

# Dimensional Stabilization of Wood

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**Abstract** This paper comprehensively reviews the relevant literature and presents the methods and processes used to investigate the dimensional stabilization of wood using various modification techniques, including (a) hydrophobization of wood surfaces to block the entrance and exit of water; (b) impregnation treatment with bulking agents, such as resin and wax, to maintain wood in a swollen state and diminish dimensional changes caused by moisture; (c) chemical treatment with different chemical agents to reduce the hygroscopicity of the wood; and (d) high temperature heat treatment, which modifies wood components, reducing accessible hydroxyl groups and decreasing the possibility of water absorption. The results of dimensionally stabilizing wood via different treatments are interpreted and compared, and the effects of treating conditions and parameters on the dimensional changes of wood are analyzed.

**Keywords** Dimensional stability · Chemical modification · Moisture content · Impregnation modification · Acetylation · Heat treatment

## Introduction

Wood is a natural and important engineering material because of its attractive physical and mechanical properties and low price [1, 2]. However, wood is susceptible to dimensional changes attributable to moisture, which considerably limits its use in some applications. A large effort was conducted to modify and improve the properties of wood with different techniques, including physical and chemical modification processes [3–7, 8•, 9, 10, 11•, 12–14]. The effects of wood modification processes on the chemical and mechanical properties of wood have been extensively summarized and reviewed [15, 16]. However, there are few systematic reviews that examine the dimensional stability of wood, which is crucial for both interior and exterior wood use. Thus, the objectives of this paper are to review the literature comprehensively, discuss the body of work and compare the processes that dimensionally stabilize wood. The main findings of this review are summarized below.

## Surface Hydrophobization

The hydroxyl groups, which are contained in the components of the wood cell wall, are responsible for the adsorption of moisture vapor from the surrounding air, thereby resulting in dimensional changes. Therefore, the dimensional stabilization of wood is always associated with the transformation of wood from hydrophilic to hydrophobic [17]. The hydrophobization of a wood surface occurs by blocking contact between the surface hydroxyl groups and surrounding moisture, which serves to prevent the absorption of water from the environment. The majority of wood surface hydrophobicity studies have involved the use of hydrophobic coatings and plasma treatment.

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## Coating Protection

Coatings can be used to stop water absorption into the wood by blocking the direct contact with water, thereby dimensionally stabilizing the wood. Good surface coatings sufficiently retard the rate of moisture absorption, which minimizes the steepness of moisture gradients in the wood. Superhydrophobic surfaces, with water contact angles larger than  $150^\circ$  and sliding angles less than  $10^\circ$ , have many attractive characteristics, such as water repellency, lubricity, self-cleaning, antifouling, and others [18]. A low surface energy coating on a surface with a high surface roughness can create a superhydrophobic surface. Extensive studies have been conducted to develop superhydrophobic surfaces on solid wood substrates [17–24]. Many methods have been developed to produce superhydrophobic surfaces on wood substrates, such as the sol-gel process [20], chemical methods [17, 23], and deposition methods [22].

Wang et al. developed zinc oxide nanorods on wood surfaces via a wet chemical method. The surfaces appeared to be superhydrophobic, and their water contact angle reached  $153.5^\circ$  [17]. Hsieh et al. reported that the fluoro-containing silica coatings on wood surfaces exhibited good superhydrophobicity and low moisture adsorption capacity with a maximum water contact angle of  $168.3^\circ$  [19]. A drop-coating method was used for silica particle coating on wood surfaces. The result was wood with superhydrophobic properties, a water contact angle reaching  $153^\circ$  and a sliding angle less than  $5^\circ$ . It was also reported that these coatings show resistance to pure water, corrosive water, and some organic solvents [18]. A superhydrophobic film on a wood surface, with a water contact angle of  $164^\circ$  and sliding angle of less than  $3^\circ$ , was achieved using the combination of silica nanoparticles, which have a high surface roughness, and a low surface free energy film of perfluoroalkyltriethoxysilanes (POTS). This was performed using a sol-gel process and a POTS reagent fluorination treatment [20]. A water contact angle of  $158^\circ$  and sliding angle of approximately  $4^\circ$  were observed using superhydrophobic, spherical-like  $\alpha$ -FeOOH films on wood surfaces. This method uses a hydrothermal reaction process followed by self-assembly of an octadecyltrichlorosilane (OTS) monolayer [21]. It was revealed that the polysiloxane networks on the wood surface, which were bonded to the wood by polycondensation via surface hydroxyl groups, increased the hydrophobic properties of the coated wood surface by decreasing the surface concentration of hydrogen-bonding sites and hindering the formation of hydrogen bonds between such sites and water molecules [22]. A similar polycondensation reaction took place using potassium methyl silicate to obtain superhydrophobic wood surfaces with  $153^\circ$  water contact angles via a solution-immersion method [25]. Uniformly distributed stearic acid modified microlamellar ZnO lamellar

particles can create a superhydrophobic coating on a wood surface, with a water contact angle of  $151^\circ$  and sliding angle of  $5^\circ$  [23]. It was reported that organic nanoparticle coatings improved the hydrophobicity of both high-density and low-density hardwoods to different degrees depending on their penetration and spreading on the wood surfaces of different surface roughness and porosity [26]. The use of coatings to protect wood from dimensional changes caused by moisture is limited by the ability of the hydrophobic coatings to coat the entire, microscopic capillary structure and form a fully protective layer, because of the porous structure of wood [26]. The porous nature of wood often allows the passage of some moisture. Thus, it is critical to obtain thick continuous hydrophobic surface films, which can effectively block absorption.

## Plasma Treatment

Water repellent characteristics and hydrophobicity can be achieved using a novel surface modification technology, known as plasma treatment. Plastic-like, or even diamond-like, carbon layers can be created on the outer layer wood surface via plasma treatment, using different organic gases or liquids as precursors [27–29]. This technique has a distinct advantage in that it is a dry process, which does not introduce moisture to the wood, unlike the wet coating modifications. Furthermore, plasma treatment is very intense and efficient. It uses electrical gas discharges and creates large numbers of ions.

Hexamethyldisiloxane (HMDSO) was introduced by plasma treatment to obtain hydrophobic wood surfaces [30–32]. HMDSO is polymerized with wood surfaces through plasma treatment, resulting in a cross-linked macromolecular structure involving Si-O-Si and Si-O-C linkages. It has a water contact angle value of  $130^\circ$  [30]. HMDSO can be mixed with different gases, such as He [33],  $N_2$  [29] and  $SF_6$  [34], and used as a precursor during plasma treatment, which improves the hydrophobic characteristics of wood surfaces. The results suggest varying degrees of successful water repellency, depending on the gas mixture, plasma exposure time, wood species, and distance between plasma source and wood substrate. Water repellent wood surfaces were generated using a  $N_2$ /HMDSO mixture plasma treatment, which exhibited better hydrophobic properties with longer water absorption time than those treated with a HMDSO liquid [29]. Different gases, including argon, methane, ethene, and silane/nitrogen, were applied by plasma treatment to develop water repellent characteristics on wood surfaces under atmospheric pressure conditions [27]. The silane/nitrogen plasma exhibited the largest contribution to the hydrophobic characteristics, with a water contact angle of  $145^\circ$  and no noticeable water absorption [27]. Gaseous fluorine and liquid fluorine plasma treatments were performed on pine surfaces, indicating that plasma treatment in the liquid phase resulted in better water repellency than in

the gaseous phase [28]. The fluoropolymer coatings were deposited via Ar/CF<sub>4</sub> plasma on black spruce, and their hydrophobic characteristics were found to be dependent on different plasma conditions. In addition, it was demonstrated that a minimum fluorocarbon layer thickness of 80 nm is required to create water repellency on wood surfaces [35].

Plasma treatment has been used to develop hydrophobic wood surfaces, which can consequently reduce or delay the water and moisture sorption of the wood. It seems that this treatment is a very promising approach for dimensionally stabilizing wood products in wet and humid conditions.

## Impregnation Treatment

The dimensions of wood can be stabilized either by blocking the wood cell lumen, which reduces water absorption, or swelling and bulking the fibers of the cell wall structure [8••]. The deposition of water-insoluble materials within the cell wall structure is an effective and practical approach for keeping the wood cell wall structure in a partially or completely swollen state. This can be achieved via impregnation treatment with various appropriate agents, such as resin and wax, by which the dimensional changes attributable to atmospheric moisture can be considerably minimized [36].

## Resin Impregnation

Impregnation with thermoset resins, such as urea-formaldehyde (UF), phenol-formaldehyde (PF) and melamine-formaldehyde (MF), is a practical method for depositing and forming water-insoluble resin within the wood cell wall structure. The process insolubilizes the initial, penetrated, unpolymerized, and water-soluble condensation resins using heat.

It was reported that significant dimensional stability improvements were made in wood impregnated with different formulations, which can be attributed to the introduction of melamine-urea formaldehyde (MUF) and migration of nanofillers into the wood cell wall [9]. The dimensional stability of Japanese cedar was improved up to 60 via 30 % resin loading of low molecular weight phenolic resins [37]. A comprehensive study of wood modified with PF, MF, and UF resins showed that dimensional stability was enhanced by 71, 68, and 49 % at weight percent gain (WPG) levels of approximately 33–35 for the three resins, respectively. Bulk coefficients ranged from 9–15 % and moisture excluding efficiency varied between 31–47 % [8••]. The dimensional stability of southern yellow pine was increased by impregnating the wood with MF and melamine-ammeline-formaldehyde (MAF) resins [38]. Anti-shrink efficiencies (ASE) of 71 and 68 %, maximum bulk coefficients of 15 and 13 %, and moisture excluding efficiencies of 45 and 41 % were achieved for

bombax ceiba at WPG levels of 32 and 33 for PF and MF, respectively [39]. A thermosetting resin treatment can also enhance the dimensional stability of bamboo (*Bambusa tulda* Roxb.) [40]. Spruce and poplar were treated with low molecular weight and low polymerizing degree melamine resin. They exhibited significantly enhanced dimensional stability and were protected against weathering [41].

It was revealed that the diffusion of resins into wood cell wall layers depends on the various properties of the resin and wood, such as the molecular weight and concentration of resins, wood moisture, and extractive content [42, 43]. Resin molecular weight is the most important factor in determining where the resins are deposited in the wood structures, such as on cell lumen and/or in the cell wall [44]. It was noted that the low and medium resin molecular weights of 290 to 480 can penetrate the cell walls, but those with higher molecular weights, approaching 820, mainly remain in the cell lumen [37]. High molecular weight resins deposited in cell lumens can block the path for moisture or water access to cell walls, thereby retarding the moisture or water sorption. Thus, it can inhibit short term dimensional changes in wood [9]. However, the bulking effect of low molecular weight resins, which migrate into cell wall substances, significantly contributes to the dimensional stabilization of the wood [9, 37, 44]. In addition to the physical bulking of cell walls, resins chemically react with both cellulose and lignin hydroxyl groups within the cell wall substances. These reactions can form a highly rigid, cross-linked network, which can also reduce the water absorption capacity and dimensionally stabilize the wood [8••, 38, 40–42]. Therefore, the dimensional stabilization of resin-impregnated wood is obtained from the combination of bulking effects and resin chemical reactions, which penetrate the cell wall [36].

Thermoset resins are also widely used to obtain resin-treated, compressed, or densified wood, which improve dimensional stability [6, 45–47]. They also show promise for additional uses [36, 48]. The modification process, namely viscoelastic thermal compression (VTC), includes the impregnation of wood with thermoset resins, followed by a pressing and curing step in high temperature molds. During this step, the wood cell wall is softened and plasticized by resin [49]. Then, the wood is compressed to a high density by deformation of the cell walls, but without fracturing the cellular structure [50]. In the meantime, the resin monomers polymerize themselves and form a rigid network between cell walls at high temperature, consequently maintaining the dimensions of compressed wood. Gabrielli and Kamke thermally compressed PF resin-impregnated poplar (*Populus* sp.) and found the dimensional stability to be significantly improved compared to untreated specimens [6]. The resin-impregnated Japanese birch (*Betula meximowicziana*), which was densified at 150 °C, had lower equilibrium moisture contents than the controls, which were not compressed and not impregnated with resin [47]. A study

of the combination of PF resin modification and the VTC process showed that greater dimensional stability can be achieved by higher molecular weight PF, though both low and high molecular weight resins can reduce irreversible swelling in wood [45]. It was noted that steam pretreatment can be used to remove matrix substances in wood, thereby making resin impregnation easier in highly compressed PF resin-impregnated wood, because of a lower pressing pressure [46].

### Wax Impregnation

Impregnating wax into solid wood is an effective method for improving wood quality and increasing its utilization. Because of their hydrophobic properties, waxes are widely used in the coating industry as water repellents for wood surfaces and paper materials [25, 51•, 52, 53]. Their use as wood-modifying agents also improves dimensional stability, weathering durability, white-rot and brown-rot fungi resistance, and mechanical properties [54–57]. Wax treatment physically fills the large cell lumens to slow the sorption rate of moisture. Wax can also be deposited within the wood cell wall structure to modify its properties [58•]. Wax has been used as a bulking agent to reduce swelling and shrinking, thereby improving dimensional stability [36]. However, during wax impregnation, there is no chemical reaction between wax molecules and wood substrates [6].

Attempts have been made to modify and improve the properties of wood using wax impregnation processes. In addition, some studies have examined the effects of wax modification processes on water repellency [52, 55, 58•, 59] and mechanical properties [25, 53, 60]. It was reported that treating wood with various paraffins reduces the moisture sorption and water uptake, improving the dimensional stability of Scots pine sapwood (*Pinus sylvestris* L.) and beech (*Fagus sylvatica* L.) [58•]. This study also noted that the viscosity and polarity of melted waxes, and the size of cell cavities, significantly affected the penetration depth. It was revealed that the penetration of different wax types is attributable to their molecule size and properties [60]. Paraffin wax [59] was used as a water repellent, which decreased the hygroscopicity level of beech. The equilibrium moisture content of wood impregnated with montan wax reduced by up to 25 %, while treatment with a mixture of montan wax and boric acid did not exhibit consistent results for different compositions [55]. Bleached soft wood pulp treated with various concentrations of paraffin and microcrystalline petroleum waxes resulted in an increase in water resistance [52]. It was found that the wax treatment decreased the water uptake of pre-treated timber via multiple techniques, such as acetylation, thermal modification, and dimethylol-dihydroxyethyleneurea modification [61••]. Natural wax-line extractions from the leaves and bark of Aleppo pine (*Pinus halepensis* Mill.) exhibited hydrophobic

properties in pine and beech, which can replace 50 % of the paraffin wax in water repellent formulations [62].

In addition to improving the dimensional stability of wood, wax treatment can improve the strength [52], hardness [25], MOR, MOE, and impact strength [53] of wood depending on the weight percentage gains, wood species, wax types, and wax properties. The mechanical property improvements caused by wax treatment include increased density, reduced moisture content, and flexible wax macromolecules, which mechanically reinforce the wood since there is no chemical reaction taking place [61••]. Therefore, wax treatment is a promising method for maintaining the mechanical properties of wood, which are reduced by other treatments.

However, wax treatment reduces adhesion of wood [63], and it does not improve subterranean termite resistance [64]. Moreover, it is easy for the wax to convert to a liquid when the temperature is above its melting temperature [51••], thereby limiting its utilization.

### Chemical Modification

Considerable effort has been devoted to the chemical modification of wood to improve the properties of wood materials [48, 65–68]. This section reviews the effects of chemical modification, typically by acetylation and furfurylation, on the dimensional properties of wood. The treatment conditions and the reasons for dimensionally stabilizing wood are analyzed and discussed.

#### Acetylation

Acetylation is a chemical modification method, which occurs between the hydroxyl groups of wood and the acetic anhydride molecule [69]. The ester linkages formed between the wood and acetic anhydride modifies the hydroxyl groups, which consequently prevents the interaction of water with the wood [70]. Acetylation was found to efficiently improve dimensional stability, and therefore, biological resistance against fungal decay [3, 5, 11••, 65, 69, 71–81].

The swelling and shrinkage in both radial and tangential directions, and the moisture absorption capacity of beech wood (*Fagus sylvatica*) treated with non-catalyzed acetic anhydride significantly decreased, indicating that acetylation dimensionally stabilizes wood [5]. *Pinus sylvestris* wood samples, treated in 50 % (v/v) acetic anhydride in xylene, exhibited an increase in the water repellency and dimensional stability as the acetylation duration increased [3]. The anti-shrink efficiency of wood acetylated by acetic anhydride/xylene and acetic anhydride/pyridine solutions was found to be a function of weight percent gain (WPG) [60]. The comparison of results described in previous papers demonstrated that acetylation of pine with up to 20 % WPG has a positive effect on the



dimensional stability, resulting in an anti-shrink efficiency of up to 70 % [11••, 15, 65, 67]. Higher modification levels, which used 22 % WPG, did not result in an additional increase in the anti-shrink efficiency [15], indicating that the bulking effect of acetylation reaches a maximum at approximately 20 % WPG. However, excess WPGs will result in over-swelling in cell wall, which may degrade the wood structure and form micro-cracks. Cell wall over-swelling was reported in rubberwood (*Hevea brasiliensis*), which was acetylated by hexanoic anhydride at a WPG of 25 % [77]. Improvements in dimensional stability are influenced by the chemical structure of the anhydrides used. At a comparable WPG, the levels of water sorption for pine treated with linear chain carboxylic acid anhydrides are the same, with substituent groups having different molecular sizes. This shows that improved dimensional stability correlates with the cell wall bulking, rather than with the degree of the OH substitution level [46, 47, 53]. Minato et al. concluded that dimensional stabilization via acetylation is mainly attributable to the bulking effect while decreased hygroscopicity, as indicated by the OH level, plays a minor role [36, 60]. However, a conflicting result was reported, suggesting that dimensional stabilities were not equal for rubber woods, which were modified with acetic and hexanoic anhydride below a WPG of 10 %. Therefore, further investigation is required to clarify the effects of different acetylation solutions on the dimensional stability of wood, thereby confirming these findings. Acetylation reduces the number of OH groups, which can sorb moisture via hydrogen bonding. Therefore, the equilibrium moisture content (EMC) is reduced [15]. Thus, the reduction of EMC indicates an increase in dimensional stabilization. The reductions in EMC are different for different species, which are acetylated at the same WPG level [46, 47, 53]. This may be explained by the differences in the content or structure of the components, namely lignin, cellulose, and hemicellulose in different species. In addition, the reaction sensitivity of acetylation to the OH groups in different wood polymer components varies [69]. The reactivity of lignin with acetic anhydride in the cell wall is higher than that of hemicelluloses, followed by cellulose [46]. However, Gardner reported that, according to the results obtained using carbon-13 nuclear magnetic resonance spectroscopy with cross polarization and magic angle spinning (C-13 NMR CP/MAS), lignin is not acetylated to great extent. The acetylation occurred mainly within the carbohydrate portion of yellow poplar (*Liriodendron tulipifera*) and red oak (*Quercus rubra*) wood [82].

In addition to the study on the effect of acetylation on dimensional stability, numerous investigations have been conducted on the influences of acetylation on the mechanical properties of wood [3, 46, 48, 60]. The literature results regarding the effects of acetylation on the mechanical properties of wood are dependent on wood species and treatment methods [48]. However, there is no common consensus.

Moreover, some studies have used various techniques to examine the chemical structure [83, 84] and physical microstructure [85] of acetylated wood. They showed that acetylation caused no microstructure damage [85]. Acetylation, via a vapor-phase treatment with acetic anhydride and pyridine, can avoid wood structure breakdown, reach the highest degree of dimensional stabilization and not embrittle wood [36]. Resistance against weathering and biological decay was also reported in acetylated wood [48].

### Furfurylation

The chemical modification of wood products with furfuryl alcohol is called furfurylation [86, 87]. The furfuryl alcohol, which has a sufficiently small molecular size, can impregnate wood cell walls and polymerize within the wood structure using a catalyst, heat or penetrating radiation [88]. Furfuryl alcohol originates from biomass waste [87] and is a renewable and natural material with no added metals or halogens [89]. It has been proven that furfurylated wood is an environmentally acceptable product [89, 90]. Therefore, furfurylation is an environmentally friendly alternative to wood treatment with heavy metals [91].

The polymerization between furfuryl alcohol molecules and wood polymers can cause wood to permanently swell [90], generally increasing the dimensional stability [48]. Epmeier and his co-workers reported that more than 50 % of anti-shrink efficiencies and low equilibrium moisture contents for three wood species were achieved by furfurylation. This was one of the most effective modification methods for improving dimensional stability, compared to other modifications in their study [67]. Two wood species (Japanese cedar and Scots pine), which were treated with furfuryl alcohol and/or borates, exhibited anti-swelling efficiency improvements of up to 85 % [88]. Comparable property change results were also observed in other woods that had been furfurylated. The dimensional stability of furfurylated wood increased more significantly, and with higher modification levels, with the higher retention of polymerized furfuryl alcohol [49, 87]. A 70 % furfuryl alcohol mixture was used to treat *Pinus pinaster*. The treated wood with a WPG of 38 % exhibited a greater than 40 % decrease in the equilibrium moisture content and an increase in dimensional stability (ASE by 45 %) [86]. However, it was reported that furfurylation substantially decreased the dimensional stability of moso bamboo [92]. This was attributed to the special cell wall structure of bamboo which resulted in the delamination of cell wall because of excessive penetration and the extraction of hemicellulose by furfuryl alcohols.

Similar to thermoset resins, furfuryl alcohol can be used to impregnate wood for fixing densified or compressed wood [64, 93, 94]. The polymerization of the furfuryl alcohol solution in the wood structure can reduce the spring back effect of

wood after undergoing a high temperature and pressure treatment, which significantly increases dimensional stability [64, 94]. Densified furfurylated wood products exhibited a higher dimensional stability and increases in other properties when compared to those modified with prepolymer. This was attributable to the small molecular size of furfuryl alcohol monomers, which more easily penetrate the wood cell walls [93].

There are other chemical modifications reported, such as hydroxymethylated resorcinol treatment which improved the dimensional stability of veneer by acting as a wood surface stabilizer [95].

## Heat Treatment

Using heat to treat wood has been studied for many years, and has been used commercially during the last decade [11•, 96–99]. This technology is eco-friendly and does not require the use of chemicals. The effects of heat treatment on the dimensional stability, moisture sorption, and other wood properties have been extensively reviewed [11•, 48, 100]. Heat treatment, at temperatures ranging from 160 to 220 °C in different shield gases, causes the hemicelluloses and lignin to degrade [96, 97]. Consequently, this process leads to an increased dimensional stability and decay resistance [96–99, 101]. The recent literature is reviewed with regard to the effects of heat treatment on the dimensional stability of wood. Recent results regarding the effects of different variables, such as wood species, types of media gas, maximum temperature, and duration at maximum temperature, on the equilibrium moisture, and anti-shrinking efficiency (index of dimensional stability) of wood are summarized in Table 1.

Various wood species exhibited different dimensional stability improvements after they had been heat treated [102, 105]. The increase in dimensional stability was higher for Uludag fir than for Hornbeam, though the maximum improvement for both species was experienced with a treatment at 210 °C for 12 h. It was revealed that the extent to which dimensional stability was enhanced by heat treatment was different for European birch, European aspen, Norway spruce, and Scots pine, which were treated in vegetable oils or steam atmosphere for 1 h at 200 °C [116]. Oak, lime (basswood), and birch exhibited different weight loss during the treatment process and variations in dimensional stability after high temperature treatment [117]. The dimensional stabilities of black locust, common alder, western prickly juniper, and plum were improved using heat treatment [118].

Carbonization and oxidation, which accompany the dimensional stabilization of wood during the heat treatment process, cause significant losses to strength properties [36]. This phenomenon can be minimized by heating the wood in the absence of air, such as in a vacuum, or using shield media. Nitrogen gas, steam, and vegetable oils are common shield

media, which are used to protect wood against oxidation during heat treatment (see Table 1). Furthermore, they also play a role in transferring heat to the wood substance. When nitrogen gas was used as shield media in heat treating systems, it did not affect the improvement of dimensional stability of heat-treated rubberwood compared to treatment in a vacuum or air [115]. At the same treatment temperature, wood treated in nitrogen gas exhibited a slightly lower EMC than wood treated in an air and vacuum. Wood samples treated at the same temperature in a vacuum, air and nitrogen exhibited comparable ASEs, but higher than those of untreated controls [115].

Heat treatments led to an increase in the dimensional stability of wood, which is dominated by the maximum heating temperature [106, 109–112, 119–123]. Gympie messmate wood, which was modified with a two-step steam-heat treatment at temperatures of 180–240 °C for 4 h, exhibited a significant increase in dimensional stability with increasing temperature [112]. A comparable increase in dimensional stability was also observed in the heat treatment of *Pinus nigra*, which was treated at varying temperatures (190, 200, 212, and 225 °C) and durations (60, 120, and 180 min) [110]. When *Populus ussuriensis* was treated at different temperatures in oil, the ASE increased as the temperature and soaking time increased (Fig. 1) [109, 119]. In addition, a 20.5 % improvement in dimensional stability was reported during the oil heat treatment of Aspen [107]. The dimensional stability of different wood species, such as Chinese fir, Douglas fir, jack pine, and rubberwood, increased when heat treated using steam with increasing temperature and treatment time [106, 120, 122–124].

The duration or soaking time, at the maximum temperature during the heat treatment process, also plays an important role in altering the dimensional stability of wood [108, 109]. Generally, wood swelling decreased with increasing treatment times [105, 109, 120, 122, 125].

The treatment parameters for North American species were optimized by the GRTB research group using a thermogravimetric system and based on the dimensional stability and other properties of wood after heat treatment [126]. Poncsak et al. also investigated and developed a method for shortening the process time, but not reducing the quality of heat-treated jack pine [123]. A model, which includes different heat treatment conditions related to dimensional stability, such as temperature, oxygen concentration, steam pressure, and time as functions of heat-treated wood properties, was developed to predict desirable properties [114].

It was shown that heat treatment results in a greater decrease in the tangential direction swelling rate than the radial direction swelling rate in Chinese fir [120]. This may be explained by the different wood structure in different directions, which impacts the swelling capacity of the wood cell wall. It was also reported that the effects of heat treatment on the dimensional stabilities of sapwood and heartwood were different for *Pinus pinaster* [113] and Chinese fir [108].

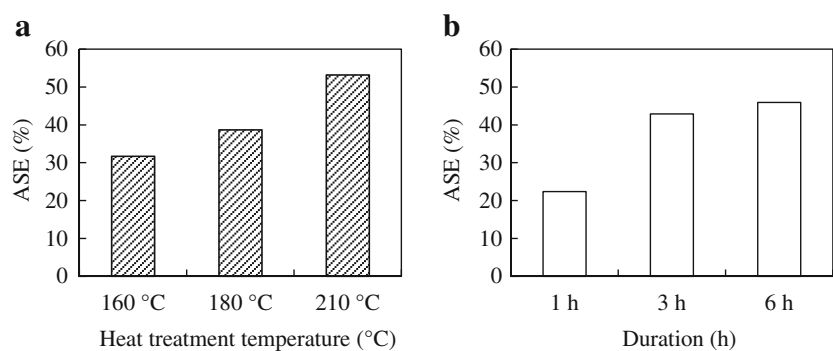
**Table 1** Effects of heat treatments on the dimensional stability of wood

Wood species	Media	Conditions		Changes in dimensional stability		Reference
		Temperature (°C)	Duration (h)	ASE (%)	EMC (%)	
<i>Pinus pinaster</i>	Steam	210	12	-57	-46	[102]
<i>Eucalyptus globulus</i>	Steam	210	12	-90	-61	[102]
<i>Pinus pinaster</i>	Steam	190	8	-	-50	[102]
<i>Pinus radiata</i>	Oil	180	3	-(29~31)	-	[103]
<i>Acacia hybrid</i>	N <sub>2</sub>	210~230	2~6	-(20~48)	-	[104]
<i>Abies bornmulleriana</i> Mattf.	Steam	210	12	-(44~57)	-	[105]
<i>Pseudotsuga menziesii</i>	Steam	220	4	-43	67.47	[106]
<i>Coriolus versicolor</i>	Oil	220	6	-21	42.8	[107]
Chinese Fir	Steam	230	5	-72	-	[108]
<i>Populus ussuriensis</i>	Oil	210	3	-56	-	[109]
<i>Pinus nigra</i>	Steam	225	3	-66	-	[110]
<i>Hevea brasiliensis</i>	Vacuum	210~240	1~8	-(20~38)	-	[111]
<i>Grevillea robusta</i>	Vacuum	210~240	1~8	-(12~42)	-	[111]
<i>Eucalyptus cloeziana</i> F. Muell	Steam	240	4	-68	-64	[112]
<i>Pinus pinaster</i>	Steam	200	6	-48	-	[113]
<i>Quercus mongolica</i>	Steam	220	2/4	-(35/43)	-(56/60)	[114]
<i>Hevea brasiliensis</i>	Air/vacuum/N <sub>2</sub>	240	-	>40	>50	[115]

Heat treatment can also be used to improve the dimensional stability of OSB boards, plywood [127], densified wood [121, 128], and other wood composites [129].

Several factors contribute to increasing the dimensional stability of wood by heat treatment, including (1) the loss of hygroscopic hemicellulose polymers during heat treatment [11, 100], which leads to a decrease of hydroxyl groups and consequent reduction of the hygroscopic nature [104, 111]; (2) the cross-linking or bridging of cellulose chains as a result of the splitting of two hydroxyl groups on adjacent cellulose chains under high temperature conditions [36]; and (3) the cross-linking of aromatic rings in lignin [130]. However, some studies disagree that cross-linking can contribute to improvements of the dimensional stability of wood, because of the shrinkage of heat-treated wood in organic solvents or basic solutions [131, 132].

**Fig. 1** Anti-swelling efficiency (ASE) of heat-treated wood at different treatment temperatures (a) and at different treatment times (b). Data adapted from [109]



## Conclusions

Different wood modifications have been extensively studied and applied for protecting wood against dimensional changes attributable to moisture. Each has advantages and disadvantages. Based on the literature review, it can be concluded that:

1. Both coatings and plasma treatment can be used to develop wood hydrophobic surfaces, which can consequently reduce or delay the water and moisture sorption of the wood, while also dimensionally stabilizing the wood. The limitation of using coatings to protect wood against moisture dimensional change is the inability to coat the entire pore structure of the wood. Plasma treatment is a very promising approach for dimensionally stabilizing wood products.

2. Wax treatment is an efficient method for improving the dimensional stability and mechanical properties of wood. However, wax reduces the adhesion of wood, and the low melting point of wax also limits its utilization.
3. Acetylation and furfurylation are efficient, environmentally friendly ways to improve dimensional stability.
4. Heat treatment can significantly improve the dimensional stability of wood. However, the strength properties of heat-treated wood are affected by the heat treatment. This requires further research to preserve or improve its mechanical properties while maintaining the advantages of the heat treatment for using this type of wood for structures. Nevertheless, this product can be used successfully on numerous applications such as wood sidings, furniture, floors, doors, windows, playground equipment, etc.

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#### Compliance with Ethics Guidelines

**Conflict of Interest** The authors of this paper declare that they have no conflicts of interest.

**Human and Animal Rights and Informed Consent** This article contains no studies with human or animal subjects performed by the author.

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