic constants of the cellulose microfibrils to the moisture content of the material. This method can accurately predict and distinguish the moisture-induced deformation of wood and wood-based products.

Scholars usually use numerical methods to study the durability of glulam. The inner moisture distribution and the creep effects of members have been simulated. Zhou et al. (2010) studied the coupling of wet and thermal stress in glulam and successfully simulated the distribution of water content, temperature and stress in glulam. Hexagonal glue-laminated timber with large cross-sections, made from small diameter logs was studied by Li et al. (2018). The water content and the stress distribution were predicted by using the water transport and mechanical finite element models. The results showed that the established moisture transfer model was suitable for simulation. The most intuitive effect of moisture distribution on glulam is deformation, so Lee et al. (2019) studied the effects of different tree species and sizes on the moisture-related strain in glulam. By reflecting the nonlinear behavior of shrinkage based on the change in moisture content, a new method for predicting the size change of glulam was proposed. Fortino et al. (2019) proposed a numerical methodology to evaluate the moisture-induced stresses in glulam beams of timber bridges in Northern European climates and under mechanical loads. A hygro-thermal multi-Fickian model for prediction of moisture content, relative humidity and temperature in wood is sequentially coupled with an orthotropic-viscoelastic-mechanosorptive model for calculation of wood stresses.

3 Accelerated aging tests for wood and wood-based products

3.1 Summary of accelerated aging tests

Since the 1950s, many scientists in the United States, France, Japan and other countries have conducted research on the durability of wood-based panels. Among them, the United States is leading the research in this field, while other countries have elaborated on this research according to their own climate characteristics and have formulated corresponding artificially accelerated aging test standards. The National Standards Bureau of the United States defined the ASTM D1037 (1996) six-cycle accelerated aging test, which is mainly used to study the aging resistance of phenolic resin wood-based products. Accelerated aging processes also include European standards BS EN 1087-1 (1995) and Canadian Standard CAN/CSA-O188 (1978), which are different in terms of the effect and ability to accelerate aging. Typically, the appropriate aging test should be chosen according to the material of the test and the environment in service. In this paper, the experimental methods used for the dry–wet cycle aging of wood, wood-based products and bamboo in the past few decades are summarized in Table 1.

3.2 Comparison of different accelerated aging tests

Mcnatt and Link (1989) used the ASTM D1037 6-cycle accelerated aging test to analyze wood-based panels, which simplified the test steps of the ASTM D1037 6-cycle method. The results show that removing the step of 20-h freezing from the aging cycle has little effect on the final results. Subsequently, River (1994) in North America compared different artificially accelerated aging tests for the first time and studied the degradation of internal bonding strength, elastic modulus and ultimate bending strength of wood-based panels after ASTM D1037 6-cycle testing and VPSD aging. Norita et al. (2008) carried out two kinds of accelerated aging test at different temperatures. Based on the internal bonding strength of wood-based panels, the relationship between the two aging tests was analyzed and the effect of temperature on soaking wood-based panels was discussed. Through the artificially accelerated aging test of wood-based panels, Alexopoulos (1992) obtained the same aging conditions as the ASTM D1037 6-cycle aging test and BS EN1087-1 aging test.

Kojima and Suzuki (2011a, b) from Japan also carried out artificially accelerated aging tests on different wood-based panels. The aging tests used include ASTM D1037 6-cycle, JIS-B, APA D-1, V313 and VPSD. Using internal bonding strength and bending strength to define the deterioration rates, Kojima et al. (2012) compared the degradation of wood-based panels under different artificially accelerated aging tests. The results show that the ASTM D1037 6-cycle is the most stringent artificially accelerated aging test and has the best correlation with

Table 1 Summary of dry–wet cycle accelerated aging tests

Classification	Aging test	Aging step	Test material	References
Standard aging test	ASTM D1037(6) (1996)	49 ± 2 °C, soaking in warm water for 4 h → 93 ± 3 °C, steam treatment for 3 h → − 12 ± 3 °C, frozen for 20 h → 99 ± 2 °C, oven drying for 3 h → 93 ± 3 °C, steam treatment for 3 h → 99 ± 2 °C, oven drying for 18 h	Wood-based panel Bamboo recombined Wood Glulam	Kojima and Suzuki 2011b; Huang 2009; Zhang 2013; Li et al. 2015; Paridah et al. 2012
	BS EN1087-1 (1995)	Divided into four stages: soaking for 90 min in 20 °C cold water to 100 °C → Boiling water for 1 h → Boiling water for 1 h → Soaking, cooling in water at 20 °C for 1–2 h	Bamboo recombined wood Glulam	Zhang 2013; Li et al. 2015; Paridah et al. 2012; Huang 2009
	CAN/CSA-O188 (1978)	Divided into three stages: boiling water for 1 h → Boiling water for 1 h → soaking, cooling in water at 20 °C for 1 h	Glulam	Li et al. 2015; Paridah et al. 2012
	JIS-A (1994)	Soaking at 70 °C for 2 h → Soaking at 20 °C for 1 h → Oven drying at 60 °C for 24 h	Wood-based panel	Norita et al. 2008
	APA D-1(6) (1994)	Soaking in water at 66 °C for 8 h → Drying at 82 °C for 14.5 h → Setting at room temperature for 1.5 h	Wood-based panel	Kojima and Suzuki 2011b
	EN 321 V313(3) (1993)	Soaking at 20 °C for 72 h → Freezing at -12 °C for 24 h → Drying at 70 °C for 72 h → Setting at room temperature for 4 h	Wood-based panel Bamboo recombined wood	Huang 2009; Kojima and Suzuki 2011b
Other aging test	VPSD(10)	Vacuum immersion for 0.5 h → Pressure immersion (290 kPa) for 1 h → Drying at 60 °C for 22 h	Wood-based panel	Lehmann 1978; Kojima and Suzuki 2011b;
	CDB	Soaking in boiling water for 2 h → Drying at 107 °C for 18 h	LVL	River 1994; Paridah et al. 2012
	JIS-B	Soaking in boiling water at 100 °C for 2 h → Soaking at 20 °C for 1 h → Oven drying at 60 °C for 24 h	Wood-based panel	Norita et al. 2008
	JIS-B(6)	Soaking in boiling water for 2 h → Soaking at 20 °C for 1 h → Drying at 60 °C for 21 h	Wood-based panel	Kojima and Suzuki 2011b
	–	Sinusoidal variation in relative humidity between 45 and 75%	Glulam	Norita et al. 2008
	–	80% humidity and 20 °C treatment for 7 days, followed by 10% humidity and 60 °C treatment for 7 days, a total of 3 repeats	Glulam	Chomcharn and Skaar 1983

Table 1 (continued)

Classification	Aging test	Aging step	Test material	References
	–	Dry environment temperature 30 °C, relative humidity 16%, wet environment temperature 30 °C, relative humidity 80%	Birch wood	Li 2014
	–	Soaking in water for 6 h → Oven drying at a temperature of 103 ± 2 °C for 8 h	Fir wood	Miao et al. 2015

The number of cycles is indicated in parentheses in the table

each aging result. At the same time, the deterioration rate of different wood-based panels under different aging tests was studied (Fig. 3). The relationship between the internal bonding strength and aging cycle was obtained as follows:

$$IB = A + (100 - A) \times \exp(-t/B) \qquad (1)$$

where A and B are constants and t denotes the number of cycles. Coefficients A and B are determined by the nonlinear least squares regression method using artificially accelerated aging data.

Zhang (2013) studied the bonding performance and durability of glulam by various artificially accelerated aging tests Li et al. (2015) used glulam as an experimental material to compare the effects of different artificially accelerated aging tests on the mechanical properties of glulam members. Zhang (2015) tested the changes in gluing properties, dimensional stability and surface properties under five different aging conditions and optimized the artificially accelerated aging tests by carrying out normal electrification aging test and four different artificially accelerated aging tests for bamboo wood electro thermal composite board. Huang (2009) studied the effects of different artificially accelerated aging tests on the physical and mechanical properties of bamboo recombinant wood to select the most suitable artificially accelerated aging test for different tree species.

The deterioration of wood-based panels and glulam under the standard manual artificially accelerated aging tests in different countries is reviewed in this paper. The comparison of standard artificially accelerated aging tests is shown in Table 2.

The results of the above artificially accelerated aging tests show that the ASTM D1037 6-cycle method is the most stringent artificial aging test and has a good correlation with all the other artificially accelerated aging tests.

4 Outdoor exposure tests for wood and wood-based products

4.1 Typology of outdoor exposure tests on wood and wood-based products

To show the effect of aging on wood and wood-based products intuitively, different outdoor exposure tests were carried out. Sonderegger et al. (2015) studied various aspects of natural aging of spruce, fir and oak wood. The results show that aging changes the color of wood, resulting in the decrease in impact bending strength. However, adsorption, expansion, and fracture toughness will not or only partially exhibit modification over a longer period of time. Kránitz et al. (2016) conducted a literature review on different aspects of wood aging, summarized the natural aging of wood under aerobic and anaerobic storage conditions, and studied the wood performance under natural aging conditions Niklewski et al. (2016) studied the effect of rainfall by analyzing the difference of shelter and exposed samples over time.

Humidity will seriously affect the production and development of wood fungi, which will lead to the decline in the

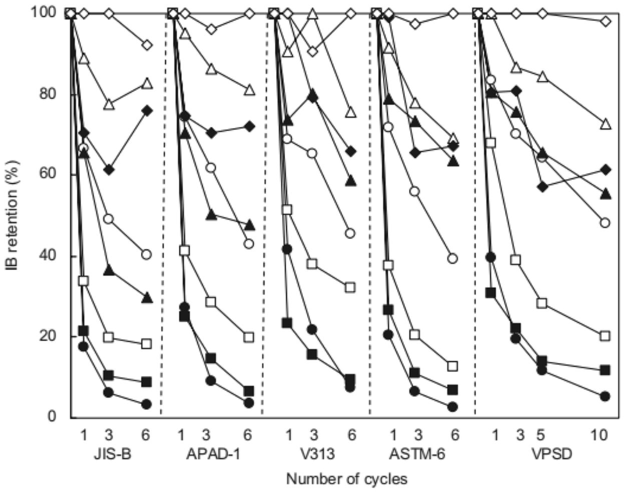


Fig. 3 Internal bond (*IB*) retention in five kinds of accelerated aging

performance of wood members. Brischke and Meyer-Veltrup (2015) studied the influence of different section sizes on water transport and fungal decay. Brischke and Meyer-Veltrup (2016) studied modelling of timber decay caused by brown rot fungi. It was found that brown decay started earlier and proceeded faster than white and soft decay. Brischke and Meyer-Veltrup (2015, 2016) carried out a series of studies on wood decay caused by humidity, and obtained the threshold of fungal growth and decay. At the same time, the effects of different decay types on the decay model were studied.

Durability of wood members is not only affected by climate, but also by load. Meyer-Veltrup et al. (2017a, b) carried out outdoor exposure tests of specimens subjected to different loads to study the effect of loads on the degradation of wood member performance. While some scholars carried out long-term monitoring of existing outdoor wood structures to evaluate their durability and service life, Brischke and Rapp (2008a, b) carried out 7 years automatic monitoring of moisture content and temperature of outdoor exposed wood, and compared the progress of decay, which laid the foundation for wood service life prediction. Using experimental data and simple numerical model, Niklewski (2018) predicted the moisture content of rain-exposed wood and studied moisture conditions and service life assessment of bridge detailing.

4.2 Correlation between artificially accelerated aging tests and outdoor exposure tests

4.2.1 Correlation between the standard aging tests and outdoor exposure tests

Methods for exploring the effect of long-term humidity changes on the durability of wood-based products include manual artificially accelerated aging tests and outdoor exposure tests. The durability of outdoor exposure tests was evaluated by exposure time, and the durability of artificially accelerated aging tests was evaluated by the change in mechanical properties after aging treatment. In recent years, with the deepening of research, the research objectives have expanded to the relationship between indoor accelerated aging tests and outdoor aging tests. Currently, there is a point of view that certain correlation is between the two methods. The results of outdoor aging tests provide a basis for the standardization of indoor accelerated aging tests. The outdoor five-year aging test and ASTM D1037 artificial aging tests of wood-based panels were carried out by River (1994) in North America, and the ultimate bending strength of wood-based panels after aging was obtained. Finally, the results of two different aging tests were compared, and it was found that the ASTM D1037 artificial aging test had a great correlation with the outdoor exposure. Some scholars have also conducted outdoor exposure tests in the United Kingdom and found that it has a good correlation with the V313 aging test. In Japan, Kojima et al. (2011) studied the results of five years of outdoor exposure of different types of wood-based panels. The correlation between artificially accelerated aging and outdoor exposure was compared based on internal bond strength, thickness swelling and bending strength. According to the results, the correlation between outdoor exposure for five years and bending strength after ASTM D1037 aging is high, but there is not a very high correlation for internal bond strength. (Fig. 4a, b), Table 3).

4.2.2 Correlation between nonstandard aging tests and outdoor exposure tests

Artificially accelerated aging tests of wood-based panels were carried out by Korai et al. (2014) in Japan to study the effect of different humidity levels on the durability of wood-based panels. The elastic moduli and internal bonding strengths of the specimens in water at 40 °C, 70 °C and 100 °C were tested. The correlation between the artificially accelerated aging tests and the outdoor exposure tests was evaluated. To explore the effect of different humidity levels on the durability of wood-based panels, Korai et al. (2015) exposed specimens to 90% relative humidity (20 °C) for 5 years, 45% relative humidity and 90% relative humidity (20 °C) for 5 years, and to a real natural environment for 5 years. The results show that the MOR and IB decrease more significantly in outdoor exposed

Table 2 Comparison of different artificially accelerated aging tests

Aging test	Characteristic
ASTM D1037 (1996)	Multicycle manual accelerated aging test to study the durability of laminated wood members
BS EN1087-1 (1995)	Study on artificially accelerated aging treatment method with better durability of glulam
CAN/CSA-O188 (1978)	Mild artificial aging test
DIN 68763(V100) (1990)	Comparable to ASTM D1037 aging conditions
EN 321 (V313) (1993)	Suitable for testing (MUF) and (PF) wood-based panels with cyanamide-modified urea–formaldehyde glue and phenolic glue
ASTM D3434 (2000)	Multicycle and mild artificial aging test

wood-based panels than in the other two aging tests. This indicates that outdoor exposure is more harmful to these materials, and the hazard of periodic humidity cycling is higher than that of constant high humidity to the wood-based panels.

Comparisons between the outdoor exposure tests and the artificially accelerated aging tests were carried out in the above research. The results show that the correlation is good, and the degree of degradation of the outdoor exposure of the wood-based panels is equivalent to that produced by the accelerated aging in ASTM D1037.

4.3 Effect of different climatic conditions on the outdoor exposure tests

Outdoor exposure tests have many shortcomings, such as being quite long and difficult to carry out. In addition, these methods are also different due to the differences in the test grounds. For the service-life evaluation of wood-based products, it is necessary to quantify the differences in deterioration among different regions and climatic conditions.

4.3.1 Weathering intensity

As originally proposed by Scheffer (1979), a climate index (CI) (Eq. 2) is used to estimate the decay potential of a wood structure:

$$CI = \left(\sum \left(T_m - 2\right)(D - 3)\right) \Big/ 16.7 \tag{2}$$

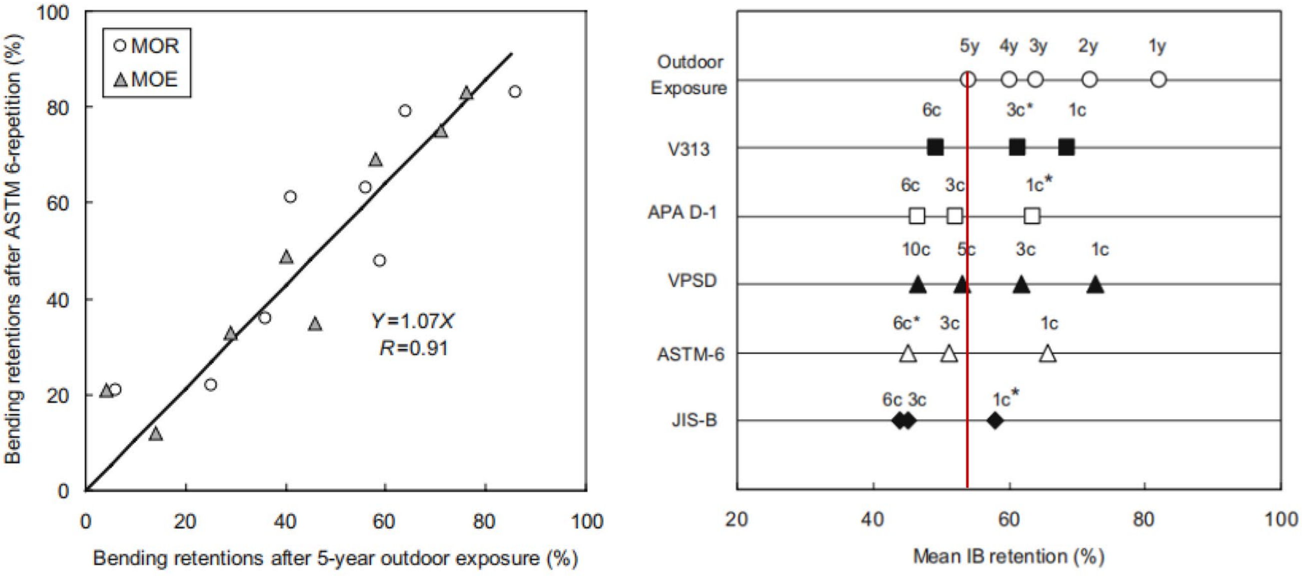
where T_m is the monthly mean temperature (°C), and D denotes the number of days in which the monthly precipitation is 0.25 mm or more.

Hasegawa (1996) proposed the degradation index (DI) and the aridity index (AI). DI is used to assess the degree of worm decay, and decay is defined by the following equation:

$$DI = \sum \left((H - 65) \big/ 10 \times 1.054^{T_m}\right) \tag{3}$$

where T_m is the monthly mean temperature (°C) and H denotes the monthly average relative humidity (%).

AI is defined by the following equation:



(a) (b)

Fig. 4 **a** Linear regression of bending retentions between the 5-year outdoor exposure test and six repetitions of the ASTM treatment. **b** Relation between accelerated aging treatments and outdoor exposure tests

Table 3 Correlation coefficients for bending properties between accelerated aging treatments and the outdoor exposure test in Shizuoka City

X-axis	Coefficient	Y-axis				
		JIS-B(6)	APA(6)	V313(3)	ASTM(6)	VPSD(10)
Five-year outdoor exposure	a	0.86	0.88	0.61	0.92	0.69
	b	10.40	11.40	30.20	8.70	25.30
	R	0.82	0.94	0.93	0.93	0.95

The numbers in parentheses indicate the number of repeated cycles

Determination of a and b by linear least squares regression $Y = aX + b$

R is the correlation coefficient

$$AI = P_y / \left(T_\alpha + 10\right) \tag{4}$$

where P_y is the annual precipitation and T_α indicates that the monthly average temperature is higher than 0 °C divided by 12 (°C).

Brischke and Rapp (2010) and Brischke and Meyer-Veltrup (2016) studied the temperature and wood moisture content suitable for the growth of different types of fungi. By establishing a function of the effect of changes in moisture content and temperature on decay, a model of wood decay caused by moisture was proposed (Eq. 5).

$$D(n) = \sum_{1}^{n} D_i = \sum_{1}^{n} \left(f\left(D_T\left(T_i\right), D_u\left(u_i\right)\right)\right) \tag{5}$$

where T_i is the average temperature and u_i is the average moisture content for day i.

Sekino et al. (2014) proposed the product of the monthly mean temperature and monthly mean precipitation as the weathering intensity (WI). By comparing the correlations among CI, DI, AI, WI and their logarithms and square roots, it is determined that WI is the most representative variable. Through the study of Kojima in Japan, it is also concluded that temperature, sunshine duration and precipitation are the main climatic factors that reduce the wood strength (bending strength and internal bonding strength) (Kojima et al. 2011). There are many disadvantages in the outdoor exposure tests, one of which is the test position limiting the results. Even if the outdoor exposure tests use the same test piece at all locations, the degree of weathering of the test piece is different between different locations. In view of the difference in the degree of weathering in different areas, Kojima et al. (2011) conducted a five-year outdoor exposure test, selected eight typical locations in Japan, and discussed the regional differences in the weathering of the wood-based panels. The deterioration rate of each wood-based panel was tested, and the test results were compared. Furthermore, the deterioration rate was calculated from the relationship between the strength retention rate and the outdoor exposure time, and the following deterioration rate equation was proposed:

$$y = -A \times \log(t) + B \tag{6}$$

where y is the intensity retention rate, t is the number of months of outdoor exposure, B is the intercept, and the A value is determined by linear regression analysis.

However, it is too complicated to perform outdoor exposure tests for each site, so the average temperature and daily precipitation of each area are selected as the weather parameters to calculate the weathering intensity to eliminate the regional differences. The weathering intensity α at each level is calculated by adding the daily weathering intensity over 1, 2, 3, 4 and 5 years and dividing the daily average temperature and daily precipitation. The weathering intensity level may be represented by the following equation:

$$\alpha = \sum (P \times T) \tag{7}$$

where P and T are the daily precipitation (mm) and the daily mean temperature (°C), respectively.

The results show that the correlation between the strength retention value and weathered intensity logarithm is high, and there is a certain degree of deterioration in the process of exposure. Subsequently, Kojima et al. (2012) improved the weathering strength equation, studied the degradation of wood-based panels exposed outdoors for more than 7 years in Japan, and compared the ultimate bending strength, modulus of rupture (MOR) retention rate and internal bond strength (IB) retention rate of the materials after 7 consecutive years of exposure. The calculation of the weathering intensity prior to the comparison, the temperature, the precipitation and the sunshine duration are introduced as the weather parameters, and the weathering intensity is calculated by combining 10-day and monthly weather parameter data. The correlation between the degradation of the wood- based panels and the weathering intensity is discussed. The improved weathering strength equation is:

$$\alpha = \sum (P \times T \times S) \tag{8}$$

where P, T, and S are daily precipitation (mm), daily mean temperature (°C), and sunshine duration (h), respectively.

As shown in Fig. 5a–c, the correlation coefficient between the IB and MOR retention rates and the weathering intensity using monthly or ten-day precipitation and temperature data is the highest (Kojima et al. 2012).

4.3.2 Climate deterioration index

Due to the complex correlation between these climatic factors, Korai and Watanabe (2015) used multiple regression analysis to study the main climatic factors affecting the strength (bending strength and internal bond strength) of particle boards based on weathered strength. They created a score based on temperature, precipitation and sunshine duration, which have the strongest effects on weathering intensity, by principal component analysis; this score is called the climate deterioration index (CDI). The results in Fig. 6a, b show that the correlation coefficient between the CDI and intensity is high. In recent years, due to climate change and human activities, the temperature worldwide has increased with the increase in greenhouse gas emissions, and Korai et al. (2017) uses three representative concentration paths (RCP) (RCP2.6, RCP4.5 and RCP8.5) to predict the national CDI under the influence of greenhouse gas emissions in

2031–2050 to predict the effect of climate change on the internal bonding strength of particleboards under different climatic conditions in Japan.

5 Suggestions for future research

In recent decades, a number of studies have been conducted by many researchers to investigate long-term humidity effects on the mechanical properties of wood and wood-based products. The reported experimental studies have helped acquire a good understanding of the degradation behavior of wood and wood-based products, provided a valuable guidance for future work. Based on the literature reviewed in this work, the following recommendations are proposed for future work.

1. More types of wood-based products are in need of outdoor exposure tests. It is found that current researches of outdoor exposure tests mostly focused on wood and wood-based panels and there were few experimental studies on glulam or CLT. At the same time, the type of finger joint, adhesive and other factors in manufacturing processes should be considered when evaluating and predicting the degradation in mechanical properties of wood-based products.
2. Degradation models of wood and wood-based products for different influencing factors such as humidity, temperature, ultraviolet radiation, worm damage, fungal decay, and their coupling effects should be emphasized in future works. Considering the environmental factors in different areas, the construction of outdoor exposure stations for tests of wood and wood-based products

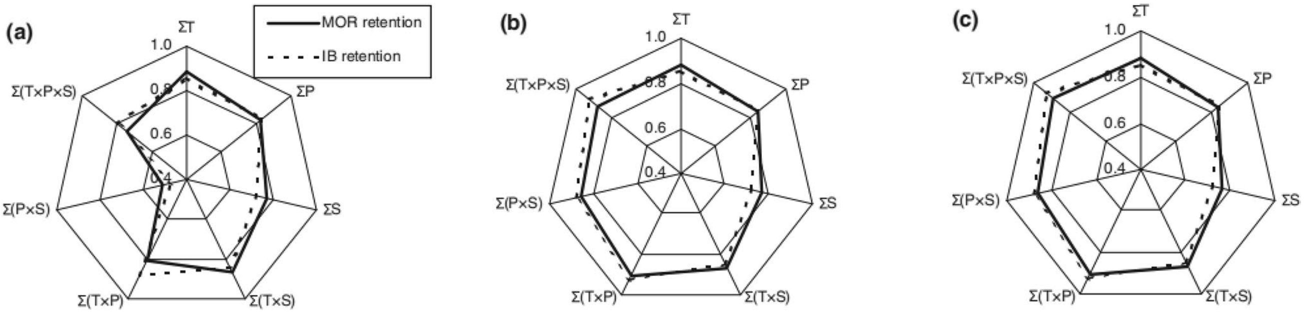


Fig. 5 Correlation between weathering intensity and mechanical properties calculated **a** daily, **b** per ten days and **c** on a monthly basis

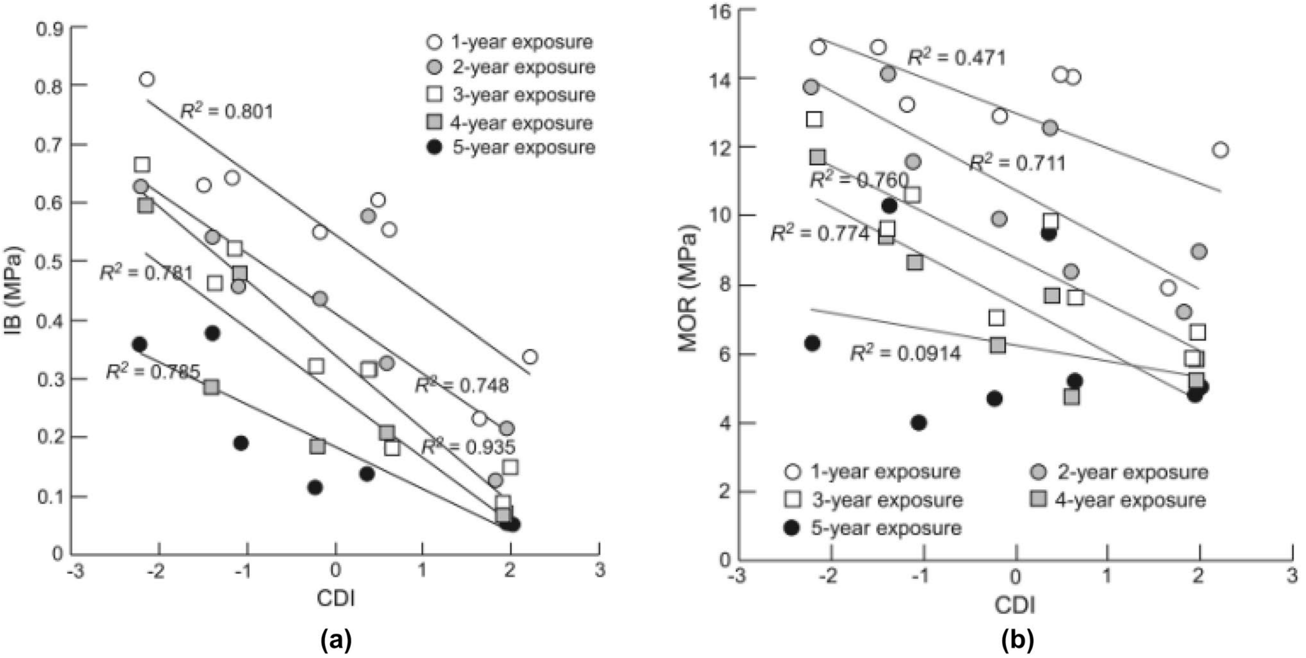


Fig. 6 Correlation between **a** internal bonding strength and CDI, and **b** modulus of rupture and CDI

should be strengthened, and more field service-life data should be accumulated. Thus, more reliable aging models for service-life prediction based on field data would be obtained.

3. Standard tests suitable for different regions need to be improved, and predictive models should be further developed in the future. Numerous experimental tests have been reported and are accessible for wood and wood- based products, however, those data are sometimes dispersed, such that uniform conclusions are difficult to determine. To assist the lifetime design of modern wood structures, predictive models for degradation behavior must be developed to correlate the accelerated aging tests in laboratory conditions to real-time aging in actual conditions.

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