
The Impact of Sorption History and Hysteresis on Moisture Pattern in a Wood-Framed Building Envelope

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ABSTRACT

Moisture present in envelope assemblies can accumulate within hygroscopic materials such as wood and cellulose insulation. The amount of moisture adsorbed by the material is dependent on the relative humidity of air to which it is exposed or to the availability of water. These relationships are available under the form of sorption curves. It is known that wood does not retain the same quantity of moisture content when exposed to the same relative humidity of the ambient air, whether wood is getting drier or wetter. This phenomenon, called hysteresis between the adsorption and desorption curves, is rarely considered during modeling or experimental studies of the building envelope. Because of hysteresis, the prior conditions of moisture exposure of wood have an impact on its performance under the next set of conditions. Therefore, the sorption history of wood should be taken into account in the assessment of the moisture performance of envelope assemblies.

This paper reviews the concepts mentioned above and then presents experimental data that exhibit the impact of different sorption histories on the moisture pattern of wood members in assemblies exposed to the same conditions. It is shown that the final moisture content depends on the sorption history.

INTRODUCTION

Moisture present in envelope assemblies can accumulate within hygroscopic materials such as wood and cellulose insulation. The amount of moisture adsorbed by the material is dependent on the relative humidity of air to which wood is exposed or to the availability of water. These relationships are available under the form of sorption curves. It is known that wood does not retain the same quantity of moisture content when exposed to the same relative humidity of the ambient air, whether wood is getting drier or wetter. This phenomenon, called hysteresis between the adsorption and desorption curves, is rarely considered during modeling or experimental studies of the building envelope. Because of hysteresis, the prior conditions of moisture exposure of wood have an impact on its performance under the next set of conditions. Therefore, the sorption history of wood should be taken into account in the assessment of the moisture performance of envelope assemblies.

MOISTURE STORAGE IN HYGROSCOPIC MATERIALS

Whereas many materials have little affinity for water and let water diffuse through their matrix, hygroscopic materials, such as wood, accumulate the diffusing moisture on their pore surface and, at higher moisture content, within their pore. Moisture moves from high concentration to lower concentration areas, and this driving potential can be represented by a gradient of moisture content, relative humidity, or energy level of water. The rate of storage depends on temperature, ratio of surface to volume, relative humidity, the diffusivity of the material, and the convective mass transfer coefficient at interfaces. The rate of moisture movement cannot be directly measured but can be examined by monitoring changes in moisture content. The moisture content at equilibrium for a given relative humidity and temperature can be measured. Sorption curves relate the equilibrium moisture content as a function of relative humidity and are developed with an exper-

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imental setup that employs steady-state conditions. In this manner, a given material is exposed to an environment at steady temperature and relative humidity. When the material mass is stable, it indicates that its moisture content is in equilibrium with the ambient conditions. The moisture content of the material is expressed as a percentage of its dry mass:

$$M = \frac{m_{moist} - m_o}{m_o} \times 100 \quad (1)$$

where

- M = moisture content (%)
- m_{moist} = mass of the moist material (kg)
- m_o = mass of the dry material (kg)

The procedure is then repeated for a higher relative humidity. The same method is used for a wet material exposed successively to dryer conditions. Sorption curves are thus developed for the full range of relative humidity for a given temperature.

The processes of desorption and adsorption of the same specimen, at the same temperature, yield different equilibrium curves. During desorption, a wet porous material retains more moisture than it can adsorb at any given relative humidity. This difference in moisture content at the same relative humidity between the adsorption and desorption curves is called hysteresis, as shown in Figure 1. There are two common explanations for hysteresis depending on the moisture content.

Green wood generally contains water in three forms—liquid water partially or completely filling the cell cavities, water vapor in the empty cell cavity spaces, and water in the cell wall. The bound water found in cell walls is attracted to wood with stronger forces than the free water held within the cell. When wood is dried, the free water is lost first, as it is held with weaker forces due to capillary action. The moisture content at which all free water of a cell has exited, but the cell walls are still saturated with water, is called the fiber-saturation point (FSP) (Tiemann 1906). It ranges from 20% to 40% of the dry weight. It follows that moisture movement above the FSP is due mainly to capillary action and is a function of the vapor pressure above the meniscus. During desorption, pores present bottlenecks full of liquid. The meniscus at the surface of the liquid is of smaller radius than the one present at the start of adsorption at the bottom of the cell. As the radius is smaller, the partial pressure of vapor above the meniscus is lower and less evaporation may take place. As the global vapor pressure is reduced further, the bottleneck will eventually be cleared and evaporation of the rest of the free water in the bottle-shaped pores will occur. At that point, the desorption and adsorption isotherms converge. This explanation applies for hysteresis in the capillary region.

In the hygroscopic region (i.e., below the FSP), a reduction of available sites for water explains hysteresis; this reduction has to do with the structure of a wood cell. The drying process below the FSP continues through water exiting the cell walls. This process occurs at the molecular level of the wood

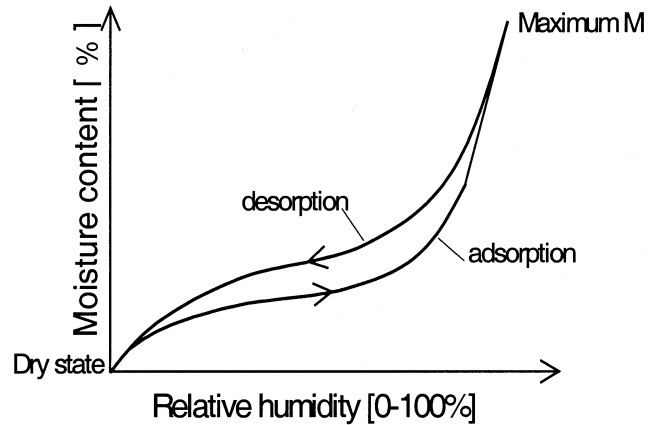


Figure 1 Schematic diagram of the sorption of a hygroscopic material showing the hysteresis between the adsorption and desorption curves.

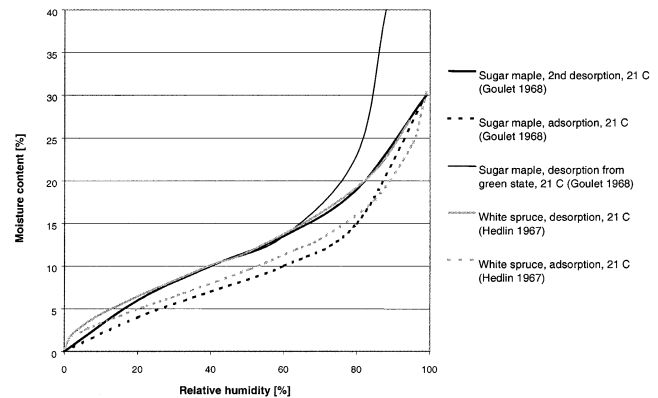


Figure 2 Sorption curves function of the relative humidity.

matrix. Spalt (1958) explained that during the cell formation, cellulose is formed in a glucose solution to precipitate on the cell walls. Cellulose is thus dispersed in water and there are few lateral cohesive bonds between cellulose fibers. During drying, the gel gets more compact and lateral bonds develop. The more the bonds, the less the mobility. Further removal of water produces distortion due to shrinkage, which also allows cellulose fibers that are approaching each other to bond. During drying, cellulose has, therefore, exchanged bonds with water to lateral bonds with cellulose fibers, which results in a reduction of available sites and explains the hysteresis below the FSP.

FULL SORPTION CURVES

Figure 2 shows typical sorption curves (wood moisture content vs. air relative humidity) of two well-known indigenous species—white spruce and sugar maple. These curves cover only the hygroscopic domain of wood (i.e., up to the FSP). As generally the case for species with low extractive content, the sorption curves are very similar. The magnitude of

the hysteresis is almost the same, and the FSP is around 30% M for typical ambient temperature.

INTERMEDIARY SORPTION CURVES

The relationship between moisture storage and moisture transfer is not completely understood since the moisture storage or release rates are not known for all sets of conditions. However, transient moisture transfer in the building envelope is more common than steady-state moisture transfer due to the diurnal cycling of temperature and relative humidity. With changing conditions, equilibrium is rarely reached.

In most cases, the drying process starts at conditions much lower than saturation and closer to the fiber saturation point. Examining the wood drying process from different starting points, Peralta (1995) observed that intermediary sorption curves fall between the full desorption and adsorption curves. This confirms the finding that the full curves should be considered as the boundary of the hysteresis (Urquhart 1960). Any point between the curves can be met depending on which conditions the material was subjected to. Therefore, temperature and relative humidity alone are not sufficient to determine moisture content. The sorption history is necessary. Starting on the adsorption isotherm, the intermediary curves of Figure 3 almost join the desorption isotherm with a differential of the relative humidity of approximately 40%. The 92% intermediary curve is the only one with the characteristic sigmoidal shape. The other ones have a simple convex form and, compared to the full desorption curve, demonstrate a smaller reduction of moisture content for the same decrease of relative humidity.

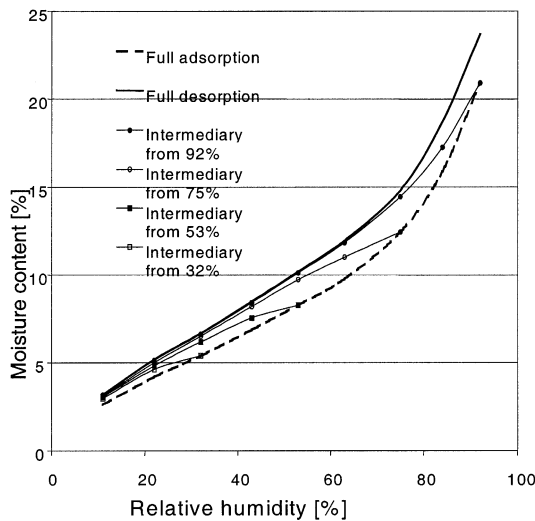


Figure 3 Full adsorption and full and intermediary desorption curves for yellow poplar according to Peralta (1995) as a function of relative humidity, at 21°C.

For any pair of desorption and adsorption curves, intermediate desorption curves can be determined from any starting moisture content on the full adsorption curve and extended to join the desorption curves following the pattern determined by Peralta. Such interpolated intermediate curves could be used to understand the variations in moisture content within envelope assemblies. One example of an analysis referring to intermediate desorption curves follows.

IMPACT OF SORPTION HISTORY

To illustrate the impact of sorption history, the moisture content variations of the wood plank and the joist of the same roof assembly, exposed to similar conditions across the assembly, are presented. The roof assembly, described in Derome and Fazio (2000), has been subjected to a full wetting/drying cycle of 190 days, and its configuration is presented in Figure 4. The 4 m long assembly was subjected to air exfiltration along its length for 91 days of winter conditions that led to a gradual wetting of the plank and the cellulose insulation. Then, spring and summer conditions induced drying. The last 56 days of the drying cycle are presented here. Figure 5 shows that relative humidity levels, measured in the middle and at the top of the assembly, are similar and almost constant throughout the duration of the period being analyzed. The presence of cellulose insulation in the whole assembly plays a role in unifying the conditions within the assembly. There is a small temperature gradient across the assembly, between 3° and 6°. Both the plank and the joist were made of spruce.

The conditions within the roof assembly induced some moisture movement in the wood members of the assembly (i.e., the gradual drying of the wood planks located below the roof membrane and the wetting/drying pattern for the wood joists located at the bottom of the assembly). The cross

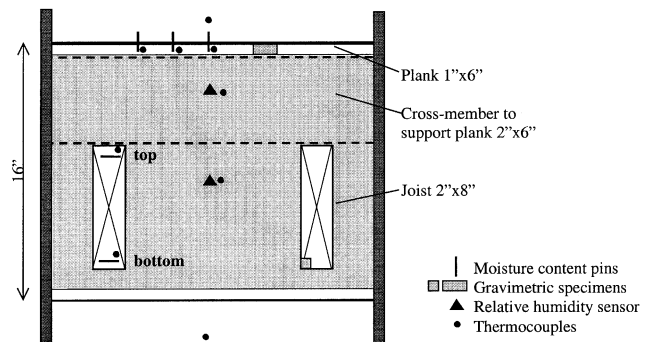


Figure 4 Cross section of the roof assembly composed (from top to bottom) of elastomeric roof membrane, wood planks, cellulose insulation, plaster on wood lath, and alkyde paint. The structure is composed of 2-by-8-in. joists and 2-by-6-in. cross members. The diagram shows the location of the sensors and the gravimetric wood samples.

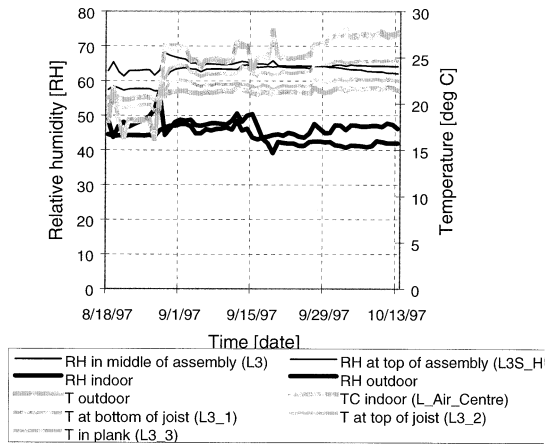


Figure 5 Temperature and relative humidity conditions measured across the roof assembly, as well as above and below the assembly.

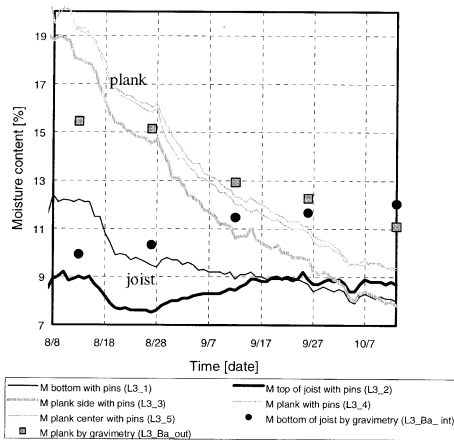


Figure 6 Moisture content vs. time for the plank and joist of the roof assembly measured continuously with moisture content resistive pins and bimonthly with gravimetric samples.

members between the wood planks and the joists were not monitored.

Figure 6 shows the variations in moisture content of the wood plank that, after being wetted through the winter conditions, is drying at a regular pace. The core of the plank dries from 19% M (moisture content) to below 9% M as measured with a pair of resistance-type moisture pins. Gravimetric measurements for the whole thickness of the wood plank indicate variations from 15% M to 11% M. The difference in the measurement indicates that equilibrium is not attained through the wood plank thickness. While it is understood that sorption curves convey equilibrium moisture content relationships with relative humidity, the continuous drying pattern of the wood plank can be approximated to follow the full desorption curve of the isotherm as shown schematically in Figure 7a.

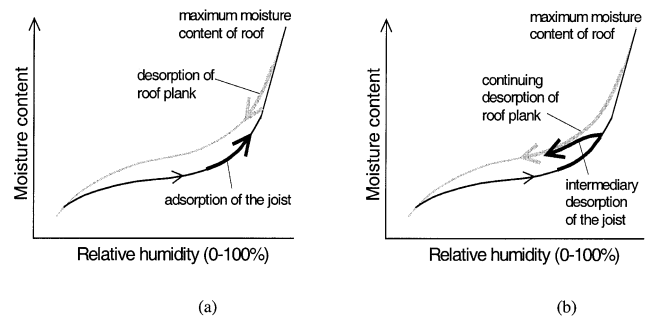


Figure 7 Schematic representation of the desorption and adsorption processes involved in the roof assembly. The gray arrow represents the desorption process of the roof plank while the black arrows show (a) the adsorption process of the joist, followed (b) by a reversal of the moisture movement according to an intermediary desorption curve.

The continuous release of the moisture from the wood plank and the cellulose insulation maintains relatively constant relative humidity conditions across the assembly, thereby inducing a gain in moisture content in the bottom joist. The joist had remained dry through the wetting part of the test. Notwithstanding equilibrium once again, the wetting pattern of the joist can be understood to follow the full adsorption curve, as shown also on Figure 7a.

Around mid-September, as drying of the assembly continues and less moisture is released, the conditions in the assembly allow the plank to continue drying and reverse the moisture transfer in the top of the joist. Figure 7b indicates the intermediary desorption curve of the wood joist when the moisture movement reverses. The first part of the intermediary desorption curve is not as steep as the full desorption curve. The same variation in relative humidity that would lead to a more important moisture content variation in the wood plank along the full desorption curve induces a much smaller variation in the moisture content of the joist along the intermediary desorption curve during the drying process. The resultant moisture contents of the wood plank and joist are not only dependent on the relative humidity to which they are exposed, but also on the previous conditions to which they were exposed, and finally on the direction of the moisture movement.

To illustrate further the sorption history shown on Figure 8, arrows have been superimposed on the data presented there. Figure 8 clearly highlights the continuous desorbing on the wood plank with the gray arrows. The black arrows are dented, marking the reversal or change of rate of the moisture transfer. While full and intermediate desorption curves do not cross over, as the full curve is an upper boundary, Figure 8 shows

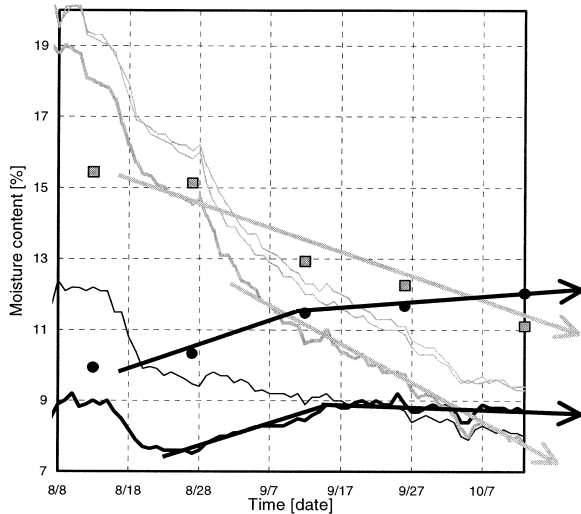


Figure 8 Data presented in Figure 6 with an overlay of arrows. The grey arrows show the decrease of moisture content in the plank. The black arrows show the change of moisture content in the joist where wetting is slowed in the gravimetric sample measurements and drying induced as measured by the moisture pins.

that the reversal of the direction of the moisture transfer takes some time to be effective through the specimen. Thus, the transient nature of moisture movement explains the crossover of the gray and black arrows (i.e., the fact that at the end of the test, the joist is more moist than the plank). One additional reason may be the increase of around 3°C of the outside temperature in the last 15 days of the test. Although other factors, such as different diffusivity and surface-to-volume ratios, may explain in part the difference in behavior between the joist and the plank, the example presented indicates that wood members within the same assembly, exposed to the same conditions, have different changes in moisture content depending on the sorption history. Furthermore, intermediary sorption curves, which result from hysteresis, may explain the different rate of change in moisture content following a reversal of moisture movement direction from wetting to drying.

CONCLUSION

This paper has reviewed the concept of moisture content, hysteresis, and full and intermediary sorption curves, which explained that similar conditions can lead to different moisture content in the wood depending on its sorption history. The paper has presented experimental data that show the impact of the sorption history on the moisture patterns of the wood members exposed to the same conditions within an assembly. The different sorption history of the plank and the joist led the wood members to have different rates of variation of moisture content and to reach different final moisture contents.

Although sorption curves are equilibrium relationships that cannot fully explain the transient aspect of moisture transfer, taking into account the sorption history can give more insight into the complex moisture behavior of wood-framed assemblies exposed to varying conditions, as it provides a basis for explaining the different moisture contents attained.

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