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Wood Sorption, Capillary Condensation and Their Implications for Building Envelopes of Wood Construction

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This paper reviews the existing knowledge and a number of controversial issues concerning the relationship between wood and moisture, around basic concepts such as adsorption/desorption, capillary condensation, and the fiber saturation point. It starts with characteristics of wood micro-structure, with a focus on the pores in cell walls, followed by sorption in wood cell walls, the potential for vapour condensation at high relative humidity (RH) conditions, the measurement of wood equilibrium moisture content (EMC) at different RH levels and the concept of fiber saturation point. The discussion is then focused on the potential impact of a number of wood structure and use-related factors on the measurement of EMC under near-saturated RH conditions, particularly about the use of the pressure plate method for predicting the moisture content of low-permeance softwood species. Recommendations were provided on further studies on EMC measurement and EMC testing methods. The intent of the paper is to improve the understanding of wood properties and behaviour in building applications, and emphasise the importance of moisture management in building envelopes.

INTRODUCTION

Like other physical and mechanical properties, sorption of water by wood is closely related to the structure of the cell walls. Softwoods (coniferous) and hardwoods (deciduous woods) have different anatomical features and also differ appreciably in chemical composition, but their water sorption behaviour is fundamentally similar. Softwoods, being simpler in structure than hardwoods, are used for discussion in this paper given their dominant use in modern wood construction. In terms of chemical composition, softwoods on average contain 42% of cellulose, 27% of hemicellose and 30% of lignin together with a small amount of extractives, with a specific gravity of the cell wall substance about 1.50-1.55 (Stamm 1964; Siau 1984). Wood is hygroscopic in nature due to the existence of hydroxyl (-OH) groups primarily in the hemicellulose and the amorphous cellulose. Approximately 50% of the cellulose is crystalline and inaccessible to water vapour or liquid water.

Wood is a porous material and it has a range of pore sizes. At the highest level of porosity, softwoods consist primarily of tubes, which can be considered to be rectangular in cross section, with length ranging from 2.5 to 7.0 mm, averaging about 3.5 mm. These are called tracheids and they make up 90-95% of the wood tissue. On average their length is about 100 times the diameter. The tracheids are tapered and sealed off at the ends, and overlap with each other in wood. Adjacent wood cells are connected by small openings, i.e. pits as a path for fluid movement. The pits in tracheids are called bordered pits, and the number, shape and closed or open status of these pathways essentially govern the permeability of softwoods. The internal diameter of the cell lumen varies greatly depending on the natural density of the wood species, being larger in earlywood (spring wood) and smaller in latewood (summer wood) for the same growth ring. Softwoods with a specific gravity of 0.4 have a lumen width of 26.1 um and a double cell wall thickness of 7.2 microns on average (Stamm 1964). A wood with a specific gravity of 0.4 has porosity about 73%, which is the proportion of the cell lumen volume in wood. The porosity of cell walls is discussed below.

In wood science, liquid water that exists in cell lumina and other capillaries is called capillary water (or free water), with properties similar to bulk water, and water existing in cell walls is called bound water (or hygroscopic water). Aside from differences in density and thermal properties (Stamm 1964), the differences between the bound water and the capillary water was also confirmed using NMR (Thygesen and Elder 2008).

POROSITY OF WOOD CELL WALLS

A variety of methods used to measure material porosity such as displacements techniques, gas adsorption isotherms, high-resolution electron microscopy, mercury intrusion porosimetry (not suitable for ultra structure of cell walls (Pfriem *et al.* 2009)), solute exclusion (only for wet specimens), thermoporosimetry and nuclear magnetic resonance (NMR) have been used to examine the pores of wood cell walls (Patrick and Arnold 1995; Hill and Papadopoulos 2001). Micropores, microvoids, nanopores and other terms have been used in the literature, but for simplicity and consistency "nanopores" is used in this paper for describing pores of wood cell walls. This is not based on the standard pore size classification system recommended by the International Union of Pure and Applied Chemistry (IUPAC) (Patrick and Arnold 1995).

Earlier studies in general suggested that dry wood cell walls were non-porous and nanopores were created as a result of cell wall swelling. The earlier mercury intrusion porosimetry indicated there was no appreciable amount of pores in cell walls of normally dried wood (Stayton and Hart 1965) and the specific gravity of dry cell walls was very close to the specific gravity of the cell wall substance (Stone *et al.* 1966). Based on the displacement techniques using water, toluene and helium, Wilfong (1966) suggested that the slight variations found in the cell wall substance gravity was a result of chemical composition variations and no extensive pores existed in the cell walls. Based on the displacement methods with silicon fluids, Weatherwax and Tarkow (1966) indicated that the cell walls had a very small volume of pores but they were accessible only during swelling.

Most studies confirm the existence of nanopores in wood cell walls. Sawabe *et al.* (1973) found the nanopores ranged from 2 to 30 nm in diameter, mostly in the range of 2.5-5 nm based on the nitrogen adsorption, and there was no essential difference in pore size distribution between wood species. Taniguchi *et al.* (1979) used both mercury porosimetry and nitrogen adsorption to study the nanopores of Japanese cypress. They found four ranges of pore size distributions with peak sizes at 9 μm, 1.3 μm, 40 nm and 4.5 nm in diameter, associated with tracheid lumina, pit openings, pit membranes and cell walls respectively, and the size of nanopores ranged from 3 to 8 nm. Based on both CO_2 and N_2 gas adsorption, Kojiro *et al.* (2008, 2010) suggested that the dimensions of nanopores in dry cell walls varied, but most of them were smaller than 0.6 nm.

The nanopore sizes change with decay and various wood treatments. Flournoy (1991; *et al.* 1991; *et al.* 1993) used the solute exclusion technique to study the pore sizes and volumes of sweetgum (*Liquidambar styraciflua* L.) before and after exposure to brown rot or white rot fungus. They reported that the sound wood had a nanopore volume of 0.35 ml/g, with 80% inaccessible to molecules larger than 1.2 nm in diameter, and there were no nanopores larger than 2 nm. Decay increased the nanopore volume and size: the maximum nanopore size was found to be 3.8 nm after the brown rot attack and 5 nm after the white rot attack. Thermal modification also changes the nanopore structure and size distribution (Pfriem *et al.* 2009). It was summarized that the majority of the nanopores had diameters of less than 2 nm (Hill and Papadopoulos 2001; Hill 2002). Relevant to this the diameter of a water molecule is 0.4 nm.

As part of wood structure, understanding nanopores is of great importance to understanding wood-water relationships including sorption and capillary condensation, wood decay, preservative treatment and various wood modifications. For example, nanopores are generally too small for enzymes associated with

decay fungi to enter, so decay fungi have to rely on low-molecular weight diffusible agents to initiate attack and increase pore sizes. Acetylation, a type of wood modifications, increases decay resistance mainly due to the cell wall bulking effect, which reduces water accessibility and eliminates the moisture source for fungal growth (Hill 2002; Papadopoulos and Hill 2003; Hill *et al.* 2009).

WATER SORPTION

Adsorption includes chemical adsorption and physical adsorption, depending on whether there is chemical bonding involved (Patrick and Arnold 1995). The adsorption of wood is a type of physical adsorption, mainly attributed to the formation of hydrogen bonding between the OH groups in cell walls and water molecules in the air. Its opposite process is desorption. A sorption isotherm is the curve when the equilibrium moisture content (EMC) is plotted against relative humidity (RH) at a constant temperature. The sigmoidal nature of the isotherms of wood has been described by a number of models such as the Brunauer-Emmett-Teller (BET) theory and the Hailwood-Horrobin Sorption theory (Siau 1984; Skaar 1988; Straube and Burnett 2005). The commonly used Hailwood-Horrobin model considers water sorbed by wood to exist in two forms: water of hydration corresponding to the water molecules that are directly hydrogen-bonded to the cell wall OH groups (monolayer), and the solid solution or dissolved water corresponding to water molecules that are less constrained but located within the cell walls (multilayer water). In recent years, the clustering theory was developed by envisioning water molecules clustering rather than layering to explain the different types of water in cell walls. Thus at low moisture content (MC) conditions water is randomly attracted to the OH sorption sites, the cluster size increases with the increase in MC, and the clusters may have an average size greater than 10 water molecules at the fiber saturation point (Hartley and Avramidis 1993). In addition, parallel exponential kinetics model was also developed to illustrate the sorption kinetics of wood (Hill *et al.* 2010a, b).

Wood sorption is characterized with sorption hysteresis. Once a tree is cut, the fresh wood starts losing moisture. The initial desorption isotherm is always above all the subsequent desorption isotherms for RHs ranging from 100% to about 65% due to the irreversible changes in wood during the first drying process; the subsequent adsorption and desorption can be considered as repeatable, with adsorption isotherms slightly below desorption curves in sorption diagrams (Stamm 1971). A typical ratio between adsorption EMC and desorption EMC is approximately 0.85 at a certain RH (FPL 2010). Laboratory EMC measurement may need to take this into account. The hygroscopic nature provides wood with the inherent moisture buffering capability and makes wood a good material for indoor humidity moderation (Yang *et al.* 2007; Wu *et al.* 2008).

CAPILLARY CONDENSATION

Different from adsorption, absorption is the mechanical take-up of a liquid by a porous solid within its gross capillary structure as a result of surface tension forces (Stamm 1964). It is associated with capillary water instead of sorption water. Capillary condensation is the change of vapour into liquid water as it enters small pores. Its occurrence depends on the capillary size and the relative vapour pressure, and the relationship between them is usually described with the Kelvin equation based on the molecular interactions at liquid/vapor interfaces. Table 1 lists capillary sizes that will fill with water under different relative vapour pressures based on the equation. Not many studies have verified this equation for nano-scale pores. The capillary condensation was observed in a wedge between fused silica surfaces using Fizeau interferometry at relative vapour pressures from 0.996 to 0.945 (corresponding to theoretical meniscus radii from 120 to 9 nm), but with considerable differences between the theoretical and the experimental data (Fisher *et al.* 1981). By studying capillary condensation between mica surfaces, it was reported (Kohonen and Christenson 2000) that the equilibrium meniscus curvatures of the condensates agreed with the Kelvin theory within a range from 5 nm to 50 nm, and the condensate had the same

refractive indices with bulk water. In both studies the high relative vapour pressures were created using salt solutions.

Based on the Kelvin equation capillary condensation would take place at nanopores in wood at 40% RH (assuming the typical cell wall pores are 2 nm in diameter) and at bordered pits of tracheids at about 95% RH (assuming the typical pores of the pit membranes are 40 nm). However, it was suggested (Stamm 1964; Skaar 1988) that the equation should not be used to predict capillary condensation when the RH was below 80%, i.e. when the corresponding pore diameters were less than 10 nm (25 times the size of a water molecule size), because the surface tension-related theories assume a large number of molecules. The derivation of the Kelvin equation is based on the ideal gas laws, but no discussions were found in the literature about whether the interactions between vapour under near-saturated conditions and wood, meet the assumptions of the related theories, particularly given the potential hydrogen-bonding between water molecules as well as between water and –OH groups of wood. The term "solid solution" used to describe multilayer moisture adsorption at high RHs in a number of sorption models also complicates this by assuming the occurrence of transient capillaries during cell wall swelling by solvents such as water. Stamm (1964) suggested that capillary condensation took place only in permanently existing capillaries, which took less than 2% of the dry cell wall volume. Regarding the sigmoid sorption isotherms of wood, the uppermost part is commonly attributed to capillary condensation, but the amount of capillary condensation, as discussed below, was suggested to be much lower than most people have anticipated (Thygesen *et al.* 2010; Engelund *et al.* 2010).

TABLE 1 RELATIONSHIP BETWEEN CAPILLARY SIZE CAUSING CAPILLARY CONDENSATION AND RELATIVE VAPOUR PRESSURE BASED ON THE KELVIN EQUATION AT AMBIENT TEMPERATURE (STAMM 1964; SKAAR 1988)

Relative vapour pressure	Capillary radius (nm)	Capillary diameter (nm)	Wood structure
0.40	1.2	2.4	Cell wall nanopore
0.60	2.1	4.2	Cell wall nanopore
0.80	4.8	9.6	
0.90	10	20	
0.95	20	40	Pit membrane
0.99	106	212	
0.995	210	420	
0.999	1060	2120	Pit opening
0.9999	10600	21200	Cell lumen

FIBER SATURATION POINT

The concept of the fiber saturation point was developed by Tiemann (1906; 1951) based on his observations of the effect of MC on wood strength. It defines the critical MC at which the cell walls are completely saturated with bound water but there is no capillary water in the cell lumina (Stamm 1964; Siau 1984; Skaar 1988; FPL 2010). The fiber saturation point averages about 30% (an oven-dry basis), varying by several percentages with wood species as well as differences in extractive and ash contents (Stamm 1964; FPL 2010). It also changes with wood treatment. For example, it increases with swelling agent treatments such as pulping (Bendzalova *et al.* 1996; Treimanis *et al.* 2009), decreases with drying (Stamm 1971), thermal modofication (Militz and Tjeerdsma 2001) and cell wall bulking effects such as acetylation (Papadopoulos and Hill 2003; Hill 2008; Thygesen and Elder 2009; Hill *et al.* 2009). For commonly used softwoods, a fiber saturation point of 28% is usually used for design-related calculations (CWC 2002).

Of practical importance, the gain or loss of bound water affects the physical and mechanical properties of wood, and the fiber saturation point is considered as the critical MC in the relationships between MC and physical or mechanical properties, such as shrinkage and swelling, thermal and electrical properties, and

strength (Stamm 1964; Stamm 1971; Rowell and Banks 1985; FPL 2010). These properties usually form the mechanisms for measuring the fiber saturation point by extrapolation (Stamm 1971; Skaar 1988; Hernandez and Pontin 2006; Almeida and Hernandez 2006). The fiber saturation point is defined to distinguish between the two types of water in wood and between adsorption and capillary condensation during moisture gain. However, under near-saturated RH conditions it is difficult to distinguish between the adsorption of cell walls and the capillary condensation at "large" nanopores, pit membranes and tips of cell lumen. Therefore it is commonly recognized that adsorption and capillary condensation overlap in an EMC-RH curve under high RH conditions (Straube and Burnett 2005). Consistent with this, it was found that loss of bound water and dimensional changes took place in the presence of capillary water, and the evaporation of capillary water may lag behind bound water desorption due to the lower water permeability of certain wood cells (Almeida and Hernandez 2006 a, b; Hernandez and Pontin 2006). Relative to cell wall moisture saturation, full water saturation with both bound water and capillary water is not defined in wood science.

MEASUREMENTS OF EMC AND FIBER SATURATION POINT

Wood exchanges moisture with the surrounding air and the amount of moisture gain or loss depends on the RH and temperature of the air, and the existing MC in the wood. Wood achieves EMC for certain environmental conditions when it no longer gains or loses moisture. Theoretically wood never reaches an EMC in service because the environmental conditions are always changing. However, because wood has a certain delay in responding to the fluctuations of environmental conditions due to the known sorption hysteresis effect, the MC of wood will normally stabilize and fluctuate over a small range, resulting in an approximate EMC in service. It was also confirmed that the variations in EMC caused by different climates were within an acceptable range for engineering design (Haglund 2007). EMCs in service are usually predicted based on typical wood sorption curves together with experimental and field validations (Simpson 1971; Simpson 1973; McIntyre 1987; Simpson 1998; FPL 2010). In the lab, EMC is traditionally evaluated under certain RH conditions maintained by the use of conditioning chambers, saturated salt solutions or pure water (Stamm 1964; Siau 1984; Nakano 2003; Neimsuwan *et al.* 2008; Saito *et al.* 2008; Zelinka and Glass 2010). When pure water is used to create 100% RH, the corresponding EMC is about 30% (Almeida and Hernandez 2006; Bassett 2006; Thygesen and Elder 2009; Zelinka and Glass 2010). However, it is difficult to precisely control and measure a high RH once it is above 95% (Straube and Burnett 2005). By modifying an existing conditioning chamber, NRC-IRC achieved RH control up to 95%. Other techniques have also been developed to improve the precision of RH control under near-saturated conditions, such as the Sartorius vacuum microbalance (Jakiela *et al.* 2008) and the dynamic vapour sorption apparatus (Zaihan *et al.* 2009 a; b), both by precisely controlling the vapour amount in the testing chambers. Like most scientific testing, errors during EMC evaluations will also be introduced by other factors such as drying methods and specimen sizes since most EMC measurements are based on mass changes (Stamm 1964; Kumaran *et al.* 2006).

In terms of measuring the fiber saturation point, methods based on the relationships between MC and physical or mechanical properties are the most common. In practice the fiber saturation point is often estimated from sorption curves by extrapolating the EMCs at high RHs to 100%, and consequently the fiber saturation point may be considered as the EMC when the RH hits 100% (Stamm 1971; Hill 2008). Such a method or definition is not scientifically precise due to its neglecting the capillary condensation near 100% RH. However, Stamm (1971) indicated the method was acceptable based on the comparisons between nine fiber saturation point evaluation methods. In terms of the precise location of the fiber saturation point in a MC-RH curve, Stamm suggested (1964) it should be the MC at the RH of 99.5%, based on his understanding that the largest nanopores were below 200 nm in radius, which corresponds to a RH of 99.5% based on the Kelvin equation.

The difficulty of precisely controlling high RHs prompted the development of the pressure plate method to measure material EMC under near-saturated RH conditions, based on the relationship between air pressure and relative vapour pressure described by the Kelvin equation (Stamm 1971; Skaar 1988; Kumaran *et al.* 2006). The method has been used to determine soil desorption curves as an indicator of moisture availability to transpiration or runoff under suction conditions. There were two ASTM standards specifically on the porous-plate apparatus, ASTM D2325-68 (2000) and ASTM D3152-72 (2000). Both were withdrawn in 2007 and replaced by ASTM D6836 – 02 (2008), which covers five methods to measure water characteristics of unsaturated soils, with suction ranging from 0 to 100 MPa.

The pressure plate/ membrane method has a history of use for pulp and wood. Robertson (1965) used it to measure the water retention isotherms of pulps, viscose rayon and cotton linters, and showed continuous MC-RH curves with the traditional sorption methods. Stone and Scallan (1967) used the pressure plate method to measure the fiber saturation point of black spruce, and suggested the fiber saturation point should be 40%, corresponding to a RH of 99.75% based on the plateau in the curve at high RH levels. Cloutier and Fortin (1991; 1993) determined the relationships between water potential and MC for aspen sapwood using the tension plate, pressure plate and pressure membrane methods for near-saturated RHs, as well as traditional sorption for lower RH levels. They found that the EMCs from the use of saturated salt solutions and the pressure membrane method were reasonably overlapped in the MC range from 0 to 200%. Based on the pressure methods, the EMC ranged from 34.6% at 96.431% RH to 82.7% at 99.927% RH (Table 2), in comparison with the EMC of 34.56% when pure water was used to create the 100% RH (Almeida and Hernandez 2006). Stamm (1971) pointed out the fiber saturation point measurements with wood specimens started from water saturation conditions such as the pressure plate method and the solute exclusion method, produced higher values than the commonly used extrapolation methods; the two types of methods measured different characteristics, with the former focused on water retention during wet wood drying and the latter focused on cell wall sorption. This was later emphasised by Hill (2008). Of relevance, Choong and Tesoro (1989) attempted to remove all capillary water using centrifuges and found that the water movement was controlled not only by the capillary pressure, but also the local wood structure. All these indicate that the pressure plate method may not remove all capillary water in wood when the equivalent RH drops below 100%.

Thygesen *et al.* (2010) used the pressure plate method, together with the traditional sorption methods, to establish desorption isotherms of untreated, acetylated and furfurylated spruce for RHs ranging from 91.9% to 99.9%. The three methods overlapped and there were no significant discontinuities in the measured EMC. However, based on the fact that the sorption curves of the untreated wood did not increase dramatically at high RH levels (up to 99.5%) and the EMC at the high end was only 40%, the authors suggested that capillary condensation did not play a significant role in the sorption curves before the RH hit 100%. Consistent with this, their calculations about the theoretical amount of capillary condensation showed that less than 0.35% of moisture was attributable to capillary condensation at the RH of 99.9%, based on the Kelvin equation and the Laplace equation. It is also of interest that the calculation indicated lower degrees of pit aspiration (pit closure) would lead to high amounts of capillary moisture in wood (Thygesen *et al.* 2010; Engelund *et al.* 2010).

In recent years, during the development of hygrothermal modelling to predict service conditions of building envelope elements, EMC of various building materials have been measured with both sorption and pressure plate method, governed by ASTM C 1498-04a (2004) and ASTM C1699-09 (2009), respectively. Both of the methods in the standards start with water-saturated specimens, using capillary saturation or even mechanical saturation. Table 2 compiles the EMC data of wood at high RH conditions in different sources. Apparently the data vary greatly with methods and wood species. For RH ranging from 99% to 99.9%, some EMC data appear to be as high as 200%, which is quite unrealistic from the perspective of wood structure and properties.

TABLE 2 COMPILATION OF EMC DATA UNDER NEAR-SATURATED OR SATURATED RH CONDITIONS

RH (%)	EMC (%)	Measurement methods	Specimen	Data source
≈ 100	Around 30	Sorption	Yellow birch (*Betula alleghaniensis*), dried, 20 mm (R) × 60 mm (T) × 500 mm (L) (Almeida and Hernandez 2006); Norway spruce (*Picea abies*) sapwood, dried and never-dried, 10 mm thick (Thygesen and Elder 2008; 2009); southern pine, dried, 62 mm × 9.5 mm × 3.5 mm (L) (Zelinka and Glass 2010)	Almeida and Hernandez 2006; Bassett 2006; Thygesen and Elder 2008; Thygesen and Elder 2009; Zelinka and Glass 2010
≈ 100	25	Sartorius vacuum microbalance	Lime wood, small pieces, 0.05 g	Jakiela *et al.* 2008
99.75	40	Pressure plate method	Black spruce (*Picea mariana*), air-dried, 100 um thick	Stone and Scallan (1967)
96.431	34.6	Pressure plate method	Yellow birch (*Betula alleghaniensis)*, dried, 20 mm (R) × 60 mm (T) × 500 mm (L)	Almeida and Hernandez 2006
99.492	41			
99.927	82.7			
99.9	40	Pressure plate method	Norway spruce (*Picea abies*) sapwood, cylinder specimens with a diameter of 14 mm and a thickness of 10 mm; and cuboids measuring 1 mm × 40 mm × 40 mm, cut from fresh wood	Thygesen *et al.* (2010)
95.96	148	Pressure plate method	Spruce, dried, 41mm × 41mm × 6 mm (L)	Kumaran (2002)
99.78	187			
95.3	96	Pressure plate method	Southern pine, dried, 41mm × 41 mm × 6 mm (L)	
96.17	135			
98.83	154			
88.6	17.2	Sorption	Spruce	WUFI 4.2 Pro (2009): Generic North American Database
99.78	187	Pressure plate methods		
100	211.2			
88.6	15.4	Sorption	Southern pine	
99.78	57	Pressure plate methods		
100	60			
99.99	19.03	Sorption?	Spruce	WUFI 4.2 Pro (2009): University of Technology Vienna-Austria Database
100	20.31			

FACTORS AFFECTING EMC MEASUREMENT

Wood is an anisotropic and inhomogeneous biopolymer material. A number of factors related to wood structure and use may have impact on EMC measurement and should therefore be taken into consideration during testing as well as test method development.

1. Concerns about Using Water Saturation as a Start Point for Measuring EMC

Regarding the use of water saturation as a start point in both of the ASTM EMC testing methods (ASTM C 1498-04a 2004; ASTM C1699-09 2009), the MC of wood after capillary saturation or mechanical saturation is highly variable and will affect the EMC results. For small specimens, particularly when the longitudinal dimension is less than the tracheid lengths (3.5 mm on average), the saturation MC depends

on the density, i.e. the maximum porosity of the wood. For large specimens, the saturation degree will mostly depend on the water permeability and the saturation method used. Real dimension wood products can rarely reach full saturation in service. The high variability of MC at capillary saturation or mechanical saturation may have contributed to the reported inconsistencies in EMC at high RH levels (Kumaran 2002; Kumaran *et al.* 2006; Wu *et al.* 2008). Moreover, since most wood used for construction has gone through drying processes such as air or kiln drying, the start point in these testing methods does not reflect the typical wetting scenarios in service. It is suggested that the sorption method should start with dry specimens and be consistent with other physical and mechanical property testing of small wood specimens (ASTM D 143-94 2000) , and the impacts of drying methods may need to be further assessed. The use of pressure plate method for measuring EMC under near-saturated RH conditions may want to start the progress after measures are taken to remove most free water from water saturated small specimens. It was reported (Choong *et al.* 1989) that most free water was removed from baldcypress of 15 mm thick with centrifugal forces at 19,400 rpm (305.8 psi) and the wood samples reached a MC around 33%. Therefore it can be assumed that free water can be removed more easily from the thinner samples used for the pressure plate method.

2. Impact of Pit Closure on EMC Evaluation

Wood is a highly porous material but is not highly permeable. While both liquid water and vapour can diffuse in wood, a slow process, the relatively fast movement of bulk water is controlled by the pits between wood cells (Comstock and Cote 1968; Comstock 1970). There are 50 to 300 pits per cell in the earlywood of tracheids and somewhat fewer in the latewood, mostly concentrated on the radial faces. In trees the pits in the sapwood are overall open to allow liquid to flow between cells through the pit membranes, which have an average pore diameter of 0.02-0.06 um. However, as a protection mechanism for the standing tree to conserve water, if water is removed from one side the pit closes completely. Furthermore, since the heartwood is dead, most pits in the heartwood are already closed or clogged, therefore the sapwood is typically about 200 times more permeable than the heartwood (Stamm 1964). Of critical importance to water permeability and therefore EMC testing, a high proportion of the open pits in the woods of the Pinaceae family (which provides most commercial softwoods such as pines, spruces and firs), particularly in the earlywood of the sapwood, become closed during drying processes (Siau 1984). The proportion was reported to be 99.5% for Chinese Yezo spruce sapwood (Bao *et al.* 2001). Consequently the capillary water flow in wood will be dramatically reduced (Siau 1984; Segerholm and Claesson 2008). So the permeability of softwoods varies greatly with cell structure, sapwood/heartwood ratio, early/latewood ratio and proportions of pit closure. Compared to the relatively permeable radiata pine and southern pine, most of the northern species such as Canadian SPF (spruce-pine-fir) are quite refractory to water penetration (and removal). Relevant to the EMC testing based on the two ASTM standards, low permeability means difficulty in achieving water saturation to start if large specimens are used, but small specimens can certainly be saturated. Lower permeability may also result in higher EMC values based on the pressure plate method because of the slower water movement and the longer time required for reaching equilibrium during testing. Moreover, the service performance may be the opposite since low-permeability species do not absorb water and wet up as quickly as highly permeable ones. Most importantly wood, unlike other materials, changes permeability by pit closure in response to a pressure differential.

3. Specimen Size and Grain Orientation

Specimen size and grain orientation are also critically important for water permeability (Siau 1984). As mentioned above, apparently the smaller the size is, the easier it is for the specimen to achieve high MC during capillary or mechanical saturation, and the faster to reach moisture equilibrium during the pressure plate testing. In terms of grain orientation, the permeability of softwoods in the longitudinal direction ranges from 15 to 80,000 times the permeability in the transverse direction (Siau 1984). The specimen thickness specified for the pressure plate testing is as thin as possible, usually about 5 mm (ASTM

C1699-09 2009). However, the dilemma of using small specimens is the maximum MC achieved during capillary or mechanical saturation rarely occurs in service, particularly for low-permeability species.

4. Time Issues related to Equilibrium and Water Absorption

The time scale is very important for EMC measurement and theoretically it takes infinite time for materials to achieve equilibrium even under constant environment conditions, particularly for complicated materials like wood. Stone and Scallan (1967) suggested using equilibrium times of one week for 100 um thick specimens during the pressure plate testing. Cloutier and Fortin (1991) also indicated very long times were required to reach the equilibriums for the pressure plate testing. Insufficient testing time may result in higher EMC values, particularly for low-permeability species. This is a practical challenge for the pressure plate method. On the other hand, time is also very important for wood to adsorb or absorb moisture in service. If hygrothermal modelling assumes that a material will reach the EMC once the RH hits a certain value, or even the maximum MC once the temperature falls below the dew point, it does not reflect the usually long time required for the material to gain or lose moisture.

5. MC of Fresh Wood and Water Logged Wood

In service wood can rarely obtain full water saturation, even for highly permeable species. For trees the combined MC of the sapwood and the heartwood ranges from 43% for Douglas-fir to 118% for balsam fir (Nielson *et al.* 1985), and it fluctuates with season, climate and growth locations. Even for trees which have been submerged in water for decades due to flooding, the wood usually still has sufficient empty space and the MC is still low enough for the logs to float, which forms the basis of underwater logging (Hatton and McGowan 1975; http://ecology.com/ecology-today/2008/09/09/underwater-timber-logging). Trees usually have higher permeability than the wood they yield. Treatment with water is often used to assess the permeability of wood before preservative treatment. Based on the long-term laboratory treatment experience by FPInnovations, most Canadian softwood species rarely reach 120% MC under several hours of vacuum and high-pressure treatment. All these facts indicate that an EMC of close to 200 % at a RH below 100% is not realistic for low-permeability species like spruce.

IMPACT OF MC ON WOOD BEHAVIOUR IN BUILDING ENVELOPES

Moisture-related properties are closely associated with wood behaviour in construction applications, such as wetting during liquid water exposure and the subsequent drying, mould and decay growth, and even dimension changes. The above discussions do not fully clarify the boundary between sorption and capillary condensation under near-saturated RH conditions. However, recent studies did suggest that the amount of capillary condensation in wood at RHs close to 100% was very low and the MC of spruce at RHs up to 99.5% was still below 40% based on the pressure plate testing (Thygesen *et al.* 2010; Engelund *et al.* 2010). The paper also identified a number of factors that may affect EMC testing. It is recommended that the EMC measurement, particularly by the use of the pressure plate method, should take into consideration the structure and characteristics of wood, particularly for woods with low permeability.

In terms of the use of wood in building envelopes, rain intrusion is generally recognized as the primary moisture source (Morrison Hershfield 1996; Glass and TenWolde 2007), although vapour condensation caused by defects in design and construction may also lead to moisture accumulation, particularly in crawlspaces and attics (Glass and TenWolde 2007). The long-term research on decay initiation and progression in wood-based sheathing products carried out by FPInnovations confirmed the minimum MC for decay to initiate is 26% (Wang *et al.* 2010a; Wang and Morris 2010), the low end of the fiber saturation point. This confirms that capillary water is required for decay fungi to grow in wood.

RECOMMENDATIONS FOR FUTURE WORK

Based on the above discussions, it is recommended to carry out the following work to better understand the moisture-related wood behaviour in building envelopes.

1. Assess the impact of different moisture start points on the subsequent EMC results under near-saturated RH conditions for both the sorption method and the pressure plate method, and explore the effectiveness of centrifuging forces in removing free water of water saturated samples;
2. Assess the impact of different wood liquid permeability caused by different species and other factors on the subsequent EMC results under near-saturated RH conditions for both the sorption method and the pressure plate method;
3. Assess the realistic time required for wood to achieve equilibrium during both the sorption method and the pressure plate method;
4. Reassess ASTM C 1498-04a (2004) and ASTM C1699-09 (2009) and revise if necessary.

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