1-1-2013

Field Study of Hygrothermal Performance of Cross-Laminated Timber Wall Assemblies with Built-In Moisture

Victoria Ruth McClung
Ryerson University

FIELD STUDY OF HYGROTHERMAL PERFORMANCE OF CROSS-LAMINATED TIMBER WALL ASSEMBLIES WITH BUILT-IN MOISTURE

by

Victoria Ruth McClung

BASc. in Engineering Science, University of Toronto, 2010

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the program of

Building Science

Toronto, Ontario, Canada, 2013

Author's Declaration for Electronic Submission of a Thesis

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my thesis may be made electronically available to the public.

FIELD STUDY OF HYGROTHERMAL PERFORMANCE OF CROSS-LAMINATED TIMBER WALL ASSEMBLIES WITH BUILT-IN MOISTURE

by

Victoria Ruth McClung

Master of Applied Science in Building Science, 2013

Ryerson University, Toronto

Abstract

Cross-laminated timber (CLT) panels have potential market in North America for building mid-rise structures due to their good structural and seismic performance, light weight, and prefabricated nature. However, to ensure long-term durability, the hygrothermal performance of CLT wall assemblies needs to be evaluated in terms of drying and wetting potential before their widespread adoption in North America. A test wall was constructed with initially wetted CLT panels, and monitored over a year. The drying behaviour of the panels was analysed, and results were compared to hygrothermal simulations. It was found from the field data that no tested wall assemblies in the given climate prevented the panels from drying in enough time to prevent decay initiation. The hygrothermal simulation program is capable of predicting general trends, and can predict if a wall be safe, but tends to be overly conservative. Further refinement of the model for wood is needed.

Acknowledgements

It is a pleasure to thank those who have made this thesis possible.

Professor Hua Ge at Ryerson University, Professor John Straube at the University of Waterloo, and Jieying Wang at FPInnovations have provided invaluable guidance in the completion of this work, and helped deepen my general understanding of building science.

I am very grateful for Sam Siassi, Robert Lepage, and Emily Vance who joined me for an exciting week of practical construction experience, and applied their elbow grease to the realization of the test wall. Rob also lent a hand collecting data, saving me a few day long trips back and forth to the test hut, and was generous sharing data from his laboratory experiments.

And finally my parents have lovingly supported me in all endeavours in life, and without them, this work would not be possible.

Contents

List of Tables

List of Figures

List of Appendices

Chapter 1 - Introduction

Cross-laminated timber (CLT) panels have potential market in North America for building mid-rise structures due to their good structural and seismic performance, light weight, and prefabricated nature. Many of these benefits are outlined in the CLT Handbook (Gagnon and Pirvu, 2011). However, prolonged exposure to moisture before and during construction as well as in service can be a durability concern for most wood products including CLT. Specifically, CLT panels stored on unprotected construction sites can be exposed to rain and sitting water, leading to built-in moisture after erection. If this built-in moisture cannot dry out within a reasonable time period, potential damage as a result of excessive moisture may occur. To ensure long-term durability and improve the design of CLT assemblies, the hygrothermal performance of CLT wall assemblies with a variety of configurations and materials needs to be evaluated in terms of drying and wetting potential before their widespread adoption in North America.

This project is a part of the multi-disciplinary NSERC strategic research Network for Engineered Wood-based Building Systems (NEWBuildS). The network of research focuses on a variety of aspects surrounding the use of massive timber systems, primarily cross-laminated timber panels and glu-lam beams and columns. Topics include material characterization, structural, fire, acoustic, and vibration performance, integration into hybrid structural systems, and product durability. This project, a part for Theme 4 focusing on durability, was developed after simulations performed at FPInnovations indicated a very low drying potential for CLT wall assemblies with low permeance membranes and insulating materials to the exterior or interior of the panels (Wang and Baldracchi 2009; RDH Engineering Group 2009). Although CLT has already been in use in Europe with no reported moisture durability issues so far, differing climates, construction practices, and wood species in North America introduce uncertainty as to the effect of potential elevated moisture content of the panels at the time of construction and in service on long-term moisture durability. Furthermore, in addition to known limitations to hygrothermal modelling of wood building envelope assemblies, no hygrothermal model has been validated for large cross-section wood outside of a laboratory environment, relying instead on standard testing performed on samples typically 25mm thick.

1.1 Objectives

The objective of the project is to evaluate the drying potential of a variety of wall assemblies including wetted CLT panels manufactured with North American wood species groups, in a Southern Ontario climate, and to provide data to help validate a hygrothermal simulation model. As a result, recommendations may be made regarding the criticality of protecting the panels from moisture sources and the suitability of different wall assemblies to ensure the long-term durability of CLT wall assemblies. The data collected will improve understanding of the effect of adjacent materials in the assemblies and wood species used for CLT manufacturing on drying behaviour, as well as help calibrate CLT material properties to allow for future hygrothermal modelling. By testing multiple samples of different species, the variability between wood species and samples of the same species may be studied to help improve material selection for CLT manufacturing.

1.2 Approach

In order to capture the drying of CLT panels in situ, a field study has been performed, incorporating four different wall assemblies and five different types of CLT panels. The field study was performed in conjunction with laboratory testing of panels from the same sources, by Lepage (2012), which empirically determined the water adsorption and redistribution coefficients to be used in hygrothermal modelling, as well as other modifications to be made to the material properties.

The field study was designed to monitor wall assemblies including insulating materials and water resistive membranes of varying orders of magnitude of vapour permeance, with panels initially wetted to a level which allowed a possibility of decay initiation in the future. The moisture content in the centre of the panels, and in the exterior and interior faces of the panels was monitored and analysed to determine differences in the amount of time required for the panels to dry to a safe level to prevent decay initiation, and differences between the wall assemblies, and the panel sources.

The data collected was then compared to the model developed by Lepage (2012), to test it validity. Additional modifications to the model were made based on laboratory testing results, which improved the agreement of the model with the field measurements.

1.3 Scope

The scale of the field testing is limited by time, space, data collection capacity. The test wall is composed of small scale panels, of the original manufactured depth, but approximately 600mm x 600mm, compared to the typical panel size of at least 1200mm x 2400mm. However, the reduced scale is not expected to cause changes in drying rate due to edge effects as the moisture content pins are placed in a central area around 150mm x 50mm large, and the edges were sealed before wall construction. The moisture pins in the interior faces were centred on the lumber element in which they were placed, however at the exterior, as the pins were inserted through the water resistive membranes, it cannot be certain where in the plank they were placed, which may introduce anomalies caused by edge effects at the boundaries between planks, as well as checks and knots in the wood.

The field test facility is located in Waterloo, Ontario, and experiences a southern Ontario. Differing climates may cause panels to dry at different rates, highlighting the need for a reliable hygrothermal model to extrapolate the results across North America.

The panels were initially wetted to extreme levels to allow the possibility of decay initiation, and more field research may need to be done to determine the highest moisture contents which may be found during construction in different climates and for different CLT products.

The moisture content data has been compared to simulation results provided by WUFI, a widely used one-dimensional hygrothermal simulation program developed at the Fraunhofer Institute for Building Physics. In the future other simulation programs should be validated.

This thesis presents a review of moisture transport in wood and current work related to modelling the hygrothermal behaviour of wood. The methodology used in this field study is detailed, and the drying behaviour of the CLT samples during the first year of testing is presented. Finally, a comparison of the field measurements to hygrothermal simulation results is made.

Chapter 2 - Literature Review

2.1 Cross-laminated timber

Cross laminated timber is an engineered wood product in use in Europe since the 1980s. It has been recently introduced to Canada and the USA as a structural panel element suitable for use in mid-rise buildings, in place of more traditional concrete, cinder block, or steel systems. Demand for CLT in North America has grown after changes to building codes in a number of jurisdictions have allowed or will allow wood structures up to six stories tall instead of four.

It is expected that the majority of CLT production will occur in western Canada, using lumber from mountain pine beetle infested forests, which is mechanically sound but often discoloured with blue stain fungus, rendering it undesirable aesthetically for many uses (Gagnon and Pirvu, 2011). Commercial production of CLT has also begun in Quebec.

Cross laminated timber, shown in Figure 2.1, is composed of at least three and typically up to seven layers of lumber boards, joined with adhesives or mechanical fasteners such that adjacent layers are aligned perpendicular to each other. This configuration increases dimensional stability and gives the panels similar strength capacities in all directions. The layers are typically composed of dimensional lumber, but other sizes or types of engineered wood product can be used if desired, and alternating layers often include different timber element sizes, though are usually symmetrical around the centre layer (Gagnon and Pirvu, 2011).

Figure 2.1 3-ply Cross-laminated Timber (Karacabeyli, 2011)

The typical panels are usually assembled with adhesives, the most common being polyurethane. The layers may be face glued only, between layers, or face and edge glued, between layers and between boards within a layer. Individual boards may be finger jointed together at the end grain to increase board length. After assembly, the panels are pressed together, both horizontally and vertically, then planed or sanded if required (Gagnon and Pirvu, 2011).

The panels may be pre-cut for each project at the production plant, and may be preassembled with insulation and other building assembly elements, allowing for accelerated construction schedule after delivery onsite.

2.2 Studies into CLT behaviour

While there have been several studies of CLT or other wood behaviour using hygrothermal simulations, few experiments including verification with field measurements have been performed. The majority of these studies utilise existing computer simulation programs, such as WUFI, which has a foundation in Fick's Law, modelling vapour and liquid transport based on a vapour pressure difference or moisture content gradient and a coefficient describing the material's permeability. However, there are indications which suggest the Fickian model becomes less accurate above the fibre saturation point of wood, around 28% moisture content (MC) (Håkansson, 1998).

Haglund (2007) developed a model to determine the effect of yearly relative humidity variations of a Swedish climate on the moisture content of wood beams. The Fickian model predicted a similar range of moisture contents as laboratory measurements of the beams, and differences were explained due to the lack of hysteresis in the model as the moisture contents were well below the fibre saturation point, never reaching higher than 18%. Goto (2011) has performed climate chamber tests of high permeance CLT wall assemblies with continuous, exterior insulation, and found the measured results for relative humidity and temperature at monitor positions within the wall assembly to be in accordance with WUFI simulations, though the moisture content within the panels themselves were not tested, and panels were not wetted. Successful work has also been done to verify the temperature and relative humidity predicted by WUFI 2D around a stud in a timber framed wall with measurements taken in a laboratory setting (Kalamees, 2003). Finally, it has been shown by Hameury (2004) that massive timber walls, where wood is directly exposed to the indoor environment can have an appreciable buffering effect, reducing the moisture load of a building. Once again a Fickian model was used, and only applied in a low moisture content range.

A principal resource used in the analysis of the field experiment is the results of laboratory testing performed on the same lot of panels used in the test wall at the University of Waterloo by Lepage (2012). This work provided material properties relating to moisture uptake of the panels used in this experiment, allowing for more accurate models to be constructed and compared to the field measurements. The studies outlined have not served to examine the actual drying behaviour of CLT panels in situ. The following description of moisture flow in wood and studies into the modelling of moisture flow in wood will support the need for the use of more data collected in situ to use in the development of a more accurate model.

2.3 Moisture Transport in Softwood

2.3.1 Structure of wood: macroscopic scale

On a macroscopic scale, the structure of wood within a tree can be divided in two ways, sapwood vs. heartwood, and early wood vs. late wood in each growth ring, seen in Figure 2.2 (FPL, 2010).

As a tree grows each year, a growth ring is developed around the perimeter of the tree, including one layer of early wood and one layer of late wood. The early wood develops in the beginning of the growing season, and has cells with thin walls and a high degree of connectivity, allowing for faster transportation of water and nutrients during the growth of the tree. Later in the year, late wood is added, which has fewer interconnecting pits and is denser, contributing more to the strength of the wood. The darker colour of the latewood marks the boundaries of the yearly growth rings.

While rings of early and late wood are repeated many times across a cross section of the truck, the trunk may also be divided into a central column of darker heartwood, and an outer layer of sapwood. The sapwood is the location where conduction and storage of water and nutrients takes place during tree growth. As a tree grows, the sapwood towards the centre of the tree is slowly converted to heartwood by the deposition of extractives, which can have many purposes but typically increase the resistance of the heartwood to mold and rot, darken the wood, and partially block the pits connecting cells.

The trunk of a tree is the basis of the three principal axes used when discussing wood, longitudinal, radial and tangential. The longitudinal direction is along the tree trunk, the radial direction is from the pith at the centre of the trunk to the bark, and the tangential direction is tangential to the growth rings.

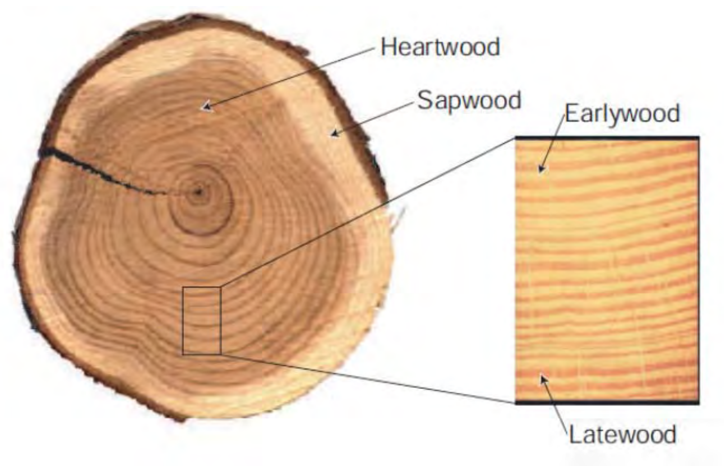


Figure 2.2 Cross section of a tree trunk (Krabbenhoft, 2003)

2.3.2 *Structure of wood: microscopic scale*

Softwood is composed of a series of long, longitudinally oriented, tapered cells, connected through pits located primarily to allow tangential flow (Krabbenhoft, 2003). The longitudinal cells are interspersed with ray cells, which are oriented to facilitate transport in the radial direction. A pit in one cell is usually paired with a pit in the adjacent cell wall, directly connecting their lumens, the cavities inside the cells. The cellular arrangement can be seen in Figure 2.3.

In green wood, ray cells allow for faster moisture transport in the radial direction, despite the higher number of pits in the tangential direction. Also, the higher number of pits, and thinner cell walls leading to higher porosity in the early wood provide less resistance to moisture flow than the more dense configuration of late wood cells with fewer pits. However, when wood is dried, many of the pits in the early wood cells become aspirated, meaning they irreversibly deform to a point block moisture transport. Pits in the late wood aspirate to a lesser degree due to the stronger structures within the cell wall. The difference in the number of aspirated pits is large enough that when in a dry state, as is used in all manufactured wood products, the late wood is actually more permeable than the early wood. The difference is also more pronounced in sapwood, as the extractives deposited in the pits of the heartwood cells already reduces their permeability.

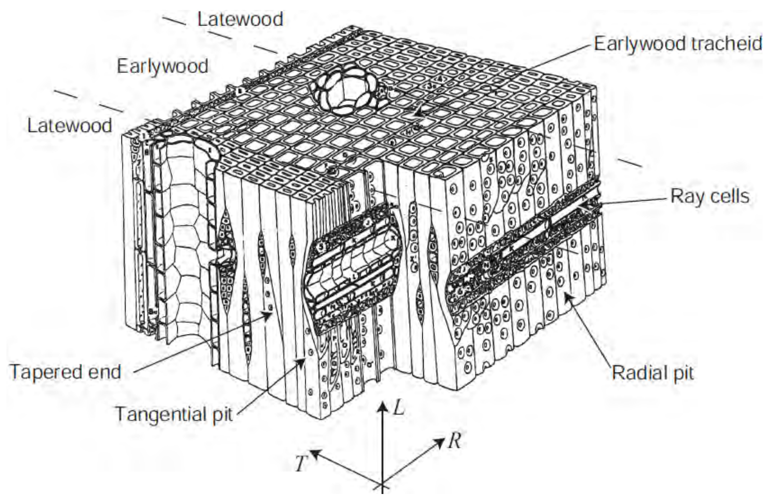


Figure 2.3 Cellular structure of softwood (Siau, 1984)

2.3.3 *Structure of wood: molecular scale*

Wood's cellular structure is composed of three polymers, cellulose, hemicellulose, and lignin (Krabbenhoft, 2003). With variation among different species, wood is composed of 40 to 50% cellulose, with the remainder divided approximately equally between hemicellulose and lignin. These polymers are joined into microfibrils and their surrounding substance, and arranged in varying layers to create cell walls and the middle lamella which binds cells together.

2.3.4 *Conditions for Wood Decay*

Decay in wood is caused by certain types of fungi which can feed on the cellulose, hemicellulose, and lignin in the wood cells, breaking them down, eliminating their structural capacity. In order for decay to initiate, the appropriate fungi spores or mycelium must be present, and the fungi must have access to sufficient moisture, nutrients, oxygen, and be in a reasonably warm environment and with favourable competitions over other microorganisms (Wang, 2010). A significant period of time can also be required for fungi to propagate to a level which can influence the strength of the wood infected, depending on the conditions. Typically, wood exposed to temperatures below 10°C, and at a moisture content in equilibrium at a relative humidity below 80% is considered safe from moisture durability issues such as mold and decay.

A review of the conditions required for decay initiation and progression by Wang (2010) has shown that a constant elevated moisture content over a long period of time is required to initiate decay. It was found that at a marginal moisture content of 26%, 6 to 12 months are required for decay initiation for typical kiln dried wood products. However, if the wood products were held in conditions ideal for decay to initiate and progress, such as a moisture contents of 40 to 80%, the wood products could lose significant strength in as little as 3 months. MC of 20% is a safe maximum moisture content level to specify, which provides a considerable safety margin for anomalous wood samples which may be extremely hydroscopic, or have poor decay resistance. Measurements taken from lumber at an active construction site of a wood-frame building during the winter rainy season in Vancouver showed that the average wood moisture content remained around 20%, before the structure was covered with roof and space heating provided (Wang, 2012). There were large variations in MC when the lumber was exposed to outside conditions. This seems to indicate that taking reasonable precautions to protect lumber and other solid wood products from wetting, less than 20% moisture content at the time of building enclosure is achievable. However, it is known that composite materials such as plywood and OSB can absorb moisture more quickly than solid wood, although they may be able to dry faster as well.

2.3.5 Moisture transport mechanisms in softwood

There are three different types of moisture in wood, free water, bound water, and water vapour. Bound water is chemically bonded to fibres in the cell walls (Krabbenhoft, 2003). Free water is liquid water existing in the lumens, present when the cell walls are saturated with bound water. Water vapour is present both in the air and in the lumens when they are not full of free water, and in small quantities in the cell walls.

The flow of free water in wood is governed by Darcy's law, which describes flow of a fluid through a porous medium.

The flow of bound water is governed by diffusion through the cell wall.

The flow of water vapour is divided into two mechanisms, the flow of air carrying water vapour through pits and lumens, and adsorption of water vapour onto the cell wall, diffusion through the wall, and desorption from the wall. In small capillaries, water vapour may also condense. These mechanisms are described with a combination of Darcy's law, and Fick's law, which uses a diffusion coefficient to relate flux to a concentration gradient.

Although the material properties of wood, especially the diffusivities of bound water and water vapour vary at a microscopic scale in different parts of the wood cell and between early wood, late wood, sapwood and heart wood, when modelling moisture movement in wood, numerical models are typically designed which utilise bulk material properties, and are based on moisture movement in general hygroscopic porous materials. They do not account for any anomalies caused by the cellular structure of wood compared to compounds where the material composing the pore structure is homogenous and impermeable. As a naturally anisotropic and inhomogeneous material, in reality wood shows large variations in property or behaviour between different wood species, within the same species, and between different grain orientations. For example, species such as SPF (a species group of spruces, pines, and firs) and Douglas fir have very low permeability to liquid and vapour compared with species such as southern pine.

2.4 WUFI simulation parameters

WUFI (Kunzel, 1995) is a hygrothermal simulation program widely employed due to its range of customisable material properties, level of verification for many typical wall assemblies and materials, and ease of use. The basic parameters required to define a material are its bulk density, porosity, heat capacity, heat conductivity, and the diffusion resistance factor a multiplier to be applied to the permeability of stagnant air to obtain the permeability of the material. The moisture storage function and liquid transport coefficients for suction and redistribution must also be defined, describing the predominant moisture transport mechanisms.

The moisture storage function describes the moisture content of a material obtained when the surface of the pore system has accumulated enough water molecules to be in equilibrium with the relative humidity of the ambient air. This includes adsorption of water vapour at lower relative humidities, capillary condensation at relative humidities close to 100%, and capillary or mechanical saturation of the pore system with free water at 100% relative humidity. The moisture storage function (MSF) is obtained by measuring sorption isotherms up to 95% RH, and through pressure plate measurements at higher relative humidities in the presence of free water. For wood, the MSF combines the moisture content derived from bound water, free water, and water vapour, and an average MSF is used, as wood typically has different adsorption and desorption curves. WUFI assumes instantaneous acquisition of equilibrium moisture content to local relative humidity with pores. In reality the equilibrium process usually takes a long time.

In Figure 2.4, a typical moisture storage function for a porous hygroscopic material is shown. In region A, water vapour molecules are adsorbed onto the pore structure's walls in a single layer. In region B, the several layers of water molecule are present on the pore walls, and region C, as the layers on opposite walls meet, capillary suction begins. In region D, the capillaries are the dominant water storage mechanism, and in region E, the capillaries are saturated, and free water exists in the pores. The arrows indicate the different curves used for wetting and drying, accounting for hysteresis.

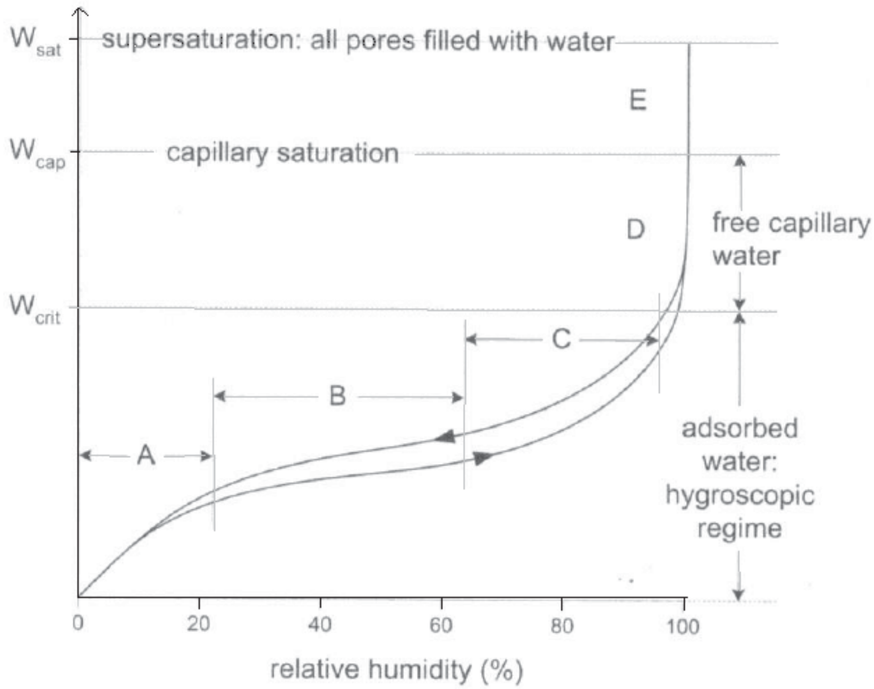


Figure 2.4 Typical Moisture Storage Function (Straube, 2005)

The rate of capillary liquid transport is governed in WUFI by two liquid transport coefficients, one for suction and one for redistribution. Based on Fickian diffusion, the liquid transport flux is expressed in terms of a moisture content gradient, and a diffusion coefficient which may be constant, or vary based on moisture content.

The liquid transport coefficient for suction describes the capillary uptake when the surface of the material is in direct contact with liquid water, for example exposed to rain. This initial suction phase is governed by larger capillaries with low flow resistance. The values for the coefficient for suction at a given moisture content is often estimated based on the free water saturation moisture content of the material, and it's a-value, or water absorption coefficient. For this project, the a-value of the CLT panels used was measured in laboratory testing by Lepage (2012).

The liquid transport coefficient for redistribution describes the further migration of water through the material. This moisture movement is driven by the higher tension forces in smaller capillaries, drawing the liquid out of the larger capillaries. While it is acceptable for some materials to estimate this coefficient as the same as the coefficient for suction up to the equilibrium moisture content at 80% relative humidity, and one tenth of the value of the coefficient for suction at higher moisture contents, this relationship does not hold true for wood. One reason for the discrepancy is the presence of the adsorption-diffusion-desorption mechanism transporting bound water and water vapour across the cell walls which is not accounted for in the typical Fickian model of porous materials (Håkansson, 1998). Changes in the permeability of the pore system may also occur due to changes in the structure of the pits in the cell walls having experienced differing states of hydration, a factor contributing to hysteresis. For this project, the profile for the liquid transport coefficient for redistribution at a given moisture content was based on the profile derived by Lepage (2012) during laboratory testing on the same CLT panels.

2.5 Hygrothermal Modelling Limitations

WUFI has been verified for a large range of building materials including many engineered wood products such as plywood and OSB. However, there are some known limitations to modelling the hygrothermal behaviour of wood at high relative humidities (Peuhkuri, 2003). As WUFI is currently limited to a single moisture storage function, does not account for hysteresis, and does not allow for input to modify the time scale required for a wood sample to attain moisture equilibrium, it is expected that the results of simulations at all moisture contents may not correlate well to measured data.

By only accounting for the different transport mechanisms affecting liquid water and water vapour in the pore structure instead of modelling bound and free water separately, errors may be introduced when the relationships between them shift. Specifically, WUFI does not address the movement of moisture by adsorption, diffusion and desorption through the cell walls, as the structure of typical porous materials is considered inactive in moisture transport (Kunzel, 1995). Several of the known discrepancies have been studied. Wang (2012) suggests that rather than a single moisture storage function, separate curves be used to define bound water sorption, capillary condensation of water vapour, and free water. A model of this type is also supported by Wadsö (1994), who described the requirements for a hygrothermal model to include the non-Fickian sorption behaviour of wood, especially at high relative humidities. Wadsö emphasises the presence of seperate models for the flow of vapour and water through the pore structure, and for sorption into the cell walls. He also specifies that the models must allow for different behaviour due to rapid and slow changes in vapour pressure and moisture content, accounting for the multiple time-scales at which different methods of sorption and transportation occur, and the effect of unsteady-state relative humidity, as is typical in walls in-situ. These factors would change the equilibrium moisture content compared to the steady relative humidity used in the cup methods and in pressure plate tests typically used to define the moisture storage function.

Håkansson (1998) has also described a retarded sorption effect at high relative humidities, which when not modelled with a dynamic sorption curve leads to simulations over estimating the penetration of moisture through wood. Håkansson monitored the adsorption, desorption, and periodic sorption behaviour of small wood samples under a variety of conditions, including at different relative humidity levels, and step sizes of changes in relative humidity. An observation was made that moisture transport appeared to be blocked, or delayed, when a series of smaller relative humidity changes was used compared to larger changes. He then developed a non-Fickian model which described moisture conductance not just as a function of moisture content and vapour pressure gradients of the sample, as a traditional Fickian transport would be, but also as a function the vapour pressure gradient raised to the power of an empirical value denoting how strong the non-linearly of the particular sample is.

As the weakness in the WUFI model for wood is most evident at moisture contents well above 20%, which is outside the range a typical, well performing wall assembly is expected to experience, efforts to refine the model become a scientific exercise in improving the knowledge of the hygrothermal behaviour of wood in extreme conditions.

2.6 Conclusion of Review

Based on the literature reviewed, it is clear that there are known limitations to hygrothermal modelling of wood at high moisture contents. There has also been little work done to evaluate the field performance of cross-laminated timber, as previous work has principally depended on laboratory measurements, which may have masked some of the inaccuracies in modelling programs. Therefore, a field experiment designed to evaluate the performance of wetted panels in a variety of wall assemblies will provide a valuable source of data which may help in beginning to address this knowledge gap. Locating the experiment in a climate representative of many of the populated regions in Canada will allow the results of testing to be applied when developing new guidelines for building envelope design containing cross-laminated timber.

The following work was designed to determine whether wetted CLT panels were capable of drying in a reasonable time period in a variety of wall assemblies in a southern Ontario climate, and whether a WUFI model is capable of predicting similar behaviour to the field data.

Chapter 3 - Experimental Setup and Procedure

3.1 Description of Wall Assemblies

To evaluate the hygrothermal performance of CLT wall assemblies, a test wall measuring 2.6 m × 2.6 m was constructed in a field exposure building envelope test facility in Waterloo, Ontario. The test wall comprises sixteen 0.6 m × 0.6 m CLT panels, each composed of one of five types of wood species, in combination with two types of water resistant barrier, and two types of insulation, chosen to provide three different magnitudes of vapour permeance, or drying potential.

The wall assemblies were designed based on the "perfect wall" principles (Lstiburek, 2007), including the structural CLT panels on the interior, followed by the rain water, air, and vapour control layer acting as a drainage plane behind the protective outer thermal control layer. The drainage planes behind the insulation were created using self-adhesive water resistant membranes. A non-vapour permeable (NVP) water resistant membrane was used for the low exterior permeance wall configuration, and a vapour permeable (VP) membrane was chosen for the medium and high permeance wall assemblies. These membranes were chosen since their ability to be fully adhered to wood would reduce potential air leakage adjacent to the wetted CLT panels and focus the experiment on the impact of vapour permeance of the assemblies. Rigid board type insulation was used since it encouraged the use of continuous insulation, and its structural properties allowed the strapping to be screwed through the insulation board, into the CLT panels, and support the cement fibre board siding while creating a 19 mm deep rain-screen cavity. Mineral wool insulation board was used as the vapour permeable insulation, and expanded polystyrene (EPS) insulation board was chosen for the rigid semi-vapour permeable insulation. The two types of insulating boards were both 76 mm thick, with the mineral wool providing a thermal resistance of 2.22 m^2K/W, and the EPS providing RSI 2.1 m^2K/W. All assemblies were built with an interior air space and gypsum drywall. The airspace was provided, both to allow services in the wall, and because a wood frame was used to support the small scale CLT panels in the test wall. The depth of the air cavity varied to allow for different thickness of CLT panel, while maintaining a constant plane for the installation of gypsum board at the interior wall surface. Manufacturer provided material data sheets are available in Appendix A. The typical wall section is shown in Figure 3.1.

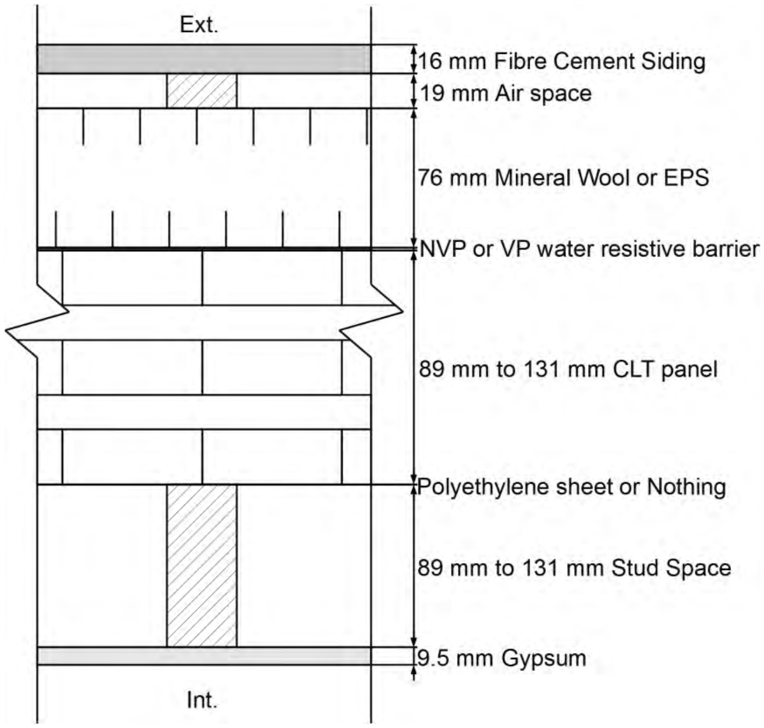


Figure 3.1 Typical CLT Wall Assembly Cross-section

As a result four categories of wall assemblies were studied: three having high, medium, or low vapour permeance materials outside of the CLT panels, respectively, but all having an unobstructed wall cavity to the interior of the panels and allowing them to freely dry to the interior. The fourth category had the medium permeance construction on the exterior but with a polyethylene sheet on the interior of the panels, creating a low interior permeance condition. The vapour permeance variations are created with the following material combinations, chosen to give three orders of magnitude of vapour permeance:

1. Low Exterior – NVP membrane and mineral wool (1.6 ng/Pa.s.m^2 combined)
2. High Exterior – VP membrane and mineral wool (1670 ng/Pa.s.m^2 combined)
3. Medium Exterior – VP membrane and EPS (64.4 ng/Pa.s.m^2 combined)
4. Medium Exterior and Low Interior – VP membrane and EPS (64.4 ng/Pa.s.m^2 combined) plus 0.15 mm polyethylene sheet on interior (3 ng/Pa.s.m^2)

3.2 Description of Wood Species

The four Canadian wood species or species groups included are Western SPF, black spruce, Eastern SPF, and hem-fir. The test also included a European CLT product with European spruce as a reference. Four samples each for Western SPF, European spruce, and black spruce were tested, one for each wall permeance category. Two hem-fir samples were tested with the low and medium exterior permeance wall assemblies, and two Eastern SPF panels were tested with the high exterior and low interior permeance wall assemblies. The Eastern SPF species group was composed largely of black spruce, although the manufacturing methods differ so they are treated as a separate category for this experiment.

The Western SPF, Eastern SPF, and hem-fir CLT panels were manufactured in a Vancouver laboratory specifically for this test wall, and included five laminations totalling 130 mm in thickness. The European spruce CLT panels were a commercial product from Europe, made of three layers and totalled 89 mm in thickness, with the edges of lumber boards glued. The black spruce CLT panels were commercially made in Quebec and consisted of three layers, totalling 102 mm in thickness. The composition of each panel type is shown in Table 3.1

Table 3.1 Panel Configuration

Panel Type	Total Layers	Layer Thicknesses (mm)	Total Thickness (mm)
A: European Spruce	3	33,23,33	89
B: Black Spruce	3	34,34,34	102
C: Western SPF	5	34,14,34,14,34	130
D: Hem-fir	5	34,14,34,14,34	130
E: Eastern SPF	5	34,14,34,14,34	130

3.3 Wetting Protocol

3.3.1 Wetting Period

Since this study aimed to investigate the wetting and drying behaviour of CLT, one of the key experimental parameters that should be defined was the level of moisture to be introduced to the panels before construction of the test wall.

Initially, WUFI models were created to determine feasible levels of built-in moisture which may be obtained through climatic exposure, and how to replicate those levels through submersion. The 1-D WUFI simulations were performed using the built-in material properties provided in WUFI by the Fraunhofer IBP for a 128mm thick 3-ply cross-laminated panel. No special consideration was made for the adhesive layers, as is consistent with models in the literature. A wetted profile was developed by exposing the horizontally oriented, unprotected panels to Vancouver weather conditions on both sides for six months starting in December, the beginning of the rainy season. The panel was initially set to have a 14% moisture content, and no absorption or emission of radiation was allowed to eliminate the effect of sunlight. A maximum possible moisture content profile was developed based on the highest moisture content attained at any point in the year at each location, mirroring the maximum profile for each face. The MC profile, shown in Figure 3.2 was then used as the initial condition for models of the four wall assemblies to be used in the experiment.

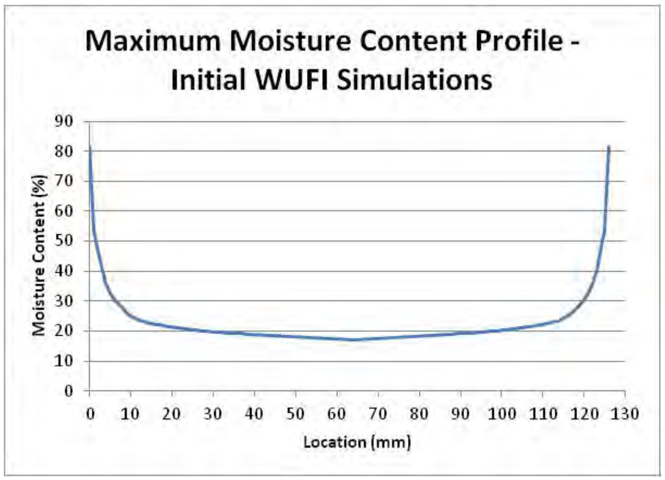


Figure 3.2 Maximum Moisture Content Profile - Initial WUFI Simulations

During the simulated natural drying after such a maximized wetting, the MC at the pin locations over time can be seen in Figures 3.3 to 3.6. Overall, the models indicated that the length of time required for the MC to drop below 20% across the whole panel was 4 weeks for high permeance, 13 weeks for medium, 59 weeks for low, and 80 weeks for low interior permeance. According to the simulation results obtained through trail and error, in order to replicate the initial wetted profile caused by weather exposure through immersing the panels in water, a possible scenario required that the panels be submersed for 4 days, dried for 3, then wetted for another 2 days in order to obtain a MC profile which penetrated deep enough in the panel without being too high at the face. Wetting was simulated by modelling the panel exposed to constant rainfall at a rate of 99mm/hour, and the length of time for wetting and drying was manually adjusted until the resulting water content profile in kg/m^3 fell within 5% of the profile obtained through environmental exposure.

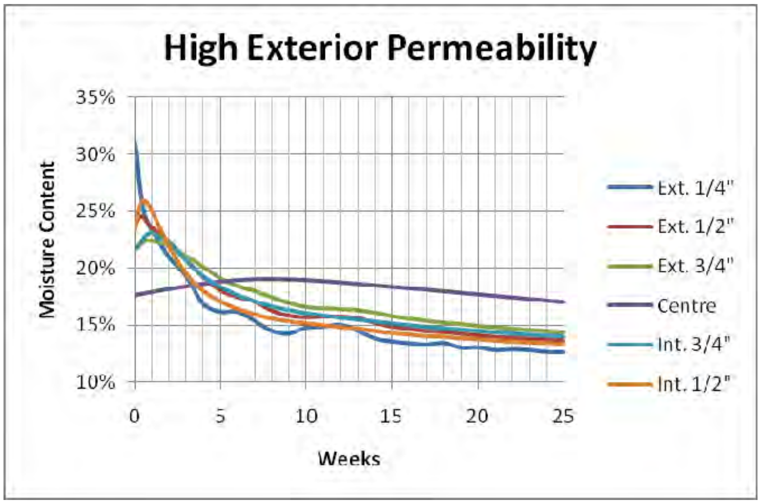


Figure 3.3 Initial WUFI Model High Exterior Permeance MC at test wall MC pin locations

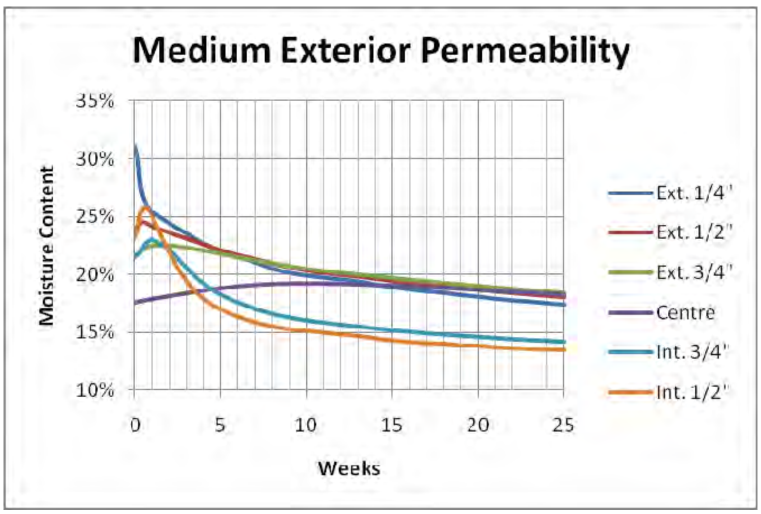


Figure 3.4 Initial WUFI Model Medium Exterior Permeance MC at test wall MC pin locations

Figure 3.5 Initial WUFI Model Low Exterior Permeance MC at test wall MC pin locations

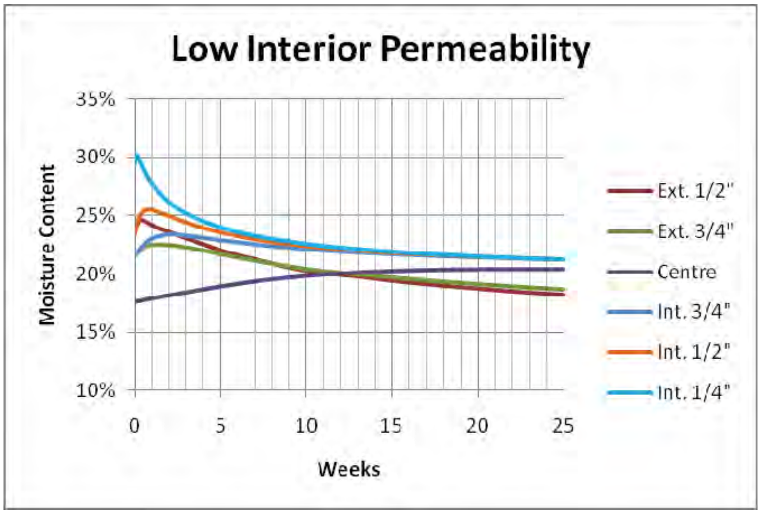


Figure 3.6 Initial WUFI Model Low Interior Permeance MC at test wall MC pin locations

Parallel laboratory testing of the same types of CLT panels was also being conducted by Lepage (2012), monitoring the wetting and drying behaviour of the panels alone. The results of these tests showed that hygrothermal modelling for CLT based on the existing model and knowledge drastically underestimated both the rate of water uptake and the drying speed.

Since the purpose of this field test was to investigate the drying potential of the CLT wall assemblies, it was imperative that the panels start in a sufficiently wetted state so that differentiation between wall assemblies or wood species could be detected. Since there would be a period of about three days between the start of panel installation and the connection of all the sensors to the datalogger, and the laboratory testing showed significant drying would occur in this timeframe for the CLT panel, a decision was made to wet the panels to an extreme level in an attempt to ensure the panels would still be wet when the data collection commenced. A period of one week, with the panels immersed in water, was chosen, as data from Lepage (2012) showed that within that time period the moisture content of the panels with a water source on one surface had risen above 30% MC penetrating up to at least 40mm in depth.

3.3.2 Wetting Method

The edges of each CLT panel were sealed in advance with polyurethane paint in order to ensure water absorption and drying in the thickness direction only. Testing of this sealing method is detailed in Appendix B. The paint was allowed to dry for at least two weeks before submersion. The original intent was to wet both sides of CLT for seven days to study the impact of the assembly permeance on the drying behaviour of both the exterior and interior of CLT assemblies. Therefore, data could be collected from the exterior faces, where the permeance of the wall materials is varied, and from the interior faces, where the panels are relatively free drying to the interior air space, and the variation in behaviour between the different species, and the samples of the same species may be analyzed.

A large children's swimming pool was used for wetting, as shown in Figure 3.7. The panels were placed in the pool in five stacks, with spacers between the pool floor, and each of the panels. Bricks were then stacked on top of the panels to act as ballast as the pool was filled with water. Unfortunately, the advertised water depth in the pool could not be obtained. The panels on the tops of the stacks were initially covered in water when wetting began, but the pool leaked water overnight until the water level stabilised about halfway up the top panel of each stack. As the pool was set up in the test facility, which has no plumbing, the amount of water available for wetting was limited. Consequently one face of some panels was left exposed to the air with only the lower face immersed. These panels were marked, and the improperly wetted faces were placed where their drying conditions were closely replicated elsewhere, usually as the interior freely drying face of the assemblies.

Figure 3.7 Soaking of CLT panels in pool

3.4 Test Wall Layout

The test wall was located on the eastern side of the building envelope testing facility as shown in Figure 3.8. Viewed from the exterior, the panels are arranged as shown in Figure 3.9.

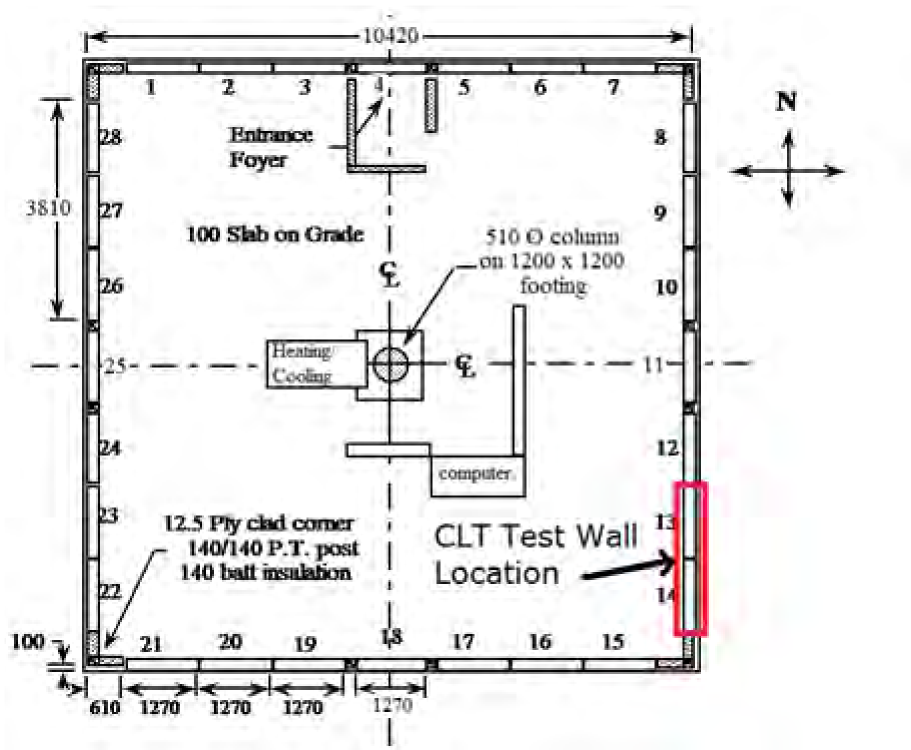


Figure 3.8 CLT Wall Location in Building Envelope Test Facility

CLT Panel Species Type All panels wetted on both sides except as indicated	A: European	A1 Int Dry	A2	A3	A4
	B: Black Spruce	B1	B2 Int Dry	B3	B4
	C: Western SPF	C1	C2 Int Dry	C3	C4 Ext Dry
	D: Hem-fir/ E: Eastern SPF	D1	E2	D3 Int Dry	E4
Wall Assembly	Type	1: Low	2: High	3: Medium	4: Low Int
	Interior Materials	9.5 mm Gypsum			
		Minimum 89mm Air Space			
		-			Poly Sheet
	Exterior Materials	NVP WRB	VP WRB		
		76 mm Mineral Wool		76 mm EPS	
		19 mm Vented Cavity			
		16 mm Fibre Cement Board			

Figure 3.9 CLT Wall Panel Layout

The Western SPF, Eastern SPF, and Hem-fir panels were mounted directly onto a stud frame. The black spruce panels and the European spruce panels were less thick, and therefore were mounted onto the frame with spacers at the screw locations, allowing the exterior faces of all the CLT panels to align. This arrangement created interior vertical cavities aligning with each of the four wall assembly types, which were relatively open to each other at the top. While the stud frame was necessary for this unconventional test wall made of many smaller panels, in typical construction this cavity may not be necessary or could be used to accommodate services within the wall.

The panels are separated from each other by a layer of spray polyurethane foam with a thickness of about 13 mm, in addition to the polyurethane paint used to seal the edges during wetting. The wall opening of the test facility for accommodating the entire CLT test wall was lined with a layer of polyisocyanurate foam board insulation and plywood, wrapped in the NVP water resistant membrane.

3.5 Sensor Configuration

3.5.1 Sensor Specifications

Three types of sensors were used in the test wall to measure relative humidity, temperature, and moisture content.

The relative humidity and temperature components were provided by Honeywell and assembled into sensor packages by Building Science Consulting Inc. The relative humidity sensors were powered with 5V, grounded, and the voltage reading provided by the signal lead was converted using provided calibration coefficients and a linear relationship into a relative humidity reading. The HIH-4000 series sensors provide an RH reading within ±3.5% accuracy. The accuracy of the RH sensors is reduced when exposed to humidity above 95% for extended periods of time. The reading remains high for an extended period after the relative humidity decreases.

The 10kΩ NTC thermistors were excited with 2.5V, and the signal lead was read across a 1kΩ resistor in parallel with the thermistor. The signal was converted to a temperature reading using a provided logarithmic relationship. The 192 series discrete thermistors provide an accuracy of ±0.2°C. Individual thermistors were used within the CLT panels to measure temperature.

The RH sensors were provided coupled with a temperature sensor in a vapour permeable water repellent package.

The moisture content sensors used within the CLT panels consisted of pairs of nails coated in non-conductive ceramic paint up to the tip. The nails were inserted into the wood approximately 25mm apart, along the grain of the wood, at differing depths. The voltage supplied by the data acquisition systems power supply, approximately 13V, was applied across the MC pins in the wood and the voltage was read across a 10kΩ resistor in series with the MC pins in the wood. The average of 10 voltage readings lasting 20ms each was taken and converted to find the resistance of the wood. If the average voltage reading was low enough such that resistance of the wood was found to be higher than 8000MΩ, around 0.02mV, the value was filtered out as data logger is not sufficiently accurate to read such low values. This corresponds to moisture contents below 11%, so is not a point of concern when evaluating moisture related durability concerns. These resistance values were converted to wood moisture content percentage values using Eq. (1) described by Straube (2002) to convert wood resistance to a Delmhorst meter reading for Douglas-fir with an average error of ±0.5% moisture content below 30% MC:

$$Log_{10}(MC_u) = 2.99 - 2.113(\log_{10}(\log_{10}(R_W))) \qquad (1)$$

where MC_u is the moisture content (%), uncorrected for species and temperature, and R_W is the measured resistance (Ω) of the wood.

The moisture content was then corrected for species and temperature using the Garrahan (1988) correction factors for moisture meter reading. Eq. (2) was used, as follows:

$$MC_c = [\frac{MC_u + 0.567 - 0.0260t + 0.000051t^2}{0.881(1.0056)^t} - b] + a \qquad (2)$$

where MC_c is the corrected moisture content (%), MC_u is the uncorrected moisture content (%), t is the temperature at the location of the MC reading (°C), and a and b are constant correction factors for difference species. The values used for a and b are outlined in Table 3.2.

Table 3.2 Garrahan (1988) species correction factors

CLT Panels	Species	*a*	*b*
A: European	Norway Spruce	0.702	0.818
B: Black Spruce	Black Spruce	0.820	-0.378
C: Western SPF	Lodgepole Pine	0.835	-0.545
D: Hem-fir	Eastern Hemlock	0.904	-0.051
E: Eastern SPF*	Black Spruce	0.820	-0.378

*The Black Spruce and Eastern SPF panels differ in manufacturing methods

3.5.2 Sensor Layout

Moisture content pins, thermistors, and relative humidity (RH) sensors were installed across the wall assemblies to monitor the behaviour of the CLT panels. RH and temperature were measured in each of the four exterior vented cavities and interior air spaces, and between the weather resistant barriers and insulation for each of the CLT panels. In total 24 combined RH and T sensors were used. Seven moisture content pins were placed in each CLT panel, located in the middle of the panels, 19 mm in from each face, 13 mm in from each face, and 6 mm in from the exterior face, except for the low interior permeance panels, where the 6 mm depth moisture measurement was taken from the interior face. Three additional thermistors per panel were inserted in the middle of each panel and 13 mm from each face. There were three more thermistors for the whole wall, two on the back of the fibre cement board sheathing, and one inserted 3mm into the interior side of the gypsum board. The typical panel sensor layout and notation for panel C1 is shown in Figure 3.10. All the sensors were monitored via a Campbell Scientific CR1000 data logging system, with a 15 minute sampling frequency.

The MC pins on the interior and exterior faces of the CLT panels were hammered directly into the wood, using a spacer to control the depth of penetration. Holes were pre-drilled to 12 mm less than the final penetration depth of the MC pins monitoring the middle of the panels, which were then hammered in to the correct location. Holes for the thermistors were also pre-drilled, and were sealed with silicone caulking after insertion. The RH sensors were taped in place on the CLT panels, as well as in the cavity spaces.

The sensor leads were passed through the CLT wall from the exterior in the gaps between the panels. The wires were draped and fastened angling up into the gap to ensure the drainage plane remained robust. Care was taken to spray insulation around the wires to reduce air leakage.

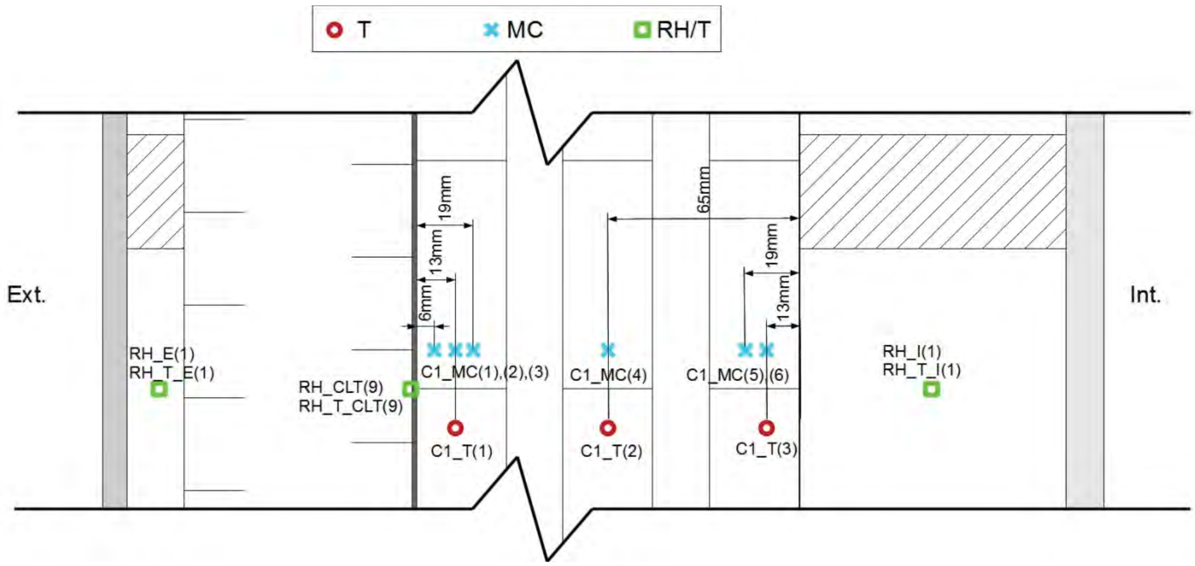


Figure 3.10 Typical CLT Panel Sensor Configuration

3.5.3 Test Hut Environmental Sensors

The exterior weather conditions were monitored using existing equipment installed on the field testing facility. Measurements were taken every hour, and included temperature, relative humidity, global solar radiation, rainfall, wind speed, and wind direction. The interior of the facility is maintained at 21°C ±1°C and about 50% ±3% RH using customized, highly controlled heating, cooling, and humidification systems with adequate fans and ceiling diffusers to evenly distribute the conditioned air.

3.6 Test Wall Construction

Test wall construction was commenced on August 16, 2011, and lasted five days. Construction drawings may be found in Appendix C. The large CLT panel and stud wall section to the left viewed from the exterior are a part of a heat flux experiment outlined in Appendix D, and provided moisture content data for a dry CLT panel in the medium exterior vapour permeance configuration. The low exterior and low interior permeance panels had Blueskin and polyethylene sheeting, respectively, applied to them within two hours after the wetting pool was drained. The insulation was installed approximately 30 hours after the wetting pool was drained, enclosing the panels in their final drying environments. 12 hours were required to attach all the sensors to the logging system, and data collection began on August 20, 2011, approximately 80 hours after the wetting pool was drained. Figures 3.11 through 3.14 show several stages during the construction of the test wall.

Figure 3.11 Panel installation

Figure 3.12 After installation of water resistive barriers

Figure 3.13 CLT test wall with insulation, strapping and cladding

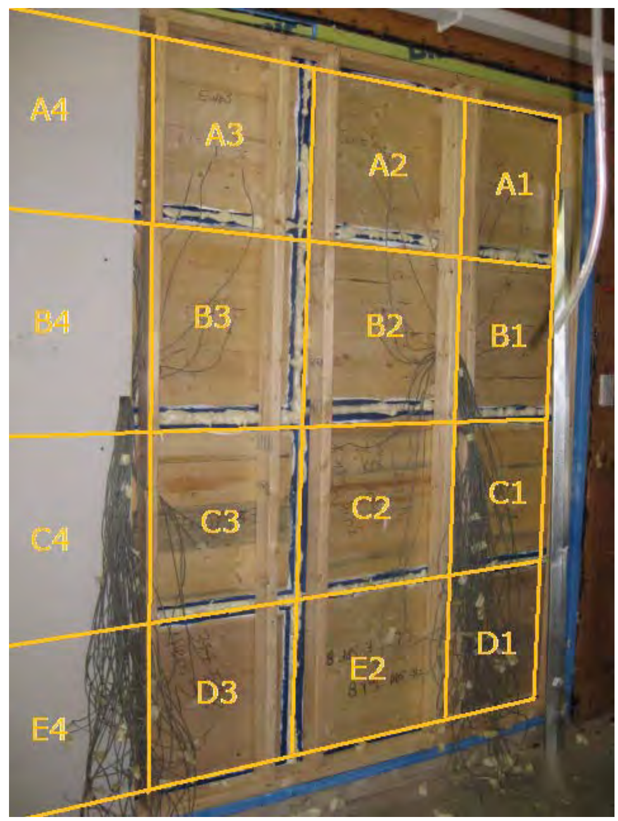


Figure 3.14 Interior of wall before drywall installation

Chapter 4 - Results Analysis and Discussion

This chapter details the short and long term drying behaviour at the faces of the CLT panels due to the effects of the different wall assemblies, then discusses differences which can be seen between species groups.

Data was collected, stored, and downloadable onsite. Unfortunately, after some time, some data intervals were found to be missing after retrieval. This was caused by a faulty outlet being used in combination with a failure of the datalogger's power supply batteries. Fortunately four full days' data was collected at the beginning of the experiment, when the wood was drying quickly, showing the major differences between the panels, in addition to the majority of the data after the initial quick drying phase, when the panel moisture content continued to change, though more slowly.

4.1 Short Term Drying Behaviour

4.1.1 Freely Drying Interior

In order to determine whether wood species has a significant effect on the drying behaviour of CLT, most of the panels were constructed with no vapour diffusion retarders impeding drying into the interior wall cavity. Given the same drying conditions, any significant difference in behaviour among panel species should be evident.

The moisture content at 13mm into the interior face of the freely drying panels is plotted in Figure 4.1. While the panels had different moisture content levels ranging between 14% and 24% when data collection began, the rate of drying did not appear to vary greatly between the different species after the first three weeks. The rates of moisture content change appeared to be relatively constant between these samples, except panels C3 and D3. Both panels had the medium permeance wall materials on the exterior. The panel C3, made of Western SPF, was the panel with the highest MC at the start of data collection and dried at a faster rate than all the other panels, despite being located within the same MC range.

The readings for panel D3 were an error, as the moisture content readings seemed to indicate the panel was behaving as if it had polyethylene sheeting on the interior face, when in fact, not only was there no sheeting, but the interior surface was not even wetted before construction. Upon further investigation, is was evident that the values recorded for the wood resistance for the moisture content pins in panel D3 were the exact same values, shift over one location as the reading for panel E4. This error was likely caused by irresolvable anomalous behaviour of the data logger as no programming or wiring errors could be found to explain it. As a result, the results for moisture content for panel D3 have been excluded from the remainder of analysis.

In the samples which started with higher MC, especially above 20%, the drying rate appeared to be faster, probably due to the higher proportions of free water in cell lumens than the bound water in cell walls. Since neither all the medium exterior permeance panels, nor all the Western SPF panels dried at a faster rate than the remainder of the panels, it seemed likely that the faster drying rate was caused by special variations and irregularities in the specific wood samples tested, and may not be indicative of significant variations between wood species. No single species was consistently wetter than another at the beginning of data collection and after two months, 10 of the 12 moisture content readings fall within 1% of each other between 12% and 13% MC, which is negligible considering the ±2% error inherent in the sensor reading. The species may have a larger effect on total moisture absorbed, or the depth of penetration of the elevated moisture content, but not the actual rate of drying of intercellular water molecules.

The relative consistency in behaviour between the freely drying interior CLT faces suggests that when at a low initial moisture content, and allowed to dry freely, wood species is not a significant factor which will affect the choice of which CLT panels to choose for a construction project from a hygrothermal perspective. This conclusion is made based on the wood species included in this research, which is very representative of the range of Canadian softwood lumber species. The results may differ when examining wood at higher moisture contents, or wood species that are much more permeable than the species included in this project, such as southern pine. Also, it appeared that the panels were thick enough that the drying behaviour of the exterior and interior panel faces was not noticeably influenced by each other in the initial drying phases. For example, the interior faces of the panels were not drying more slowly when the exterior face was exposed to a low permeance material or more quickly when the exterior face was exposed to a higher permeance material.

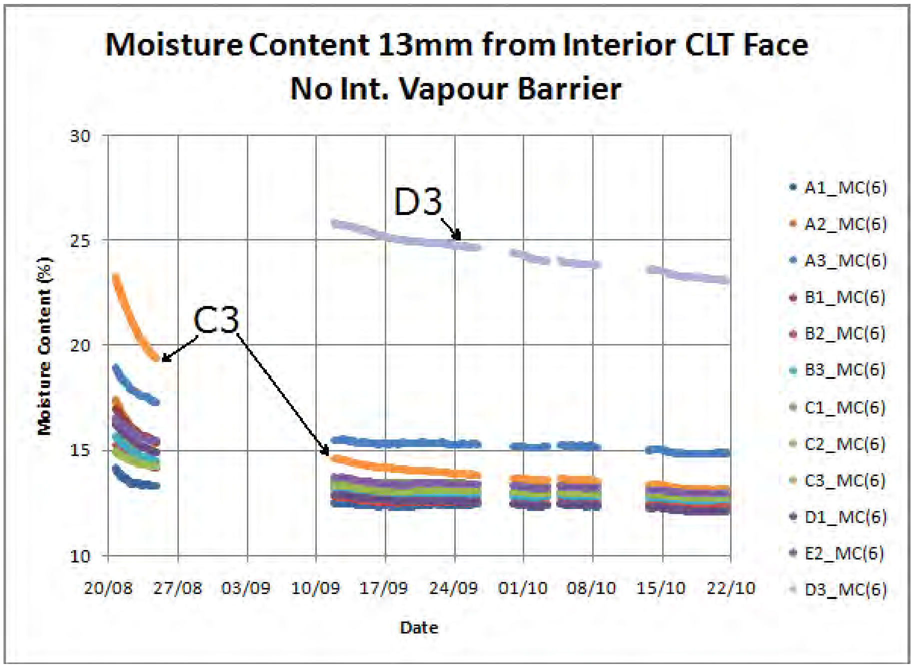


Figure 4.1 Moisture Content at 13mm from Interior CLT Face for Freely Drying Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, D-Hem-fir, E-Eastern SPF

4.1.2 Low Interior Permeance

The panels with polyethylene sheeting on the interior face showed slightly less uniform behaviour, especially in the first few days of rapid drying, as seen in Figure 4.2. The European panel, A4, dried more quickly than the others initially, which may indicate that liquid transport occurred more readily, redistributing moisture into the centre of the European panels when drying to the free surface was dramatically slowed. The rate in decline of MC for panel C4, the Western SPF panel, is extremely low compared to the other three panels after the initial drying phase.

The MC in all the low interior permeance panels remained at a very high level, with only two panels dropping significantly below 26% after two months. While it was expected that the low interior permeance panels be the worst performing hygrothermally, with the highest risk of damage due to moisture, this measured data indicates the possibility that the moisture content does not redistribute quickly enough to the centre of the panels, sufficiently lowering the MC in the outer layers in a fast enough time frame to safely prevent mould and rot.

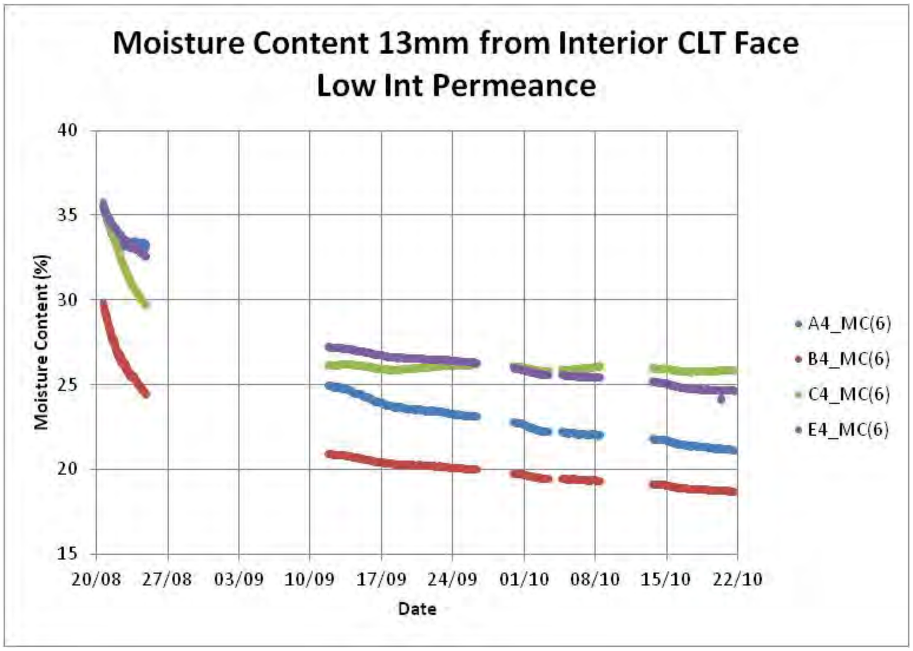


Figure 4.2 Moisture Content 13mm from Interior CLT Face for Low Interior Permeance Panels Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

The MC 19 mm into the interior face are slightly higher than at the 13 mm mark, but the drying patterns are the same, as seen in Figure 4.3. This trend of higher moisture contents deeper into the face of the panel is mirrored across the entire test wall. The MC in the centre of the panel, in Figure 4.4, is lower than at the interior face, allowing moisture to redistribute into the centre, and the rate of drying into the centre is much lower than at the face, and in some cases the MC in the centre rises. This indicates that the moisture at the interior face of the panels with polyethylene is drying into the centre of the panel, and the moisture in the centre of the panel is drying further to the exterior CLT face. Theoretically, no moisture should be allowed to pass through the polyethylene sheeting, and the MC reading closer to the surface, and 13mm deep should be higher than at 19mm deep, however the majority of the drop is likely to have occurred in the brief period of about two hours between the draining of the wetting pool and the application of the polyethylene sheeting. The difference may be maintained due to the small gaps in the polyethylene sheeting caused by the insertion of the MC pins. Attempts to seal the holes with silicone caulking were made, but may not have been 100% airtight. Some drying may have also occurred into the space between the CLT panel and the polyethylene sheeting, as the sheeting is not fully adhered to the panel.

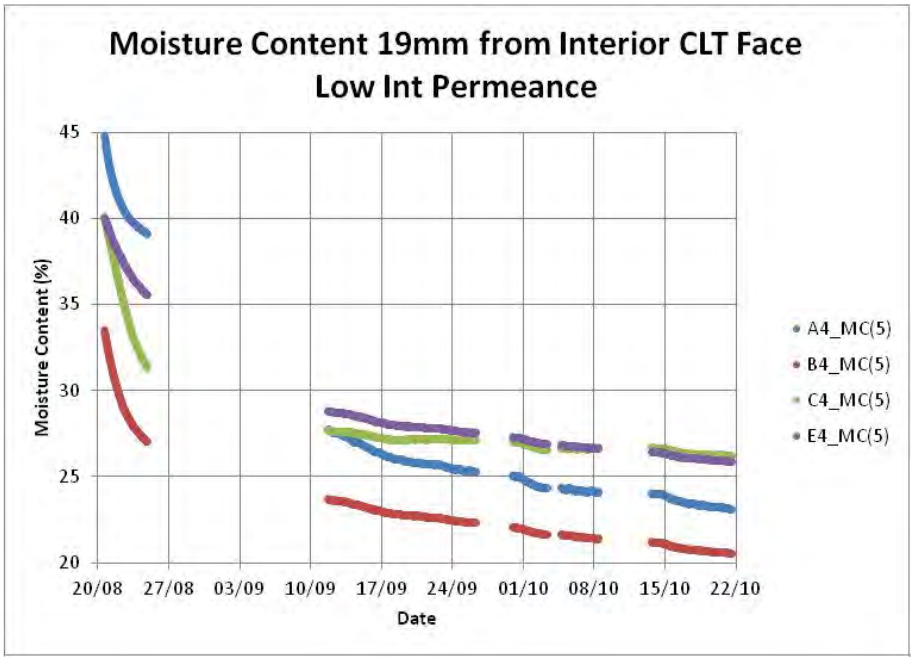


Figure 4.3 Moisture Content 19mm from Interior CLT Face for Low Interior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

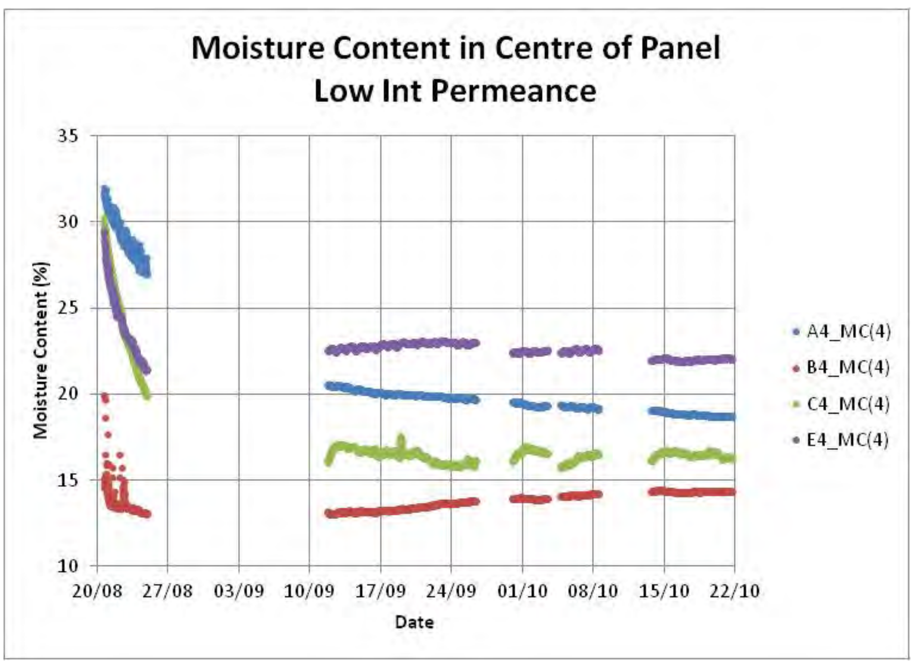


Figure 4.4 Moisture Content in Centre of Panel for Low Interior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

An additional point of concern for wood durability is the possibility of mould growth on the surface at a relative humidity above 80%. For the panels with low permeance materials adjacent to them, the RH sensors were not placed directly on the wood surface, they were placed between the non-vapour permeable membrane and the insulation for the exterior low permeance panels, and in the interior cavity for the low interior permeance panels. However, at the time of installation, extensive condensation was present on the polyethylene sheet, held against the face of the low interior permeance panels, as shown in Figure 4.5. Given the slow rate of drying, it is likely that the RH on the surface of the panel remains well above 80%, even after two months. The same elevated relative humidity is likely present on the panels with low exterior permeance, though the opaque vapour barrier masks condensation and mould growing on the exterior face of the CLT panel. Mould growing on the exterior face is not as likely to affect the indoor air quality as mould growing on the interior face.

Figure 4.5 Condensation on Interior of Polyethylene Sheet for Low Interior Permeance Panels

4.1.3 Drying on the Exterior Face

The MC records for the exterior face of the CLT panels demonstrate that the permeance of the materials adjacent is a principal factor in the drying behaviour of the wetted panels. Due to the drying that occurred during construction, before installation of the insulation, many of the panels with a vapour permeable water resistant barrier had already dried to below 26% MC before the start of data collection. When data collection began, the panels which had the non-vapour permeable water resistant barrier or polyethylene sheeting applied shortly after being removed from the wetting pool all have moisture contents in the covered faces of at least 20%, and usually well above the 26% required to initiate wood decay. The vapour retarding membranes applied prevented these panels from drying during construction as the panels with vapour permeable membranes did. Since the application of the vapour control layer is the only difference in the treatment of the panels, it is reasonable to assume that all the panels were wetted to at least 26% in the outer layers in the wetting pool. Comparing this assumed initial moisture content to the moisture contents at the start of data collection, it becomes clear that the majority of drying occurred during the time before the insulation was installed. The majority of the high and medium exterior permeance panels are at MC levels between 15% and 19% at the time when data collection begins.

Figures 4.7, 4.9, and 4.11 show the moisture contents 13mm in from the exterior faces of the high, medium, and low exterior permeance CLT panels, respectively.

4.1.4 High Exterior Permeance

All the high exterior permeance panels were below 26% MC when data collection began, and in two months time dried to below 15% MC. The MC in the exterior face of these panels is more responsive to high outdoor relative humidity creating a vapour drive into the CLT panel from outside on several occasions due to the high vapour permeance of the mineral wool insulation. The variation is small in the data collected from the test wall and should not be a point of concern in a wall assembly with high drying potential. Figure 4.6 shows an increase in exterior vapour pressure relative to the vapour pressure between the insulation and vapour permeable membrane driving moisture into the CLT panel over a period of 10 days. When the exterior vapour pressure rises above that adjacent to the panel between October 19 and 22, the panel's moisture content begins to increase. The relative humidity between the insulation and vapour permeable water resistive barrier is also plotted in Figure 4.7, over a longer time frame to demonstrate the connection.

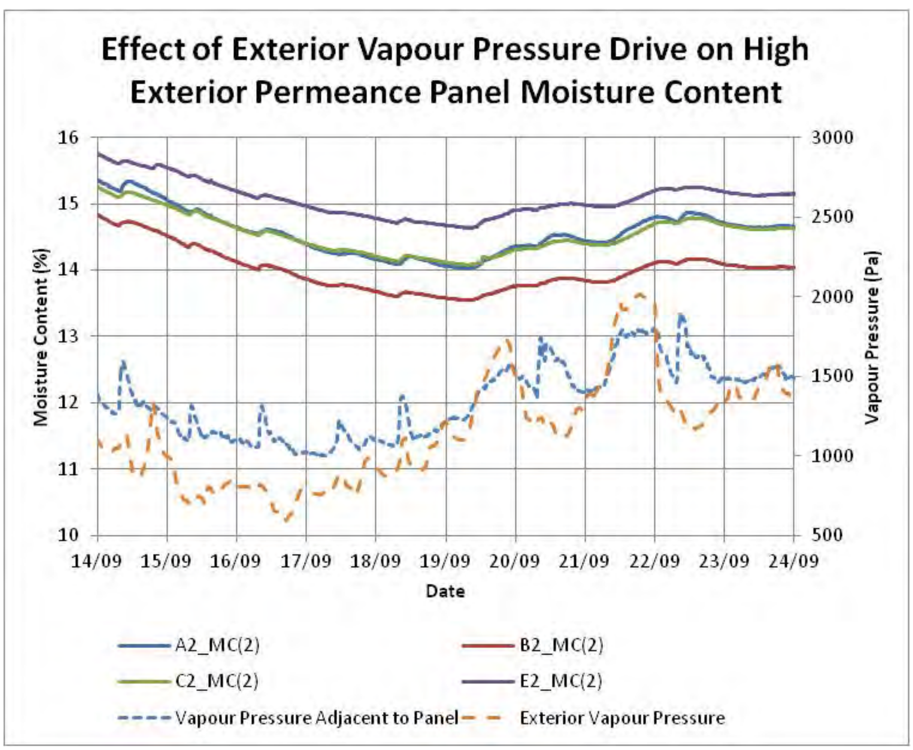


Figure 4.6 Effect of Exterior Vapour Pressure Drive on High Exterior Permeance Panel Moisture Content

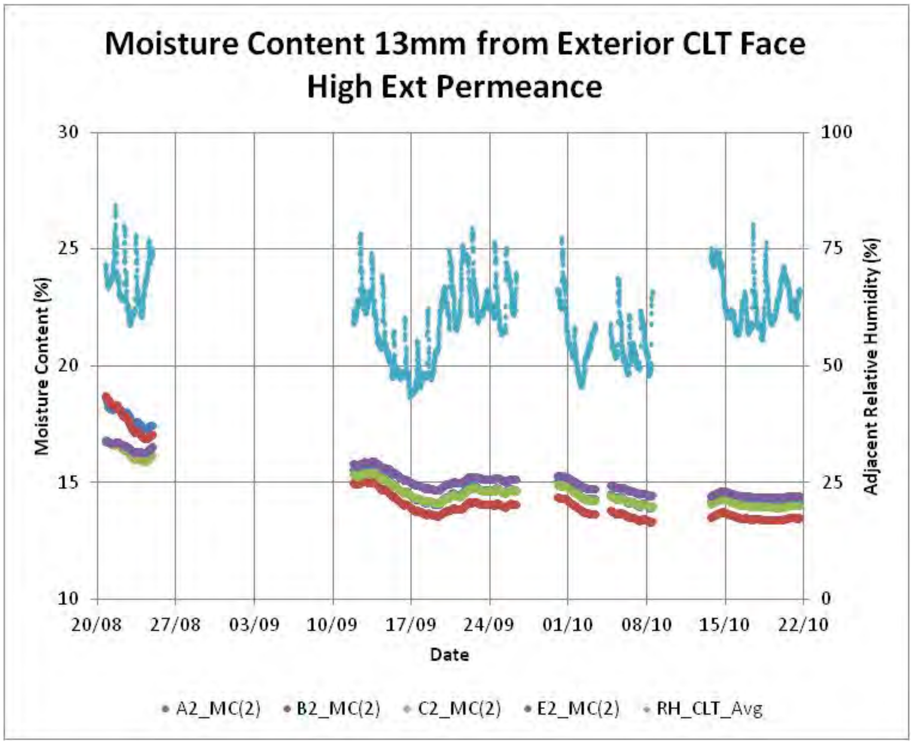


Figure 4.7 Moisture Content 13mm from Exterior CLT Face for High Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

The risk of mould growth for the high exterior permeance panels is low, as the highly vapour permeable mineral wool means the RH adjacent to the panel surface closely mirrors the ambient RH, rising above 80% only occasionally, for brief periods, as shown in Figure 4.8.

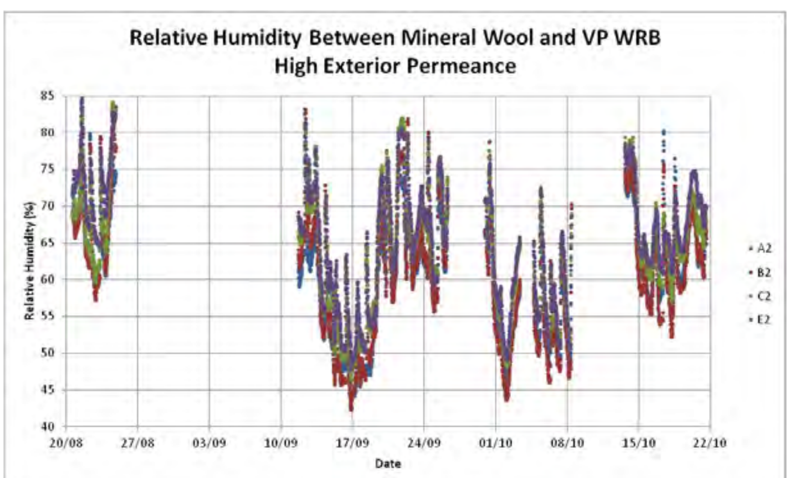


Figure 4.8 Relative Humidity Between Mineral Wool and VP WRB for High Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

4.1.5 *Medium Exterior Permeance*

The panels with medium exterior permeance which started below 20% MC when data collection began, dried at a very slow rate, or remained nearly stable. The few panels with higher MC dried to below 26% quickly, and their rates of drying slowed as they approached 21%. With the exception of panel C3, which increased in MC noticeably due to an unexplained high RH adjacent to the panel's exterior face, seen in Figure 4.10. The semi-vapour permeable expanded polystyrene insulation appeared to serve as a buffer, removing the effect of exterior vapour pressure increasing and decreasing the MC of the exterior face of the CLT on the order of several days, as was seen in the high exterior permeance panels. The source of the moisture being driven into panel C3 from the exterior is unknown, but is consistently present in all the panel's moisture content sensors in the exterior face, as well as the relative humidity sensor adjacent to the panel. Overall, since the MC is very stable, the initial MC becomes a point of concern for long term durability of the panel, since the drying period will be extended.

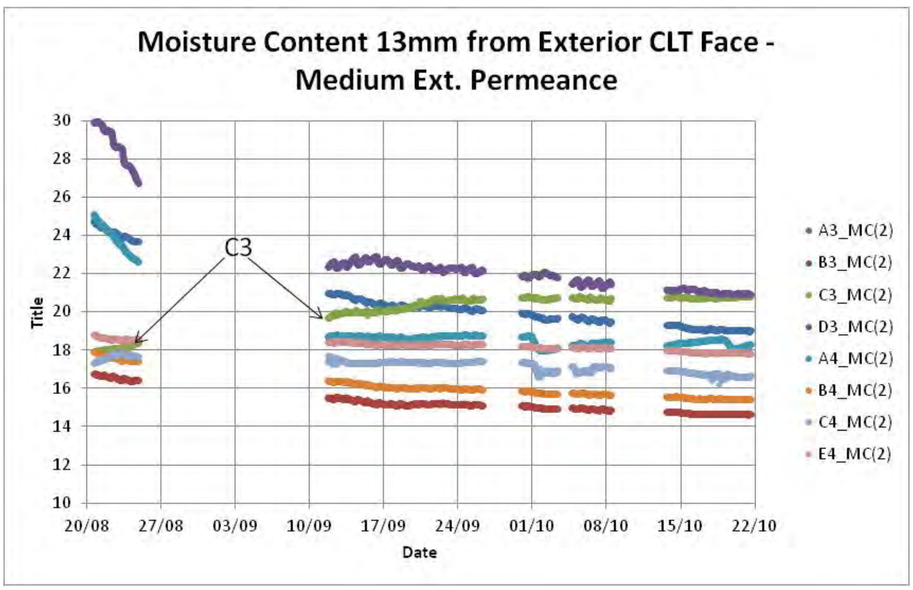


Figure 4.9 Moisture Content 13mm from Exterior CLT Face for Medium Exterior Permeance Panels Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

Although the MC in the panels with medium exterior permeance may be low enough to prevent wood decay, the relative humidity on the exterior panel face remains above 80% for the majority of the panels, shown in Figure 4.10. Although the RH for panels with both freely drying interiors and low permeance interior are included, the variation in RH is larger between panels of different wood species than between the two wall assemblies and the neither wall assembly produces an RH that is consistently higher than the other. The two panels with the highest RH levels are both made of Western SPF, which may indicate a difference in behaviour between CLT panel wood species groups, which might be attributed to changes in material properties caused by blue stain fungus. Due to the medium vapour permeance of the EPS insulation, the relative humidity adjacent to the panel is very stable compared to the RH in the same location for the high exterior permeance wall assemblies shown in Figure 4.8. This stability prevents the RH from decreasing during each day, when the ambient RH is low, as occurs for the panels with high exterior vapour permeance. These sustained, elevated RH levels for at least half the panels present a serious risk of mould growth.

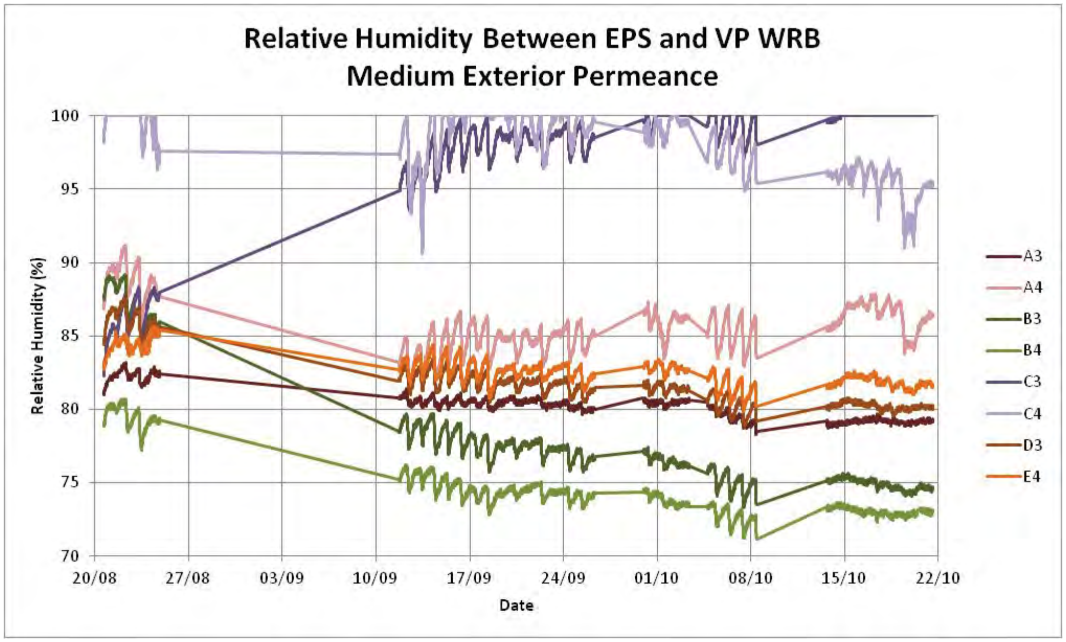


Figure 4.10 Relative Humidity Between EPS and VP WRB for Medium Exterior Permeance Panels Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, D-Hem-fir, E-Eastern SPF

4.1.6 Low Exterior Permeance

The panels with low exterior vapour permeance were again expected to perform very poorly. They appear to be reaching equilibrium between 20% and 25% MC, just below the danger zone for wood products. This indicates that moisture redistribution into the centre of the panel may occur too slowly to safely prevent moisture related durability issues for the wood species evaluated in this project.

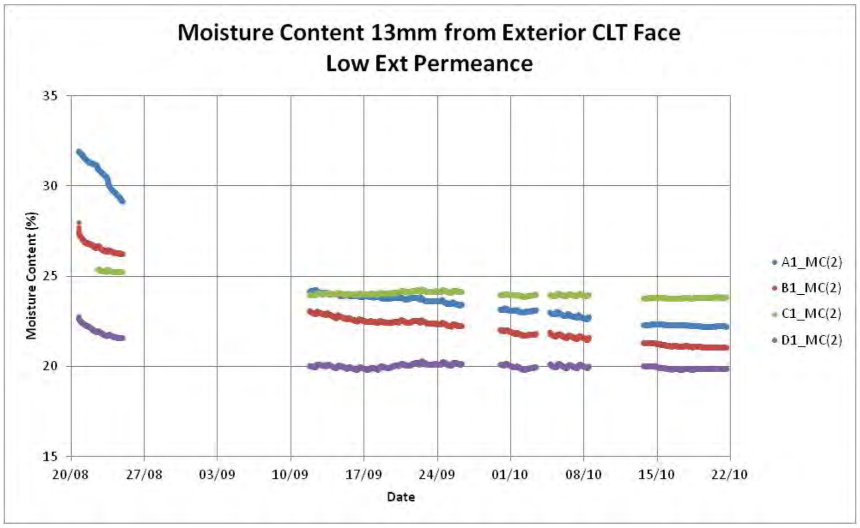


Figure 4.11 Moisture Content 13mm from Exterior CLT Face for Low Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, D-Hem-fir, E-Eastern SPF

4.2 Long Term Hygrothermal Behaviour

4.2.1 Typical Moisture Content Profiles of Drying Panels

By examining the moisture content profile of each panel over time, it becomes clear that the majority of drying occurs within the first month after installation. Graphs of the moisture contents at each pin location for each panel over 12 months are available in Appendix E, moisture content profiles for all panels are included in Appendix F, and the exterior temperature, relative humidity, and solar radiation data is shown in Appendix G. The moisture content profiles for the European CLT panels with high, medium, and low exterior permeance, and for the black spruce panels for low interior permeance demonstrate typical drying behaviour for each wall type. The profiles are plotted with the exterior side of the panels on the left. Tables of data will show the moisture content trends at the wettest moisture pin location for all the panels over time, excluding panel D3 for erroneous readings. Moisture content readings above 26%, at risk of decay, will be highlighted in red, and readings above 20%, low risk of decay, but a benchmark for safety, will be highlighted in orange to help identify panels which are wetter, or drying more slowly than others.

As a point of reference, the moisture content profiles of the non-wetted European CLT control panel is provided in Figure 4.12. The panel is in equilibrium with its environment at around 10 to 13% moisture content, fluctuating the most at the exterior face in response to changes in the outdoor relative humidity. The interior face also steadily dries 2-3% MC over the course of the year, which is consistent with the drop in the relative humidity of the interior air cavity from around 55% RH to around 50% RH.

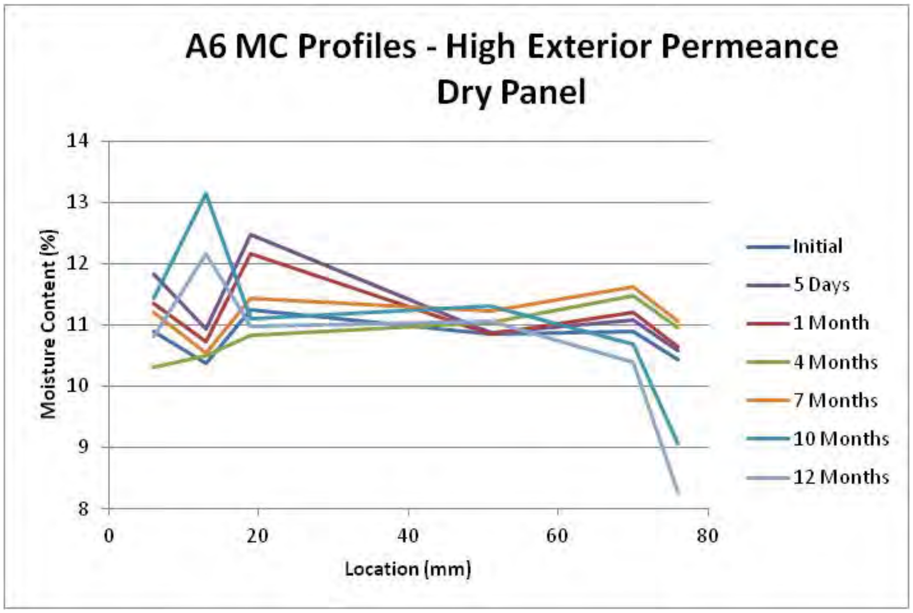


Figure 4.12 Moisture Content Profiles, A6, High Exterior Permeance, Dry Panel

4.2.2 High Exterior Permeance

As expected, the high exterior permeance panels dry quickly, falling about 5% MC within the first month. While the moisture content continues to fall in the next three months, there is virtually no change in moisture content after four months, and at below 14%, the high exterior permeance panels are not significantly different from the unwetted control panel. After data collection began, the panels were never above 26% MC, and are at no risk of decay.

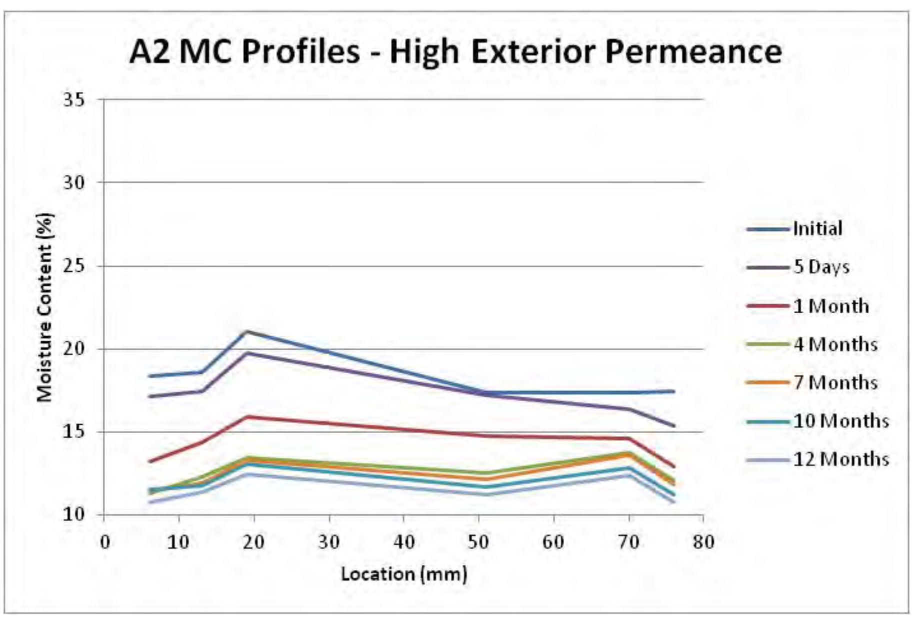


Figure 4.13 Moisture Content Profiles, A2, High Exterior Permeance

The data for all four high exterior permeance panels demonstrates the same trends. Table 4.1 shows the moisture content and corresponding change for each time interval for panels A2, B2, C2, and E2 for the moisture pin with typically the highest reading, 19mm from the exterior of the panel. Since the panels were able to dry rapidly before data collection commenced, the data shows the panels continuing to dry at a decreasing rate. The degree to which the panels had dried before data collection commenced, coupled with the time for the panels to reach equilibrium at a safe moisture content, less than 4 months, the high exterior permeance wall configuration is confirmed as a suitable method of ensuring long term moisture durability.

Table 4.1 Moisture Content 19mm from Exterior of High Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

Period\Panel		A2	B2	C2	E2
Initial	MC (%)	21	19	17	17
5 Days	MC (%)	20	17	17	18
	Change (% MC)	-1	-1	0	0
1 Month	MC (%)	16	14	15	16
	Change (% MC)	-4	-3	-2	-2
4 Months	MC (%)	13	12	12	11
	Change (% MC)	-2	-2	-3	-5
7 Months	MC (%)	13	12	12	10
	Change (% MC)	0	0	0	-1
10 Months	MC (%)	13	13	13	11
	Change (% MC)	0	1	1	1
12 Months	MC (%)	12	12	12	10
	Change (% MC)	-1	0	0	-1

4.2.3 Medium Exterior Permeance

The medium exterior permeance panels have a higher initial moisture content at 19 mm from the exterior CLT surface compare to the high permeance panels. The wettest panels do initially have moisture contents above 26%, however , they dry well below that level in the first month. Similarly to the high exterior permeance panels, the medium exterior permeance panels have very little change in moisture content after 4 months, indicating they are in equilibrium with their environment, though at a slightly higher MC level. The panels have all dried below 26% MC within a month.

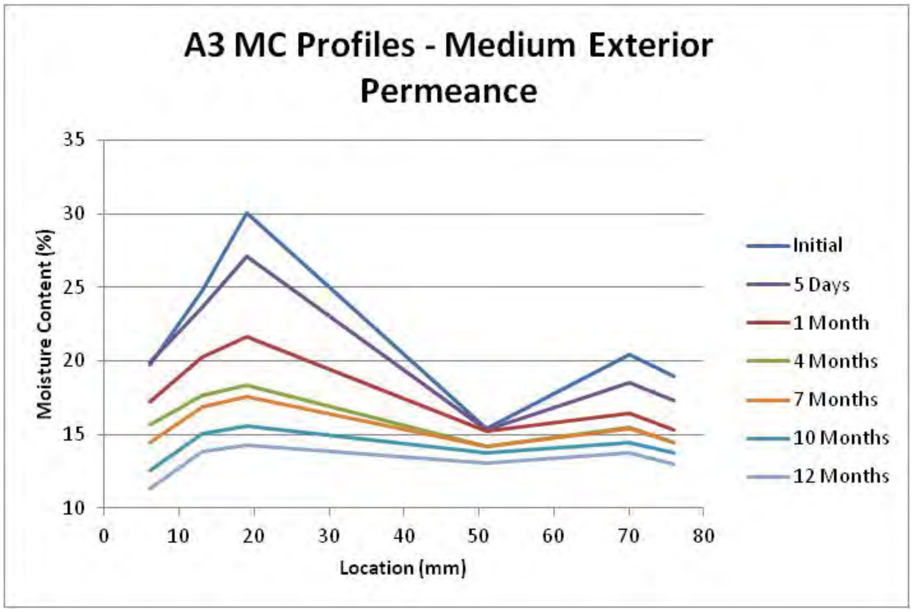


Figure 4.14 Moisture Content Profiles, A3, Medium Exterior Permeance

Table 4.2 shows the moisture content and corresponding change for each time interval for all the panels with the medium exterior permeance configuration at the location with typically the highest reading, 19mm from the exterior of the panel.

Panel A3 initially had a high moisture content which dried below 26% within a month. Panels B3 shows gradual drying, likely due to a low initial MC only 3% higher than the apparent equilibrium point. Panel C3 picked up moisture in the first month, the cause of which is not apparent. It is possible an irregularity in the CLT panel allowed for a pocket of excess water to be stored, which caused the increase. If indeed present, once the moisture source is exhausted, the MC in panel C3 should fall. While drying slowed between 4 and 7 months, over the winter, as the weather warmed, after 10 months, the panels begin to dry again.

Panels A4 to E4 have a low permeance membrane on the interior. While panel A4 had a higher initial MC, which dried below 26% in less than a month, the remaining low interior permeance panels show little drying throughout seven months, likely caused due to the migration of moisture from the interior face, across the panel to the exterior. At this location on the exterior face, these low interior permeance panels are not at risk for decay, and appear to still be drying.

Overall, the medium permeance configuration appears to allow drying in a sufficient time frame from higher moisture contents. The medium permeance wall assembly does extend the time required to reach equilibrium compared to , as drying slows over the winter months then resumes in summer.

Table 4.2 Moisture Content 19mm from Exterior of Medium Exterior Permeance and Low Interior with Medium Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

Period\Panel		A3	B3	C3	A4	B4	C4	E4
Initial	MC (%)	30	18	19	29	18	20	20
5 Days	MC (%)	27	18	19	27	18	21	20
	Change (% MC)	-3	0	1	-3	0	1	0
1 Month	MC (%)	22	17	22	23	17	22	20
	Change (% MC)	-5	-1	3	-4	-1	1	0
4 Months	MC (%)	18	15	22	23	16	19	18
	Change (% MC)	-3	-1	0	0	-1	-3	-2
7 Months	MC (%)	18	15	22	21	16	17	18
	Change (% MC)	-1	-1	0	-2	0	-2	0
10 Months	MC (%)	16	14	20	17	15	15	17
	Change (% MC)	-2	-1	-2	-4	-1	-2	-1
12 Months	MC (%)	14	13	19	16	15	15	16
	Change (% MC)	-1	-1	-1	-1	-1	-1	-1

4.2.4 Low Exterior Permeance

The low exterior permeance panels typically have a very high initial MC at the exterior face, a by-product of applying the vapour impermeable membrane shortly after removing the panels from the wetting pool. When data collection commenced, the interior, free drying face had already lowered to a safe moisture content around 15%. Over time, the interior face of these panels lowered to a moisture content 2 to 3% higher than the high permeance panels. The slight elevation in moisture content at the interior face, as well as the unchanging moisture content in the centre of the panel is likely caused by moisture from the exterior face drying through the panel to the interior. While panel A1 reaches a MC below 26% after one month, drying slows between 4 and 7 months, during colder weather, and picks up again between 7 and 10 months. Drying slows between 7 and 12 months, as the moisture content dips below 15%, and is approaching equilibrium.

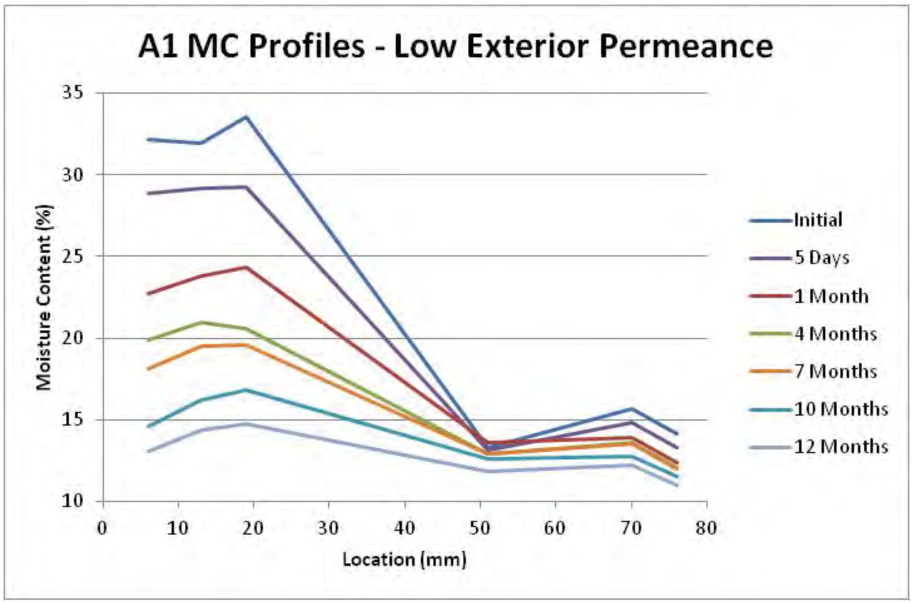


Figure 4.15 Moisture Content Profiles, A1, Low Exterior Permeance

Table 4.3 Moisture Content 19mm from Exterior of Low Exterior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

Period\Panel		A1	B1	C1	D1
Initial	MC (%)	34	37	30	27
5 Days	MC (%)	29	32	29	24
	Change (% MC)	-4	-5	-1	-4
1 Month	MC (%)	24	24	27	21
	Change (% MC)	-5	-8	-2	-3
4 Months	MC (%)	21	20	26	20
	Change (% MC)	-4	-3	-1	-1
7 Months	MC (%)	20	20	25	19
	Change (% MC)	-1	-1	0	0
10 Months	MC (%)	17	18	24	18
	Change (% MC)	-3	-2	-1	-1
12 Months	MC (%)	15	17	22	17
	Change (% MC)	-2	-1	-1	-1

Considering the moisture content 19 mm from the exterior face of all four panels with low exterior permeance, all the panels still have moisture contents at or above 20% MC after 7 months, with little change from the 4 month mark. Panel C1 remains around 25% MC after 7 months, and only drying a further 3% after a year, despite having the lowest initial reading, causing a risk of decay initiation due to the extended time frame at this elevated moisture content. While most of the panels dry to a safe level within one month, if a moisture source were to be persistent, the low exterior permeance configuration would not likely provide a fast enough mechanism to allow long term durability.

4.2.5 *Low Interior Permeance*

The low interior permeance panels, like the low exterior permeance panels, have very high initial moisture contents due to the application of the polyethylene sheeting soon after removal from the wetting pool. From Panel B4, it can be seen that the moisture from the interior face must migrate to the exterior to dry, causing the moisture content in the centre of the panel to rise. The moisture content in the interior face drops very quickly, falling the same amount in the first 5 days as in the next 25 days. In 4 months the panel appears to be nearing equilibrium, and the moisture content is relatively consistent across its depth, decreasing only another 2% over the remainder of the year.

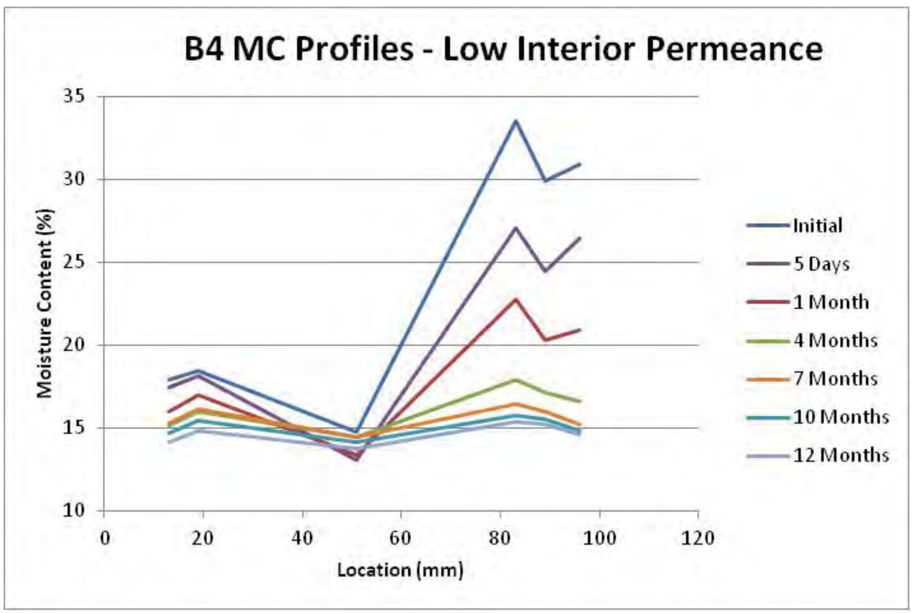


Figure 4.16 Moisture Content Profiles, B4, Low Interior Permeance

The moisture contents 19mm from the interior face for the four panels with low interior permeance show that while over a month is required until all the panels are below 26% at the highest point, a longer time period than the panels with low exterior permeance, after four months, all the panels are below 26%. After seven months, panel C4 and E4 are demonstrating a slowed drying rate despite having a relatively high moisture content, above 20%. While none of the panels are explicitly at risk of decay initiation, their elevated moisture contents after 12 months, with no notable increase in drying rate after the winter months, as seen in other wall assemblies, indicate a persistent small scale leak could cause decay due to poor drying conditions.

Table 4.4 Moisture Content 19mm from Interior of Low Interior Permeance Panels
Species Groups: A-European Spruce, B-Black Spruce, C-Western SPF, E-Eastern SPF

Period\Panel		A4	B4	C4	E4
Initial	MC (%)	45	34	40	40
5 Days	MC (%)	39	27	31	36
	Change (% MC)	-6	-6	-9	-5
1 Month	MC (%)	26	23	27	28
	Change (% MC)	-13	-4	-4	-8
4 Months	MC (%)	19	18	25	24
	Change (% MC)	-6	-5	-2	-4
7 Months	MC (%)	17	16	24	22
	Change (% MC)	-3	-1	-2	-1
10 Months	MC (%)	16	16	22	21
	Change (% MC)	0	-1	-2	-1
12 Months	MC (%)	16	15	21	21
	Change (% MC)	0	0	-1	0

4.3 Differentiation Between Species

Based on the drying data collected two trends can be identified which may indicate a differentiation in hygrothermal behaviour between wood species. First, the European spruce panels, A1 to A4, tend to have a higher initial moisture content than the other panels. While the black spruce panels, B1 to B4, fall in the same wood genus as the European, or Norway, spruce, the black spruce wood is generally known to be among the least permeable wood species, and it comes from managed forest, while the European spruce was grown on a rapid growth tree plantation. Plantation wood tends to be more porous than its more slowly grown counterpart from managed forests or old growth (Calkins, 2009), which can also lead to faster moisture uptake.

The second trend is in the slower drying configurations, the western SPF panels, C1 to C4, tend to dry more slowly, especially in cooler weather, when initially at a higher moisture content. Their behaviour is not significantly different from the other species in medium or high permeance configurations, where their moisture content starts below 20%. Since these panels are manufactured from pine beetle infected wood abundant in western Canada, and readily available to be used in CLT production, special attention may need to be paid to ensure the panels are not extraneously wetted at the time of construction, and to ensure proper building envelope design to improve the durability performance. McFarling (2006) has shown that blue-stained pine beetle infested wood picks up more moisture, faster than unaffected wood, though the moisture uptake testing performed by Lepage (2012) on panels from the same sources as the field testing experiment showed that the panels did not have significantly different water absorption coefficients, with the western SPF, European spruce, and hem-fir panels all having a-values of 12 $g/m^2.s^{1/2}$. However, this value is elevated from the typical range for softwoods of 1-7$g/m^2.s^{1/2}$ in the transverse direction (FPL, 2010).

Chapter 5 - WUFI Model Verification

The field study has provided data demonstrating how wetted cross laminated timber panels dry within four wall configurations of varying vapour permeances in a Southern Ontario climate. In order to estimate the behaviour of the panels in different wall assemblies or climates, it is necessary to use the measured data to validate a hygrothermal simulation under the same conditions before extrapolating the model to new assemblies or different climatic conditions. The following is a description of the material properties and simulation inputs used in the WUFI Pro 4.2 models of the test wall.

5.1 CLT Material Properties

The material properties used to model the CLT panels were derived from recommendations made after water uptake tests at the University of Waterloo (Lepage, 2012), and of ASTM testing at Carlton University (NRC, 2012). Both sets of laboratory testing were performed on CLT panels from the same manufacturer and material sources as the CLT samples used in the test wall of this project.

Using the pre-existing 3-ply cross laminated panel material properties provided in WUFI as a base, the recommendations from Lepage (2012) were as follows:

- Calibrate the moisture storage function (MSF) to the sample density and set the saturated and reference moisture content values equal to those provided in the sorption isotherm. This step is only necessary because WUFI defines the MSF based on water content in kg/m^3 instead of as a percentage of the total mass.
- Set water absorption coefficient, A-value, to the values found through laboratory water uptake tests. Allow WUFI to automatically generate the liquid diffusivity for suction (DWS) based on this value.
- Set the liquid diffusivity for redistribution (DWW) at 70% MC to 100 m^2/s and calibrate the slope at a value at 10 kg/m^3 lower than the value at 70% MC. The value of 1e-4, as found by Lepage (2012), was used.
- Set the saturated liquid diffusivity for redistribution to 2e-10 m^2/s at 30% MC

The rationale for the modifications to the liquid diffusivity for redistribution by Lepage (2012) is as follows in Table 5.1.

Table 5.1 Justification for Liquid Diffusivity for Redistribution for the European Spruce Panels (Lepage, 2012)

Normalized Water Content	Liquid Diffusivity, Redistribution (m^2/s)	Justification
0	0	-
0.09	7.6e-12	Same value as the liquid diffusivity for suction
0.3	2e-10	Krus and Vik (1999)
0.68	1e-4	The high diffusivity of 100 m^2/s in the saturated regime lead to simulations demonstrating increased penetration of water into the sample during wetting due to rapid redistribution which was not supported by the moisture content measurements made. By trial and error it was found that the rate of change of the liquid diffusivity had a bigger influence on the overall rate of mass loss, not the maximum value of diffusivity. Near saturated water contents, the boards swell to such a point that the cracks between them were closed shut. After a short period of drying, however, the cracks re-emerged. This results in a noticeable increase in surface area- approximately 70%. However, the effective surface area would be much less than that, due to constriction of air flow and degree of swelling of the boards. To represent the shrinkage of the boards, the arbitrary corrective value was selected at 10kg/m^3 less than saturated (corresponding to 68% MC for the European spruce panel used in laboratory testing) and, through trial and error, a liquid diffusivity of 1E-4 m^2/s was found to provide generally good agreement in terms of water content density as well as transient moisture profile.
0.70 to 1	100	Krus and Vik (1999)

The modifications were made for each of the five types of CLT panel, using their corresponding densities as measured for the panels used in the field test experiment before wetting commenced, when the panels were in equilibrium with their environment around 10% MC. This value is the same as has been used by Lepage for WUFI calibration, and likely used in the original WUFI 3-ply cross laminated panel due to the changes in hygrothermal properties of wood caused by completely drying a sample to determine its dry mass. The resulting material properties are outlined in Tables 5.2 to 5.5.

Table 5.2 Moisture Storage Functions

Relative Humidity (%)	Equilibrium Moisture Content (kg/m^3)				
	A: European Spruce	B: Black Spruce	C: Western SPF	D: Hem-fir	E: Eastern SPF
0	0	0	0	0	0
10	34.9	43.7	39.7	41.5	37.7
30	42.4	53.2	48.3	50.5	45.9
50	49.9	62.6	56.8	59.4	54.0
70	60.3	75.6	68.6	71.8	65.3
80	68.8	86.3	78.3	81.9	74.4
90	83.9	105.2	95.5	99.8	90.8
93	92.4	115.8	105.1	109.9	99.9
95	100.8	126.4	114.8	120.0	109.1
99	149.8	187.9	170.5	178.3	162.1
99.5	174.3	218.6	198.4	207.5	188.6
99.9	236.5	296.6	269.2	281.5	255.9
99.95	264.8	332.0	301.4	315.1	286.5
99.99	327.0	410.0	372.2	389.1	353.8
100	503.3	630.9	572.8	598.8	544.5

Table 5.3 Liquid Transport Coefficients, Suction, DWS

A: European Spruce		B: Black Spruce		C: Western SPF		D: Hem-fir		E: Eastern SPF	
WC (kg/m^3)	DWS (m^2/s)	WC (kg/m^3)	DWS (m^2/s)	WC (kg/m^3)	DWS (m^2/s)	WC (kg/m^3)	DWS (m^2/s)	WC (kg/m^3)	DWS (m^2/s)
0	0	0	0	0	0	0	0	0	0
68.8	5.60E-12	86.3	3.50E-12	78.3	4.30E-12	81.9	3.90E-12	74.4	8.20E-13
503.3	2.20E-09	630.9	1.30E-09	572.8	1.70E-09	598.8	1.50E-09	544.5	3.20E-10

Table 5.4 Liquid Transport Coefficients, Redistribution, DWW

A: European Spruce		B: Black Spruce		C: Western SPF		D: Hem-fir		E: Eastern SPF	
WC (kg/m^3)	DWW (m^2/s)	WC (kg/m^3)	DWW (m^2/s)	WC (kg/m^3)	DWW (m^2/s)	WC (kg/m^3)	DWW (m^2/s)	WC (kg/m^3)	DWW (m^2/s)
0	0	0	0	0	0	0	0	0	0
68.8	5.6E-12	86.3	3.5E-12	78.3	4.3E-12	81.9	3.9E-12	74.4	8.2E-13
128.4	2.0E-10	160.9	2.0E-10	146.1	2.0E-10	152.7	2.0E-10	138.9	2.0E-10
289.5	1.0E-04	365.5	1.0E-04	330.9	1.0E-04	346.4	1.0E-04	314.1	1.0E-04
299.5	100	375.5	100	340.9	100	356.4	100	324.1	100

The A-values determined in laboratory testing (Lepage, 2012) of the European, western SPF, and hem-fir panels ranged between 0.010 and 0.014 $kg/m^2.s^{1/2}$. An average A value of 0.012 $kg/m^2.s^{1/2}$ was applied to all these panels, as well as the black spruce panels which were not tested but are in the same species genus as the European spruce panels, in order to simplify the material properties for future use. The eastern SPF panels had a significantly lower average A value of 0.005 $kg/m^2.s^{1/2}$. The A values found by Lepage by testing approximately 600mm x 600mm, full thickness panels are around a magnitude higher than the values found by the NRC (2012) ranging between 0.0017 and 0.0025 $kg/m^2.s^{1/2}$ for panels from the same sources. The NRC values were found by testing smaller, 100mm x 50mm samples, cut to 25mm thick in such a way to include a glue layer, which likely resulted in the wetting surface being freshly sawn, unlike the typically exposed surface of full size panels. The smaller test specimens likely reduced or eliminated the effects of checking, and the cracks between lumber elements within a layer, which would increase the amount of water uptake in the full scale panel. For reference, Figure 5.1, taken from Lepage (2012), shows the results of mass change during wetting and drying of a European spruce panel (Er1). The laboratory measurements taking during water uptake testing are compared to simulations using the pre-existing 3-ply cross laminated panel material properties provided in WUFI with a low A value (3-ply CLT Baseline), and the results when the material properties are corrected for density and the measured, higher, A value (3-ply Corrected). The increase in A value has the greatest impact on wetting of the panel, as the WUFI models of the test wall showed little difference between the use of the larger and smaller A values during drying.

Table 5.5 Average Panel Densities, A-values, Reference Water Contents (at 80% RH), and Free Water Saturations

Panel Type	Average Density (kg/m^3)	A-value ($kg/m^2.s^{1/2}$)	Reference Water Content (WC) (kg/m^3)	Free Water Saturation (kg/m^3)
A: European Spruce	428	0.012	68.8	503.3
B: Black Spruce	536	0.012	86.3	630.9
C: Western SPF	487	0.012	78.3	572.8
D: Hem-fir	509	0.012	81.9	598.8
E: Eastern SPF	463	0.005	74.4	544.5

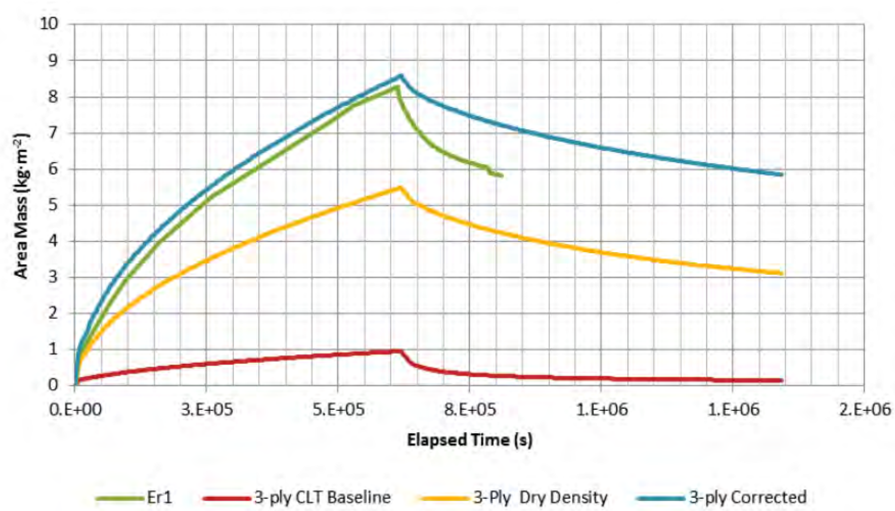


Figure 5.1 (Lepage, 2012) Comparison of mass change during wetting and drying in laboratory water uptake test (Er1) to WUFI simulation of pre-existing CLT model (3-ply CLT Baseline) to model corrected for density and A value (3-ply Corrected)

The vapour diffusion resistance factor is the value used in WUFI defining the multiplier required to attain a depth of air which has the same vapour diffusion resistance as material in question. Assuming values taken at 5°C and an air pressure of 101.3kPa, the conversion of permeability to water vapour diffusion resistance factor, μ, is as follows where permeability, Δ, is expressed in ng/m.s.Pa:

$\mu = 187.6/\Delta$ (3)

The initial value for μ in WUFI for 3-ply cross laminated panels, which was also used by Lepage (2012), is 203, translating to a permeability of 0.92 ng/m.s.Pa. However, it is possible to input a moisture dependant water vapour diffusion resistance factor profile with respect to relative humidity, which accounts for the higher permeability of wood at higher RH levels. Therefore, the profile based on the average values found in wet and dry cup water vapour permeability testing completed by the NRC (2012) was used, shown in Table 5.6, and is the same for all wood species. While at higher water contents the use of the humidity dependant water vapour diffusion resistance factor compared to the constant value produced little change in drying behaviour, indicating the dominance of liquid diffusion, some improvements were made in the agreement of the model for low moisture contents. For comparison, Figures 5.1 and 5.2 show the results of WUFI simulations for panel A2, with the high permeance wall assembly, with a constant μ of 203, and the moisture dependant values, respectively.

Table 5.6 Moisture Dependant Water Vapour Diffusion Resistance Factor

Relative Humidity (%)	μ (dimensionless)
0	1876*
25	469
35	208
45	187
75	46.9
85	28.8
95	18.76

* extrapolated from data

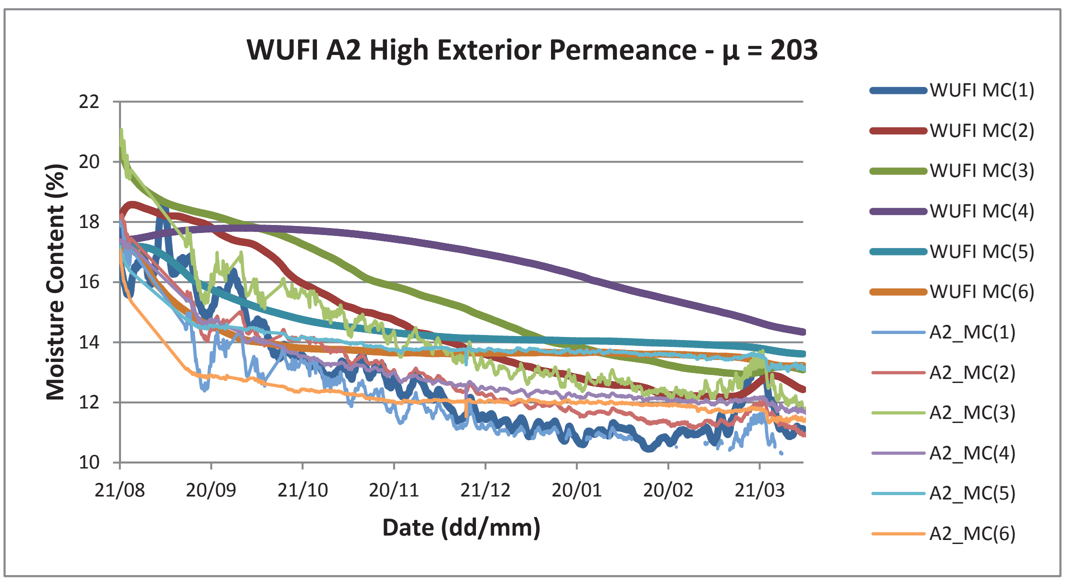


Figure 5.2 Panel A2 Simulation results with constant μ = 203

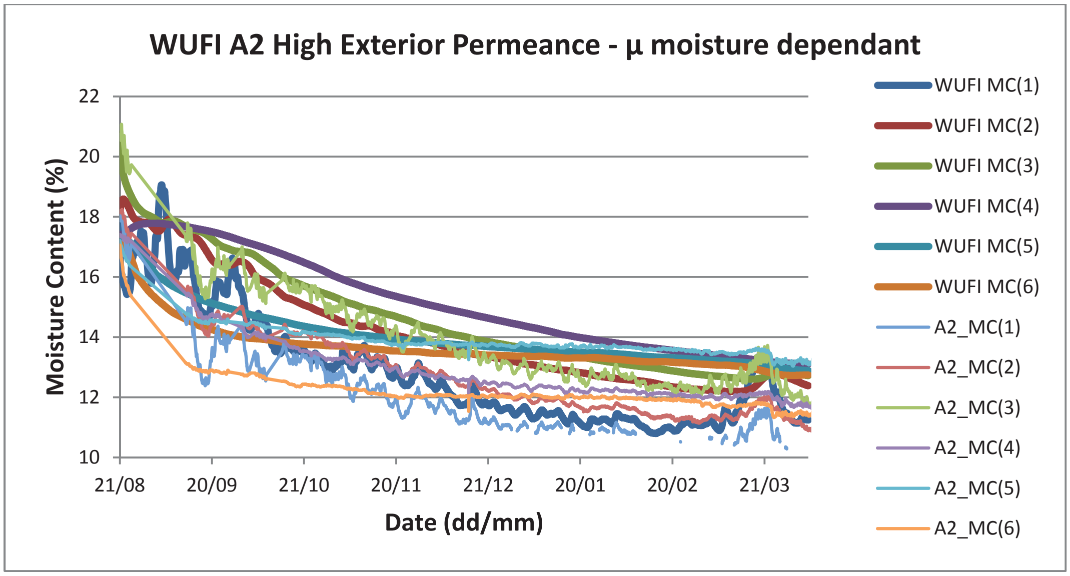


Figure 5.3 Panel A2 Simulation results with moisture dependant µ

5.2 Panel Initial Moisture Content

The initial panel moisture content profiles were set to match the initial values collected when data acquisition commenced. In order to facilitate extraction of data allowing the moisture content of the panel at each exact sensor location to be found, the simulation file divided the CLT panel into multiple layers, with 1mm wide slices present at the sensor locations. After some trial and error, in order to prevent the moisture contents in these slices from rising or falling sharply initially, rather than linearly extrapolating the moisture content between pin locations, the measured MC was applied for the entire section of panel between the face of the panel, the mid points of the pin locations, and extended 6mm into the centre of the panel. The initial moisture content profile for B1 is provided in Figure 5.3 as an example. While likely not an exact replicate of the complete moisture content profile, this method provided better results than if the moisture content slope changed suddenly at each pin location.

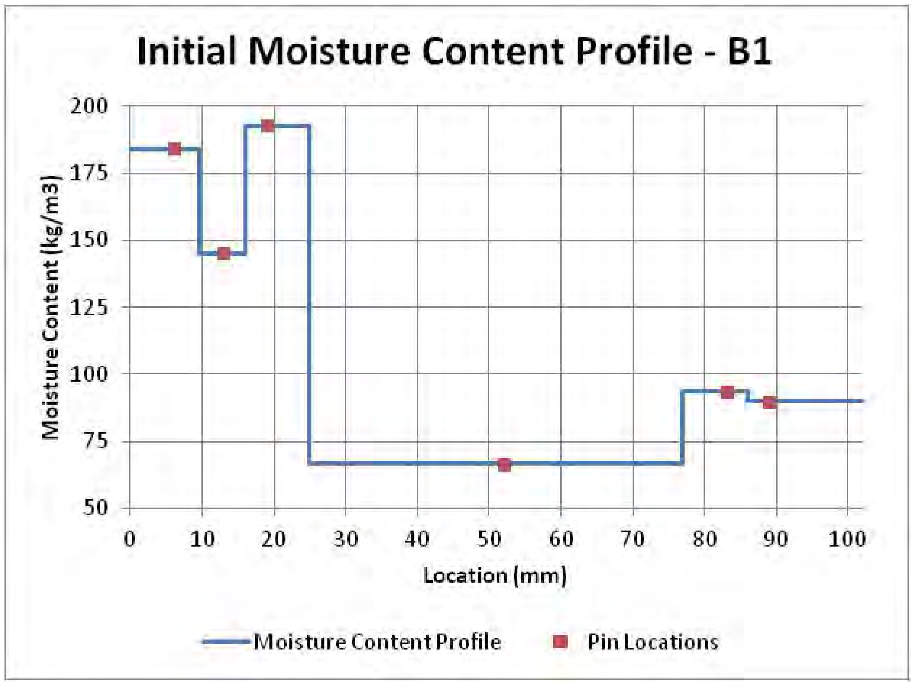


Figure 5.4 Initial Moisture Content Profile - B1

5.3 Climate Conditions

The interior climate conditions in WUFI were set to a constant 20°C and 50% relative humidity reflecting the conditions in the test hut. A custom weather file was created for the exterior climate. The hourly values for temperature, relative humidity, global solar radiation, rainfall, wind speed, and wind direction where measured locally with the pre-existing test hut instrumentation. When gaps were present due to instrumentation error, they were filled with the average temperature and relative humidities measured in the exterior air cavities of the test wall since the air cavity is well-ventilated. Further data gaps as well as the necessary data for rainfall, solar radiation, and wind speed and direction, were filled with values provided by the Ontario Climate Centre, measured at a station in Waterloo, Ontario.

5.4 Wall Assemblies

The properties of the insulation and WRBs within the wall assembly were set to match the properties specified by the manufacturers, in Appendix A. Other materials were set as to the WUFI properties in the North American database. The wall assemblies were modelled including the exterior ventilated cavity and cement fibreboard cladding, and the ventilation rate in the cavity was set to 200 air changes per hour to simulate a well vented cavity, as was constructed.

5.5 Simulation results

The simulation results for moisture content at each pin location over time are presented along with the measured data. The WUFI results appear as the darker, thicker lines, and the measure data appear as the thinner lines in a colour a few shades lighter.

5.5.1 High Exterior Permeance

The simulation results for the High exterior permeance panels are in generally good agreement with the field data. The WUFI results are usually no more than 2 or 3% MC different than the pin measurements, and when different, tend to overestimate the moisture content. The two notable deviations are the overestimate of up to 5% of the moisture content in the centre of panel A2 and the lack of reactivity of the moisture pins deeper into the exterior face to the exterior RH changes. The overestimate of the moisture content in the centre of the panel may be associated with a deviation in the initial moisture content profile compared to the real panel. Since the difference causes an overestimate of the moisture content, which is already at a low level, it is not a major point of concern. The second point at which the simulation differs considerably to the field measurements is the lack of response of the simulation model at 13 and 19mm in from the exterior face to the exterior RH changes compared to the measured data. The simulation reacts with a similar magnitude, and at the same time as the field data at the location 6mm in from the exterior face, marked with the dark blue line. However at 13 and 19mm deep, the red and green lines respectively, the reaction to the external RH change in the simulation is muted and delayed, almost indistinguishable at 19mm deep. However in the field data, these pins react with almost equal magnitude, and at the same time as the pins at 6mm deep. Again, as this difference is relatively inconsequential at these low moisture contents, the difference is not a major point of concern.

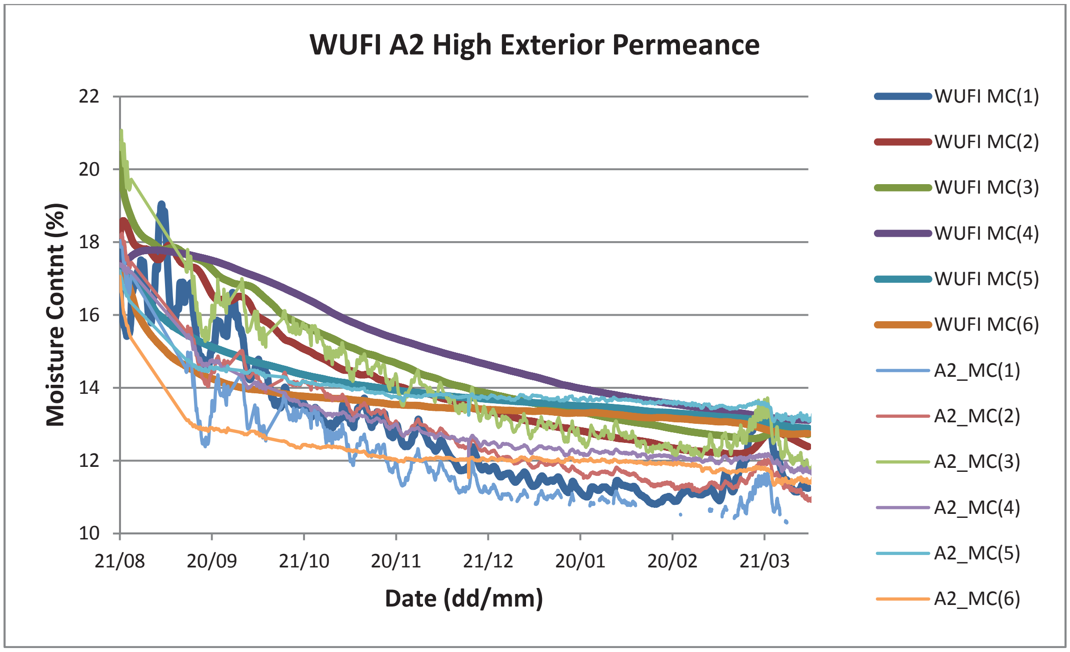


Figure 5.5 WUFI A2 High Exterior Permeance

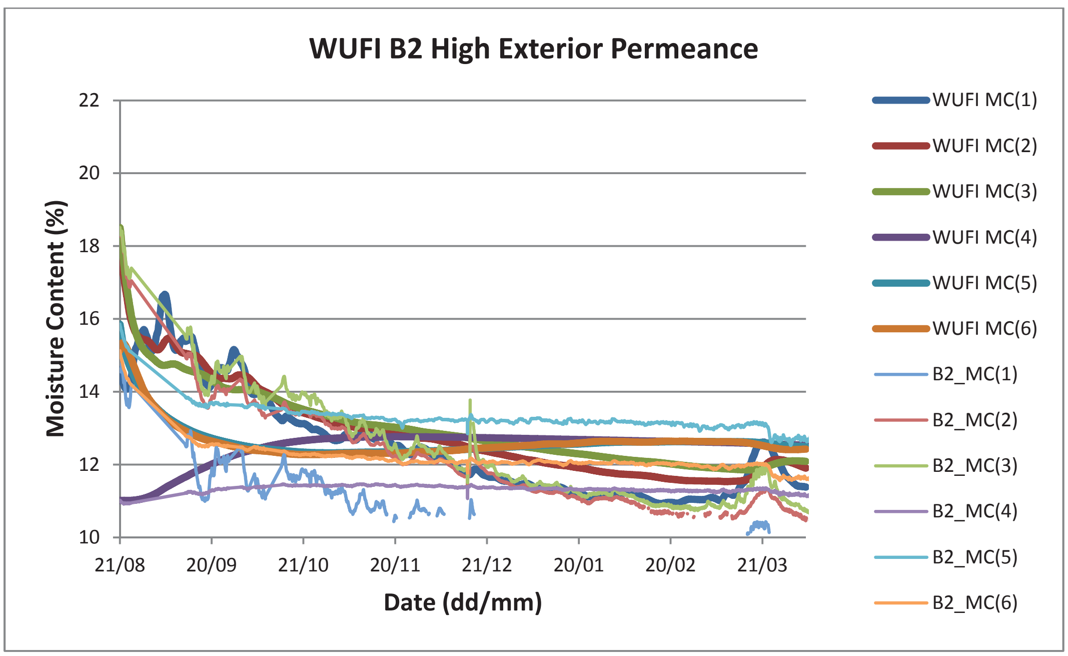


Figure 5.6 WUFI B2 High Exterior Permeance

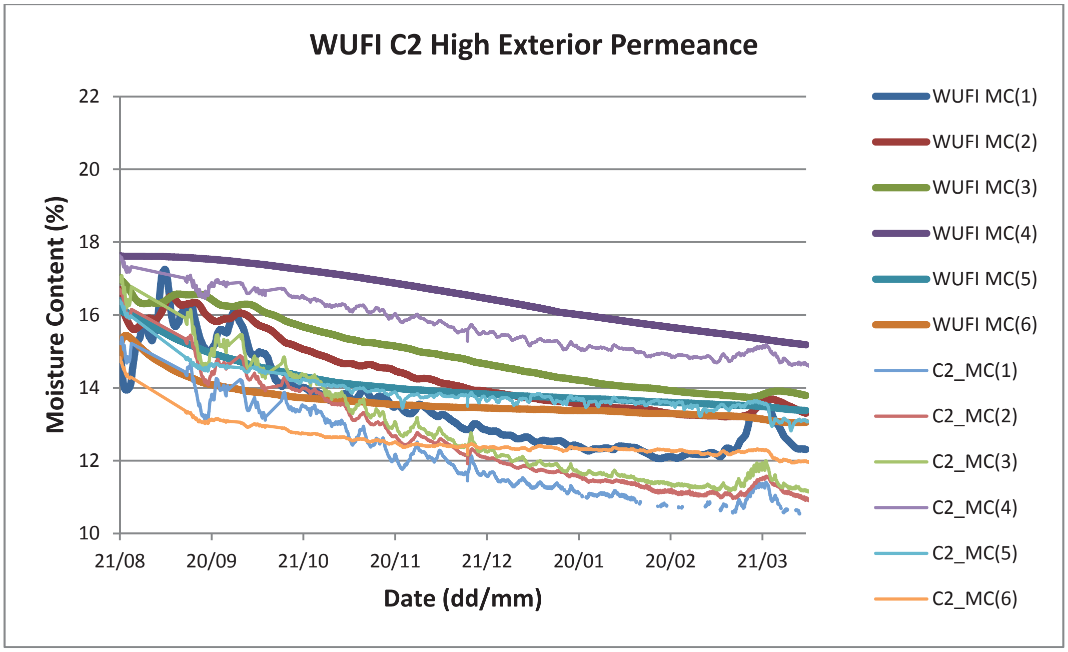


Figure 5.7 WUFI C2 High Exterior Permeance

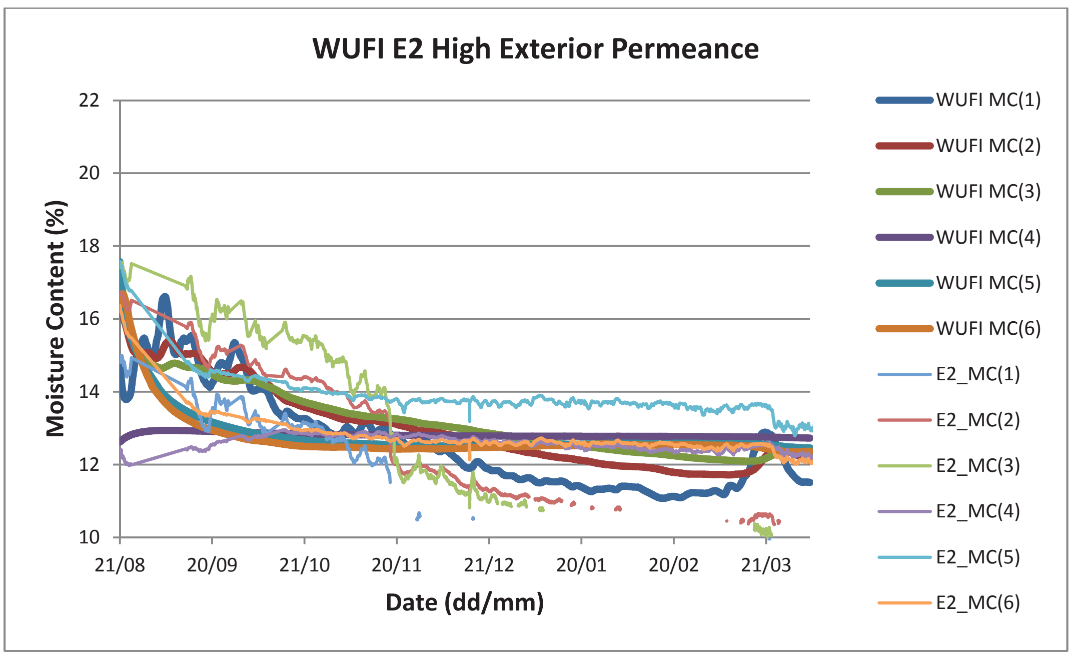


Figure 5.8 WUFI E2 High Exterior Permeance

5.5.2 Medium Exterior Permeance

The simulation results for the medium exterior permeance panels are similarly in good agreement with the field data. In panels A3 and B3, the simulation results are lower than the measured data, but not by more than 2% MC, and at a low moisture content where decay is not an issue. The underestimate of the moisture content at the exterior face of panel C3 however is significant, at around 7% moisture content.

However, this difference in drying behaviour further supports the hypothesis that there may be an extraneous moisture source near the exterior face of panel C3.

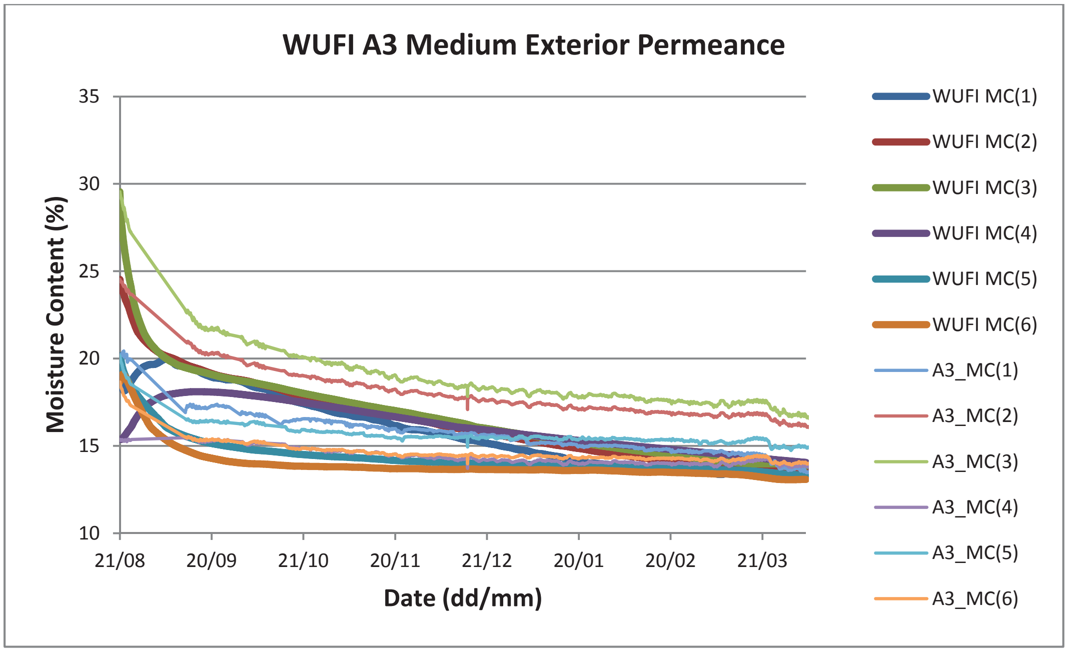


Figure 5.9 WUFI A3 Medium Exterior Permeance

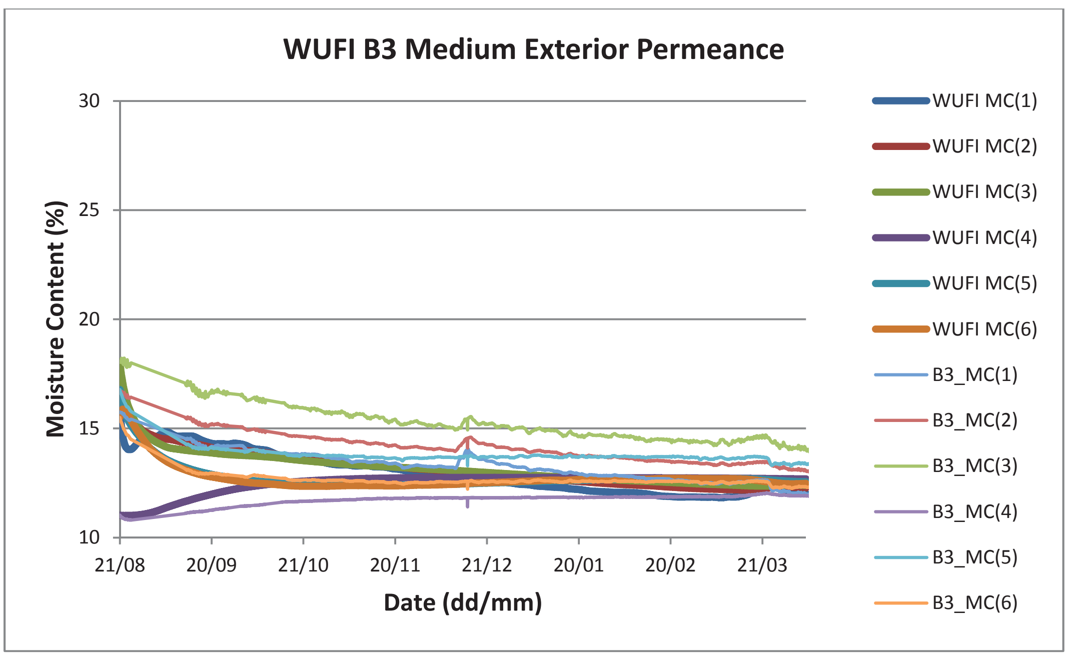


Figure 5.10 WUFI B3 Medium Exterior Permeance

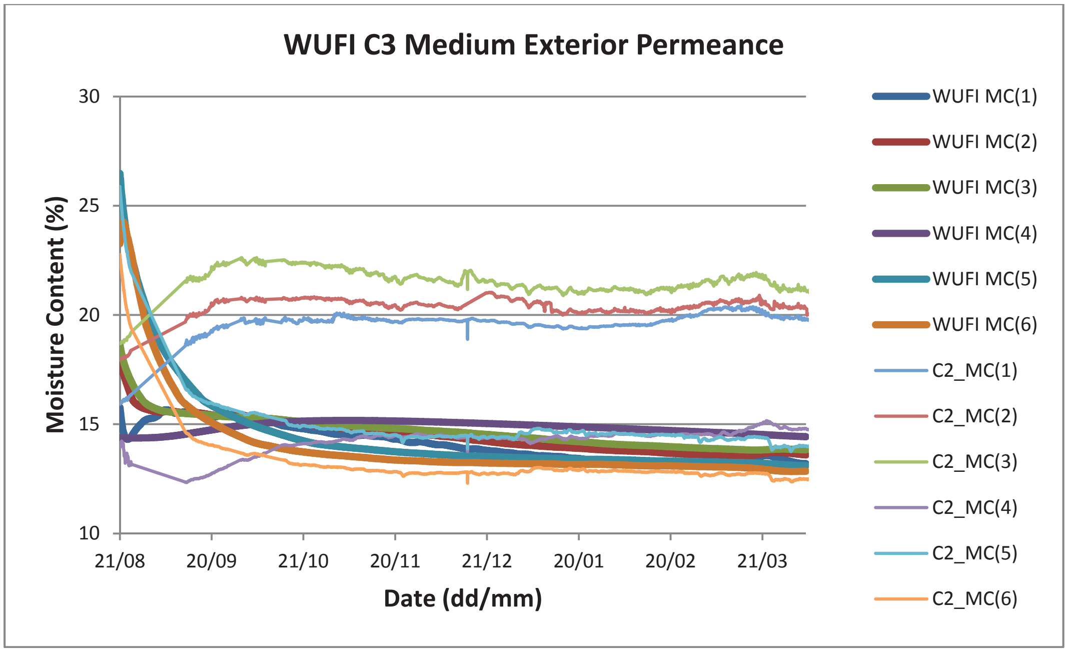


Figure 5.11 WUFI C3 Medium Exterior Permeance

5.5.3 Low Exterior Permeance

In the simulations of the low exterior permeance panels, WUFI predicts the moisture content at the interior freely drying face very well. In two of the panels, A1 and B1, WUFI predicts that the centre of the panel will raise by 5 to 8% moisture, which is not reflected in the measure data, and also predicts a slower initial drying rate at the locations with extremely high moisture content at the exterior face. While this underestimate of drying is conservative, it may be caused by an inaccurate estimation of initial moisture contents at the exterior face inputted into the simulation as the moisture pins become considerably less accurate over 30% MC. The rate of drying appears to be similar after the third month at the interior face.

In panel C1, WUFI over predicts drying at the exterior face, predicting a MC of around 21% when the field measurements indicate levels close to 25%. Furthermore, the field measurements show little drying after three months, and combined with a similar phenomena in panel C3, this may indicate that the material properties of western SPF require further investigation at higher moisture contents.

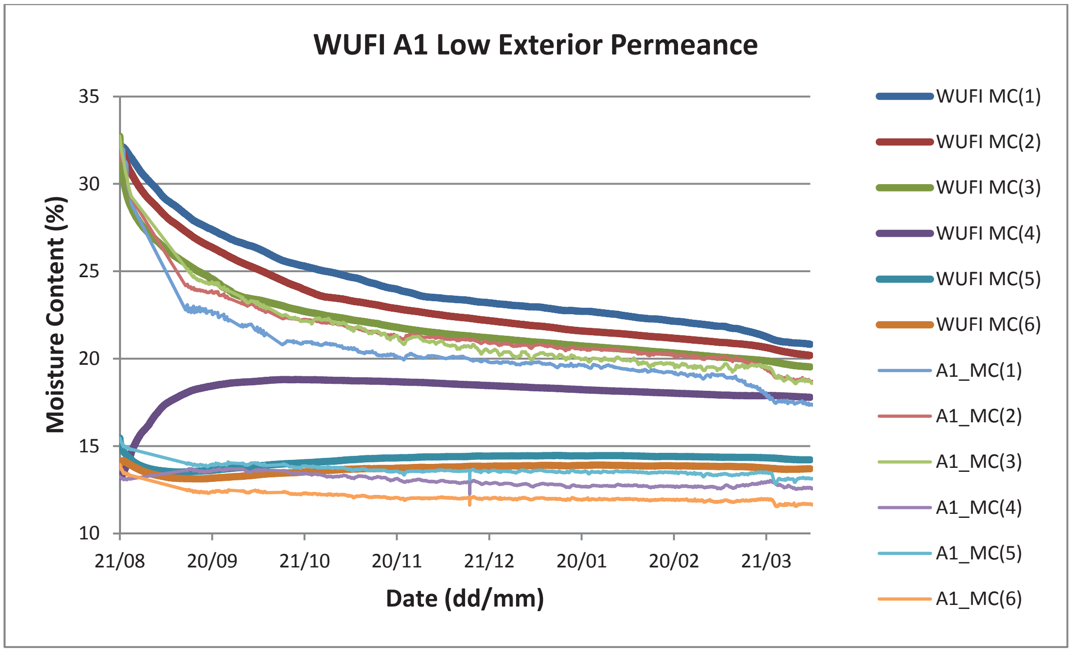


Figure 5.12 WUFI A1 Low Exterior Permeance

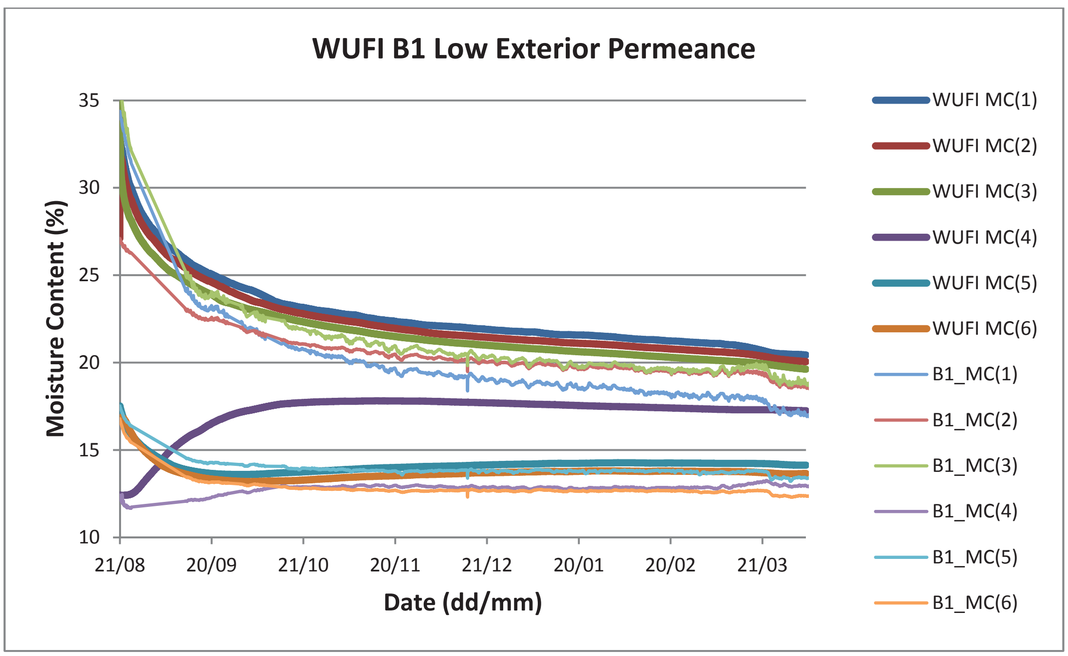


Figure 5.13 WUFI B1 Low Exterior Permeance

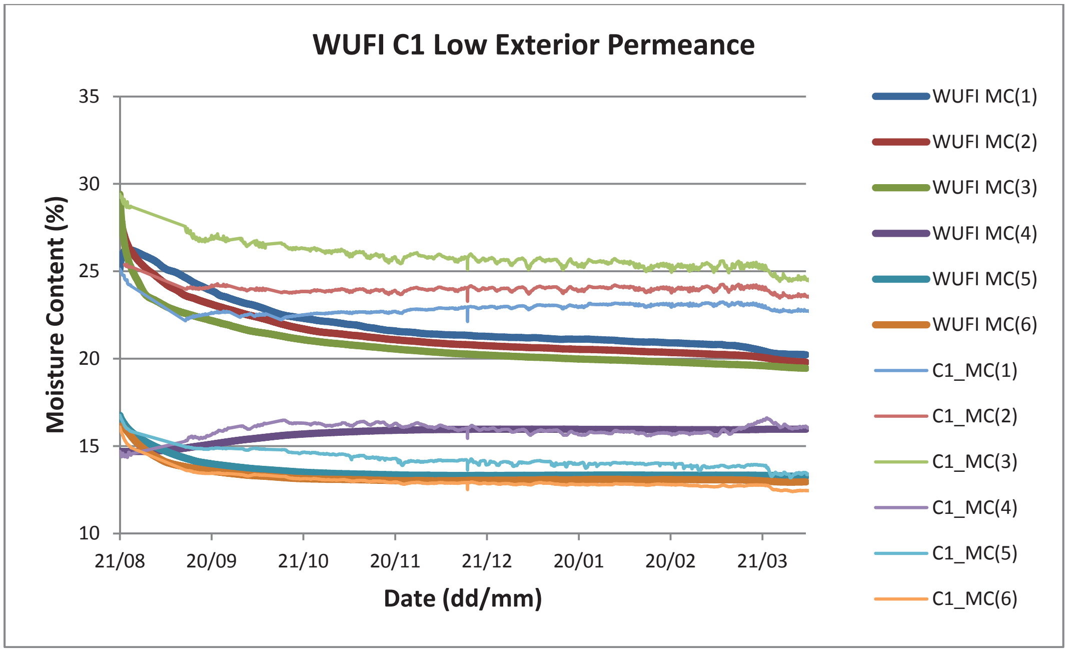


Figure 5.14 WUFI C1 Low Exterior Permeance

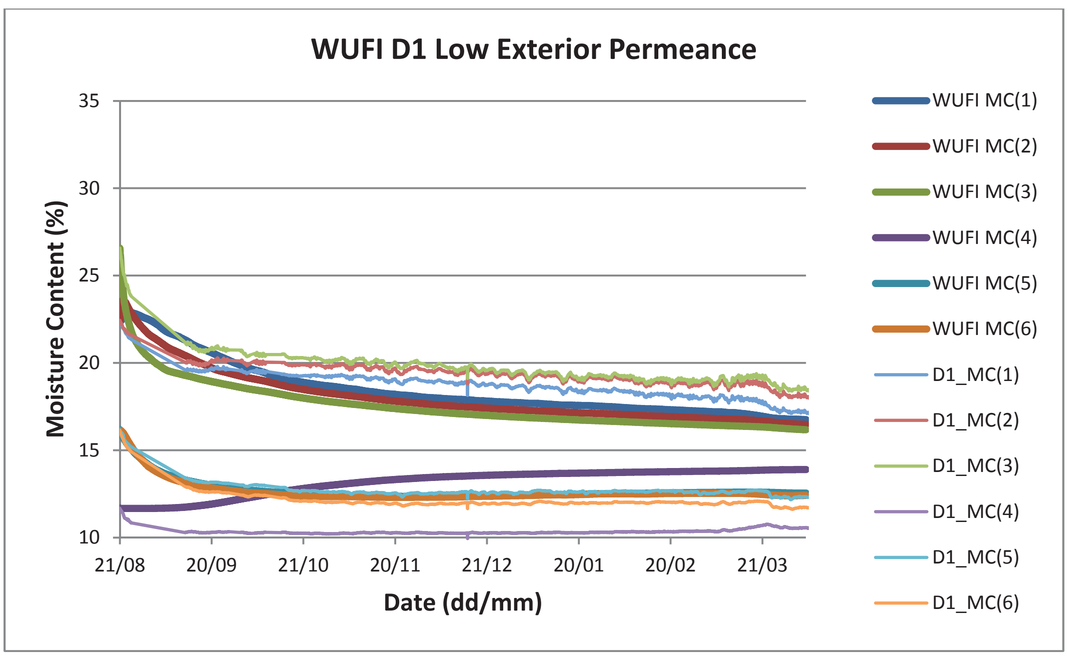


Figure 5.15 WUFI D1 Low Exterior Permeance

5.5.4 Low Interior Permeance

The correlation of the WUFI simulation results to the field data is poorest in the panels with low interior permeance and medium exterior permeance. These are also the panels with the highest initial moisture contents. Panel B4 has the best results, with WUFI overestimating drying by less than 2% MC at the interior and exterior face, and predicting a moisture content in the centre of about 3% MC higher than the field measurements. For this low interior permeance panel configuration, the moisture content sensor in the centre of the panels is plotted in green, and a MC sensor is present 6mm in from the interior face instead of the exterior face. In panel E4, WUFI over predicts the MC by up to 5% MC in the centre and at the exterior face. In panels A4 and C4, WUFI over predicts the moisture content in the centre of the panel by 10% MC and at the exterior face by up to 5% MC. In all three of the these panels, this difference causes the centre of the panel to appear to be the location with the highest moisture content, and to have a moisture content around 26% after six months. At the interior faces of B4, C4 and E4, adjacent to the low permeance membrane, WUFI predicts a lower MC than the field measurements. The difference is relatively small for panels B4 and E4 at less than 2% MC, but in panel C4, the 5% MC difference cause the panel to appear to dry below 26% MC at the face in just over two months instead of four months.

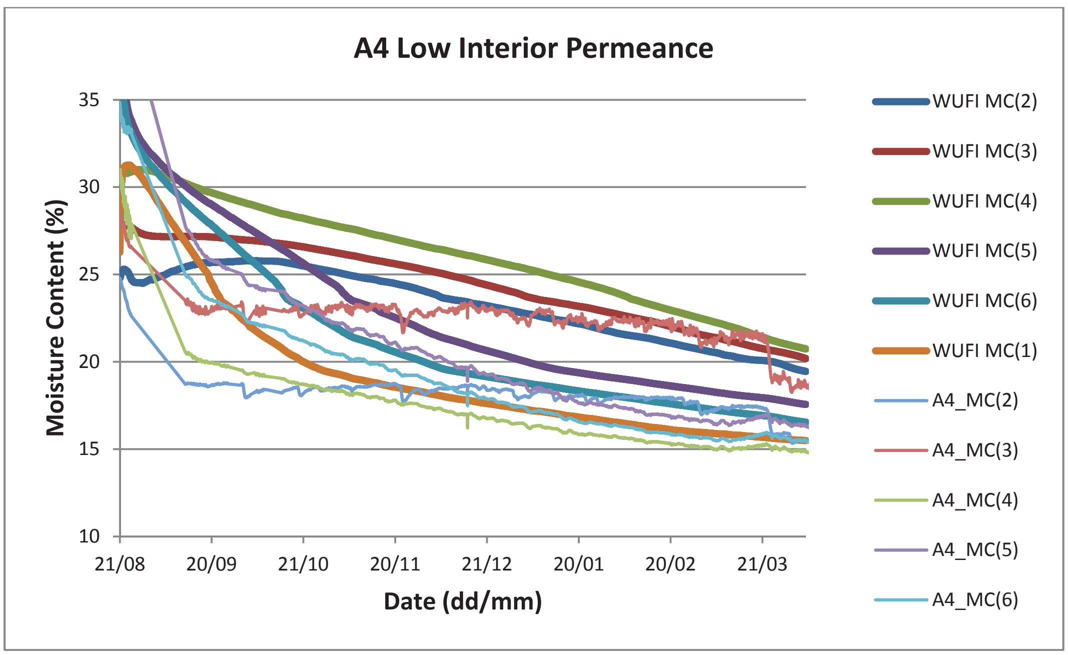


Figure 5.16 WUFI A4 Low Interior Permeance

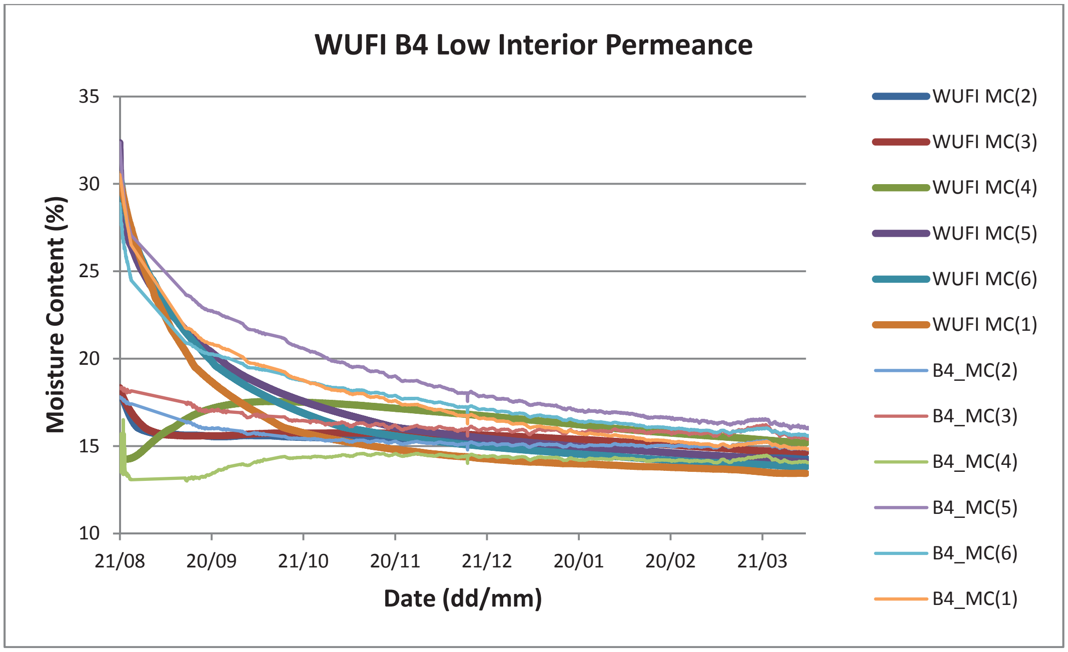


Figure 5.17 WUFI B4 Low Interior Permeance

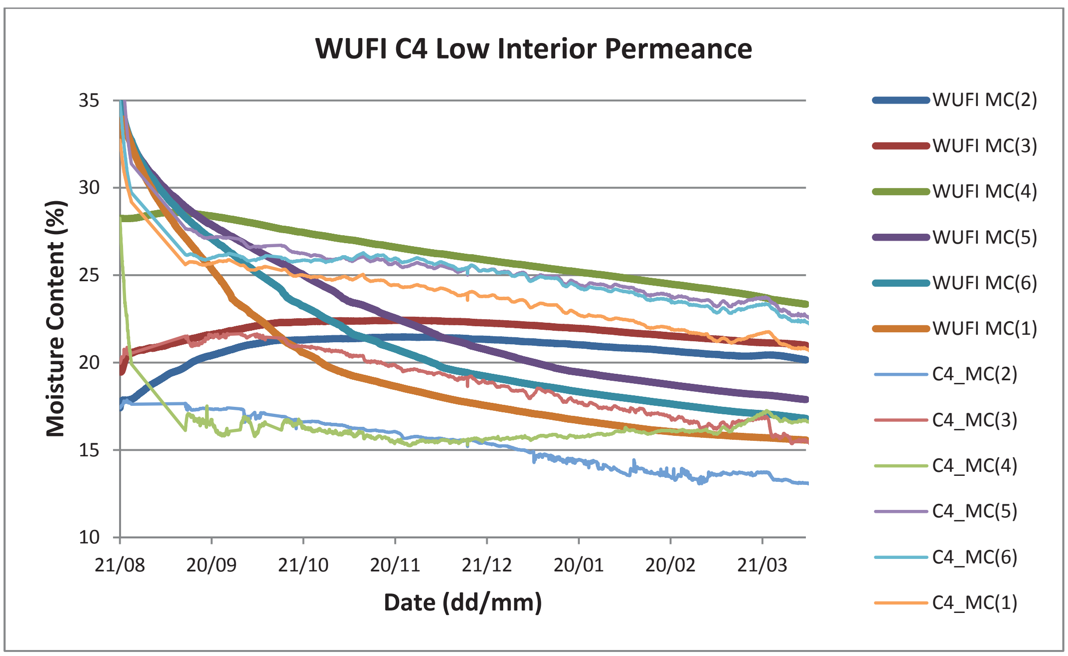


Figure 5.18 WUFI C4 Low Interior Permeance

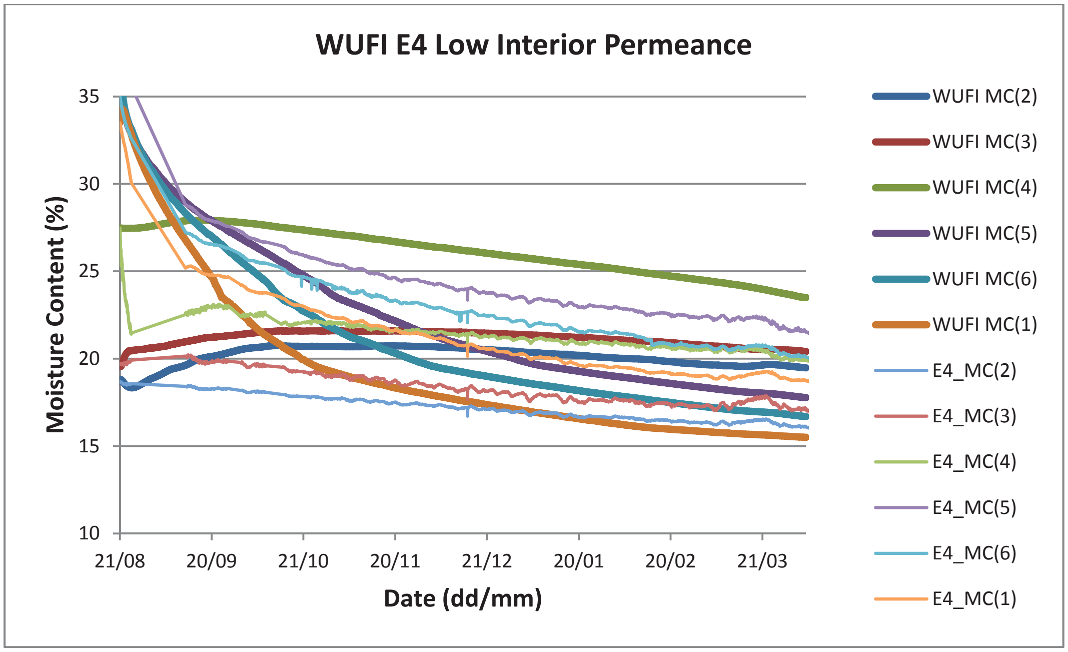


Figure 5.19 WUFI E4 Low Interior Permeance

5.6 Simulation Trends

Overall, general trends can be modelled in WUFI. While accuracy is not high, WUFI can typically indicate, within 5%MC, the moisture range which may be found at a particular location within a panel. The model is useful to help determine if a wall assembly will be safe in a given climate, though is more likely to cause a user to believe that a wall assembly requires more time rather than less time to dry than field measurements show.

The current WUFI model does not model more subtle behaviour captured in field measurements such as the high reactivity of the wood at greater depths to the external relative humidity. The model also indicates greater levels of moisture uptake in the centre of the panels during drying than seen in the field data.

5.7 WUFI Simulations with climate variation

WUFI simulations were performed to help evaluate the magnitude of the effect caused by the difference in climate between Toronto, or southern Ontario, and Vancouver. The estimated drying times as a result of the simulations are also summarized. The western SPF panels were simulated with the same parameters used for modelling the test wall assemblies aside from different weather files, and a more extreme initial moisture state. The initial moisture contents were set at 30%MC at the faces of the panels, up to 25mm deep, and 15% MC in the centre of the panels. The customised weather file reflecting the actual conditions experienced by the test wall in Waterloo was replaced with the cold year climate data provided in WUFI, for Vancouver or for Toronto. The interior conditions were not changed from the 21°C and 50% RH environment found inside the test hut facility. The simulation period was a two years, beginning in November. The results are plotted at the sensor locations in the centre of the panels, and at the pins closest to the interior and exterior faces of the panels.

For the high exterior permeance panel the moisture contents at the central, and at the inner moisture pin are virtually unchanged, seen in Figure 5.20. At the outer pin, where the wood is more responsive to changes in the exterior environment, the variation in moisture content is larger, though the range in which the moisture contents is found is very similar. In the winter months, there is no significant difference between the climates in the drying stage, with the Vancouver simulation showing moisture contents less than 1% higher than in Toronto. After drying to below 15%MC the difference increases to around 1%MC, but has no significant effect on the moisture durability of the CLT panels. In late summer the moisture content at the exterior face peaks in response to changes in the exterior conditions, at different times in each climate, but the magnitude of the peaks are similar, the increase in moisture content is not sustained, and the panels are not at risk for decay.

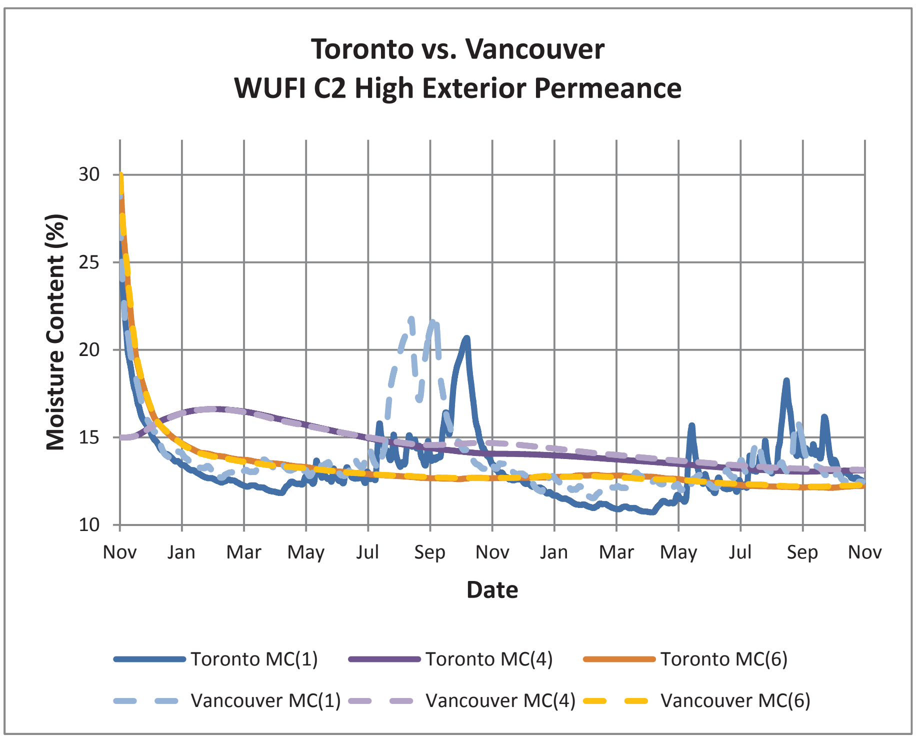


Figure 5.20 Toronto vs. Vancouver Weather WUFI C2 High Exterior Permeance

For the medium exterior permeance, low exterior permeance, and low interior permeance panels, the results at the central and inner moisture content pin is again virtually unchanged between the Toronto and Vancouver climates, see in Figures 5.21 to 5.23 respectively. For the medium exterior and low interior with medium exterior permeance panels, the moisture contents in the outer pins tend to be slightly higher in the Vancouver simulations over the spring and summer, but are typically only up to 1% MC higher than the Toronto simulations.

For the low exterior permeance panel, the moisture content at the outer pin for Vancouver tends to be slightly lower than Toronto, indicating the warmer Vancouver climate in spring may slightly accelerate drying although the difference is again less than 1% MC.

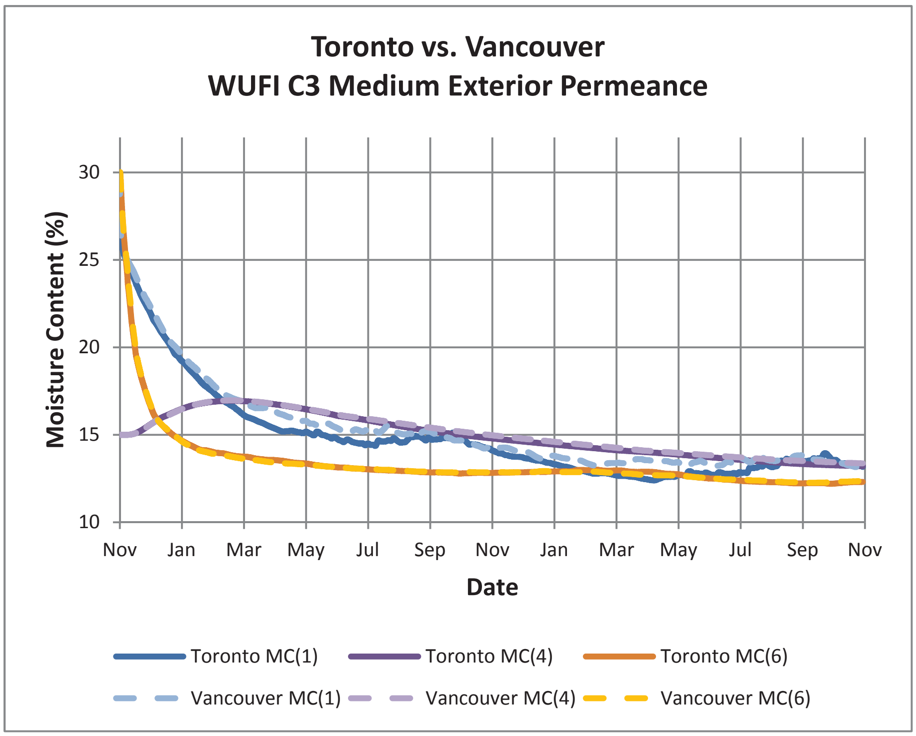


Figure 5.21 Toronto vs. Vancouver Weather WUFI C3 Medium Exterior Permeance

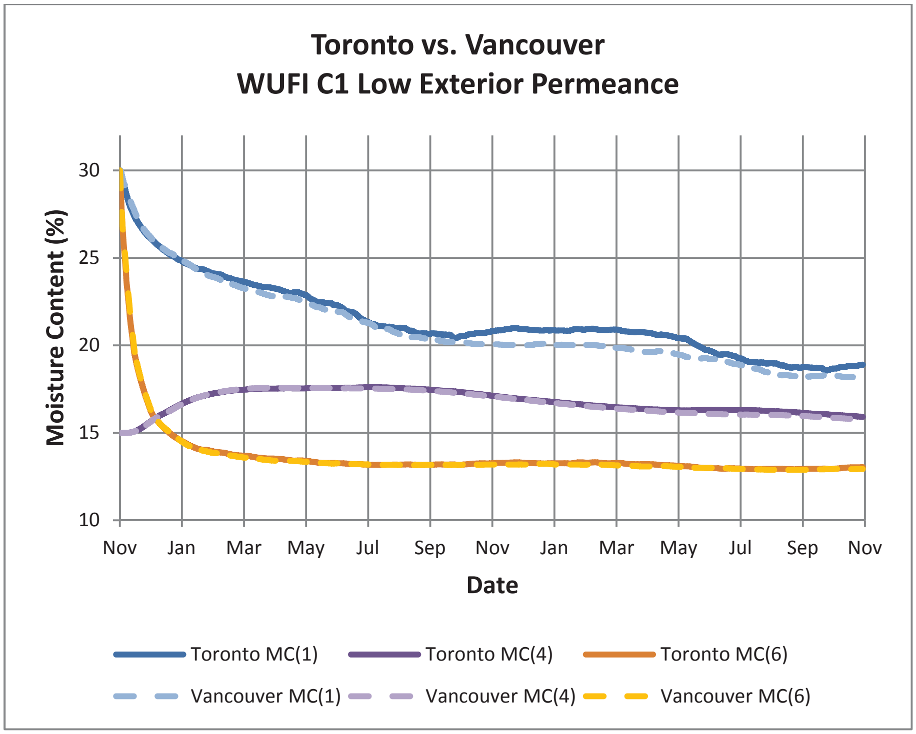


Figure 5.22 Toronto vs. Vancouver Weather WUFI C1 Low Exterior Permeance

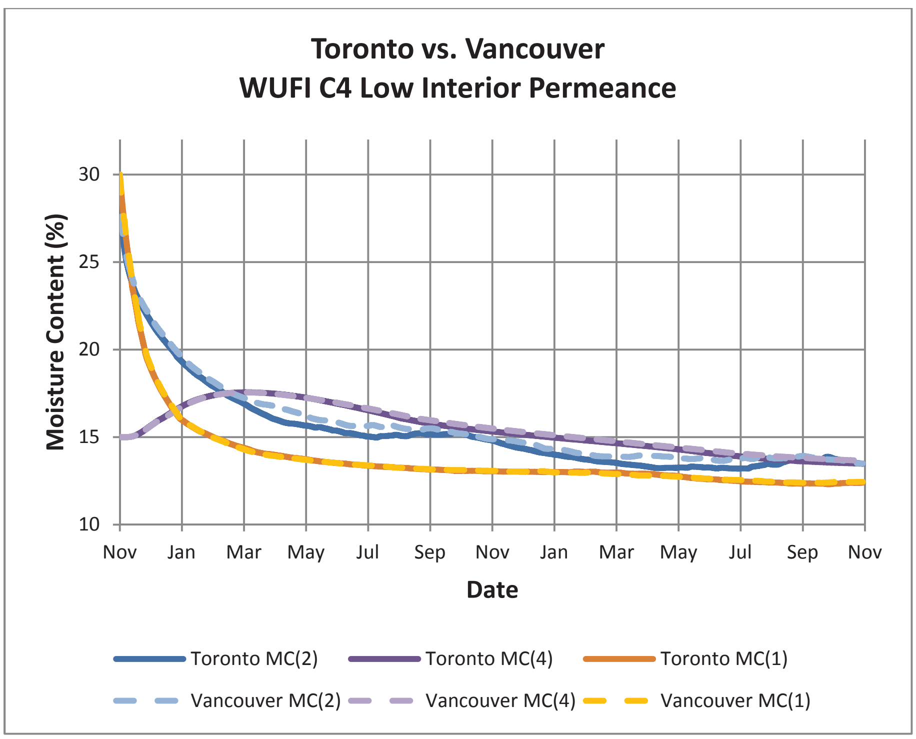


Figure 5.23 Toronto vs. Vancouver Weather WUFI C4 Low Interior Permeance

Table 5.7 presents a summary of the time required for each face of each panel to dry below 26% MC, and below 20% MC. The variation in drying time between climates usually occurs on the order of several days. The notable exception is for panel C1, at the exterior face with low exterior permeance, The time until the panel has dries below 20% MC in Vancouver is 15.3 months, while an additional 3.3 months are required in Toronto. Drying is likely slower in Toronto because the lower outside temperatures increase the overall vapour pressure drive towards the exterior, slowing drying towards the interior when the low permeance exterior membrane is present. Referring to Figure 5.22, it is apparent that this delay is caused by a considerable decline in drying rate during the second winter of the simulation, where the Toronto panel hovers around 21% MC , and the Vancouver panel hovers around 20% MC. In both climates, the low exterior permeance panels spend an extended time above 20% MC, which indicates these panels are most likely to be at risk of decay initiation. However, such and extended drying time was not found in the results of the field test, which underlines the need for a more refined WUFI model at high moisture contents.

The panels with medium exterior permeance take as much as 2 months to dry, though there is little apparent difference caused by the presence of the interior polyethylene sheet on the drying behaviour of the exterior face. While this time period is below the six months period expected to be necessary for decay to initiate, it is still an indication that it is important to protect panels from excessive wetting on construction site.

Table 5.7 Drying time results for WUFI simulated Toronto and Vancouver climates

Panel	Face	Toronto		Vancouver	
		Time until <26% MC	Time until <20% MC	Time until <26% MC	Time until <20% MC
C1	Interior, free drying	3.6 days	1.9 weeks	3.7 days	2 weeks
	Exterior, low permeance	1.1 months	18.6 months	1.1 months	15.3 months
C2	Interior, free drying	4.6 days	2.1 weeks	5.2 days	2.2 weeks
	Exterior, high permeance	1.3 days	1.1 weeks	1.4 days	1.4 weeks
C3	Interior, free drying	4.5 days	2.1 weeks	5.2 days	2.2 weeks
	Exterior, medium permeance	1.8 days	1.7 months	1.9 days	1.8 months
C4	Interior, low permeance	1 week	3.5 weeks	1.1 weeks	3.6 weeks
	Exterior, medium permeance	4 days	1.7 months	4 days	1.8 months

Overall, the difference in drying behaviour caused by the variation in climate between Toronto and Vancouver is extremely small. Aside from the low exterior permeance panel, when drying stagnates during the second winter in both climates, just above and just below 20%MC, there is no significant impact on the time required for wetted panels to dry, and differences are primarily evident where high permeance wall assemblies allow the panels to more directly experience the variation in exterior relative humidity, when the panel has already dried and is at equilibrium with its environment.

Chapter 6 - Conclusions

The field study has provided an opportunity to determine the behaviour of wetted cross-laminated timber panels within a variety of wall assemblies, and to verify the behaviour of the hygrothermal models in these extreme cases.

The most important summary conclusions are:

- Elevated moisture contents which allow for future decay are not likely to be developed due to typical environmental exposure to moisture on a construction site.
- Low permeance materials such as polyethylene sheeting and other non-vapour permeable water resistive barriers cause lower drying potential, and are unnecessary for good wall assembly design. However, the field data shows these panels dried in sufficient time to prevent decay initiation.
- For panel locations above 15% moisture content, drying can slow during the winter, then pick-up again in summer.
- Further development of the hygrothermal model together with refined material properties are required to more accurately model wood.

One of the first insights to come out of this study came during construction, when it was observed that the unprotected, wetted panels dried very quickly under typical southern Ontario summer conditions. While for this field test, this behaviour made it difficult to capture the initial drying phase, it does indicate that during a typical construction project, where efforts are made to protect wood on construction sites, the highest possible initial moisture content at the time of enclosure of the CLT panels due to accidental moisture exposure can be low enough to reduce potential durability problems under normal operating conditions. However, more work is required to determine the extent to which on-site exposure can cause excessive moisture accumulation under a variety of climates, and with different wood species, exposure times, and CLT manufacturing methods. Overall, it seems unlikely that if reasonable measures are taken to protect cross laminated timber panels from wetting, construction moisture alone is not likely to be a cause of long term moisture durability issues.

In terms of suitable wall assemblies, the use of high permeance envelope materials can effectively promote drying of CLT panels.

The medium permeance wall configurations are sufficiently vapour permeable to prevent moisture durability issues under normal circumstances with initially dry panels, though further investigation may be needed to determine the cause of the moisture content increase in Panel C3.

Low permeance materials, especially to the exterior, are to be used with more caution, not only because they prolonged the time period required for wetted panels to dry to a safe level in some cases, but also because the lack of steep rise in the moisture content in the centre of the panel, further indicates that the CLT panel itself is a good vapour retarder. Therefore any additional vapour barrier is unnecessary in a CLT assembly. While in the test wall, both the interior and exterior low permeance wall panels dried sufficiently quickly to prevent decay initiation, the low permeance material may have a more deleterious effect if an incidental moisture source is present, enabling a rise of local moisture content over time.

Finally, the wood species does not appear to have a significant effect on the drying rate of the CLT panels, though it appears as though the plantation grown European spruce panels tend to reach slightly higher moisture contents when exposed to ongoing moisture sources.

6.1 Further WUFI Calibration

The WUFI model used appears to correlate sufficiently well with the field measurements at moisture contents below 25% to predict general trends in the moisture content of the CLT panels. This is the range at which the cross laminated timer is expected to be found when performing well. Further refinement of the model is required to more accurately predict hygrothermal behaviour at moisture contents where there is a serious risk of decay.

Above 25% moisture content WUFI both overestimates and underestimates the moisture content of the panels. Due to the extended period of time required for decay to initiate, this inaccuracy does not lead the user to believe that any panels which have field measurements at risk for decay are not at risk after 6 months. However, as the effect of wetting at the end grain of the CLT panels was not included in this field study, and moisture uptake and penetration is likely to be higher if the edges are wetted, refinement of the hygrothermal model, or usage of an two dimensional modelling program may be required to model these situations.

Further investigation may also be made into the cause of the tendency to predict less drying or even wetting in the centre of the panels which the field data does not indicate, as well as the low reactivity to external relative humidity. These anomalies may be resolved with a different set of material properties in the existing hygrothermal model, or with the use of an alternate hygrothermal model for wood.

References

Calkins, M., 2009. *Materials for Sustainable Sites*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Forest Products Laboratory (FPL). 2010. Wood Handbook - Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S.

FPL., 2010. *Wood Handbook, Wood as an Engineering Material, Centennial Edition.* Madison: Forest Products Laborator

Gagnon S., Pirvu C., 2011. *CLT Handbook: Cross-Laminated Timber*. Quebec: FPInnovations.

Garrahan P., 1988. Moisture Meter Correction Factors. In: USDA Forest Products Laboratory, *Proceedings of a seminar on In-grade Testing of Structural Lumber*. Madison, WI, USA 25-26 April 1988. Vancouver:Forintek.

Goto Y., Ghazi Wakili K., Ostermeyer Y., Frank Th., Ando N., Wallbaum H., 2011. Preliminary Investigation of a Vapor-open Envelope Tailored for Subtropical Climate. *Building and Environment*, 46, pp.719-728.

Haglund M. 2001. Moisture Content penetration in wood elements under varying boundary conditions. *Wood Science and Technology*, 41, pp.477-490.

Håkansson, H. 1998. Retarded sorption in wood, Ph.d thesis (Report TABK-98/1012), Department of Building Science, Lund Institute of Technology, Lund University.

Hameury S., 2004. Moisture buffering capacity of heavy timber structures directly exposed to an indoor climate: a numerical study. *Building and Environment*, 40, pp.1400-1412.

Kalamees T., Vinha J., 2003. Hygrothermal calculations and laboratory tests on timber-framed structures. *Building and Environment*, 38, pp.689-697.

Karacabeyli E., Desjardins R., 2011. Cross Laminated Timber (CLT) in the Context of Wood Building Systems. Presentation at the CLT Symposium. February 8. Vancouver

Krabbenhoft K., 2003. Moisture Transport in Wood A Study of Physical-Mathematical Models and their Numerical Implementation, Ph.d thesis, Department of Civil Engineering, Technical University of Denmark.

Krus M., Vik T. A., 1999. Determination of Hygric Material Properties and Calculation of the Moisture Balance of Wooden Prisms. *Proceedings of the 5th Symposium Building Physics in the Nordic Countries*, p. 313-320.

Künzel H. M., 1995. *Simultaneous Heat and Moisture Transport in Building Components. One- and two-dimensional calculation using simple parameters.* Stuttgart, Germany: IRB Verlag.

Lepage R.T.M., 2012. Moisture Response of Wall Assemblies of Cross-Laminated Timber Construction in Cold Canadian Climates, Master's thesis, Department of Civil Engineering, University of Waterloo

Lstiburek J. W., 2007. The Perfect Wall. *ASHRAE Journal*, 13, pp.74-78.

McClung R., Straube J., Ge H., Wang J., 2012. Field Study of Hygrothermal Performance of Cross-laminated Timber Wall Assemblies with Built-in Moisture, *Proceedings of the 5th International Building Physics Conference*. Kyoto, Japan, pp. 362-368.

McFarling A.M., Byrne A., Morris P.I., 2006. Characterizing the permeability of beetle-killed wood. *Proceedings Cdn. Wood Preservation Assoc. 27*.

National Research Council (NRC), 2012. Characterization of hygrothermal properties of CLT. Report to FPInnovations. Ottawa, ON, Canada.

Peuhkuri R., 2003. Moisture Dynamics in Building Envelopes, Ph.d thesis, Department of Civil Engineering, Technical University of Denmark.

Straube J., Onysko D., Schumacher C., 2002. Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures. *Journal of Thermal Environment and Building Science*, 26(2), pp.123-151.

Wadsö L., 1994. Describing non-Fickian water-vapour sorption in wood. Journal of Materials Science, 29, pp.2367-2372.

Wang J., Mukhopadhyaya P., Morris P. I., 2012. Sorption and capillary condensation in wood and the moisture content of red pine. *Journal of Building Physics*, published online 2 August 2012, 0(0), pp.1-21

Wang, J., Clark, J., Symons, P., Morris, P., 2010. Time to Initiation of Decay in Plywood, OSB, and Solid Wood Under Critical Moisture Conditions. *International Conference on Building Envelope Systems and Technology.* Vancouver: ICBEST.

Wang, J., 2012. Field Monitoring of Vertical Movement in Wood Platform Frame Buildings. Presentation at the British Columbia Building Research Committee meeting. May 23rd. Vancouver.

Appendix A - Wall Material Properties

BlueSkin VP Material Properties

TECHNICAL DATA SHEET

BlueskinVP™ 100

Self-Adhered Water Resistive Air Barrier Membrane

Physical Properties

-Color	Blue	**-Flame Spread Index** ASTM E 84	5, Class A
-Weight Basis / Thickness TAPPI T-410	100 g/m²	**-Smoke Developed** ASTM E 84	125, Class A
-Water Vapour Transmission ASTM E96/B (Desiccant) WVT WVP	234 g/m² / 24 hours 33 Perms 1914 ng/Pa.m²·s	**-Air Permeance** ASTM E 2178 (Maximum 0.02 l/m² @ 75Pa or 0.004 cfm/ft² @ 1.57pcf)	Pass
-Average Dry Breaking Force ASTM D 5034	55 / 245N MD 48 / 214N CD	**-Acceptance Criteria for Water Resistive Barriers** ICC – ES AC38	Pass
-Accelerated Aging ICC-ES AC48 25 cycles	Pass	**-Low Temp Flexibility** ICC – ES AC38/3.3.4	Pass
-Cycling and Elongation ICC-ES AC48 100 cycles at -20°F (-29°C)	Pass	**-Peel-adhesion to Unprimed Plywood** ICC-ES AC48	Pass
-Application Temperature	Minimum 40°F (5°C)	Control baseline After 7 day water immersion	62 lbf/ft – 905N/m 54 lbf/ft – 786N/m
-Service Temperature Range	-40°F to +158°F (-40°C to +70°C)	After accelerated aging After UV exposure	72 lbf/ft – 1049N/m 77 lbf/ft – 1125N/m
		-Water Penetration Resistance around Nails AAMA 711-05 & modified ASTM D 1970	Pass

Compliance Standards

ICC AC38	**CGSB** 51.32	**AAMA** 711-05

Packaging

-Roll Length	100 ft (30.48 m)	-Roll Width/color/sku	**60"** (1.52 m) Blue HE100GUSA991 **12"** (300mm) Blue HE100GUSA987 **9"** (225mm) Blue HE100GUSA984 **6"** (150mm) Blue HE100GUSA995 **4"** (100mm) Blue HE100GUSA994

Description

BlueskinVP™100 is residential and multi-family self-adhered vapor permeable, water resistive air barrier membrane consisting of an engineered film and patented, permeable adhesive technology with split-back poly-release film. **BlueskinVP™100** is fully adhered to the wall substrate in a 'weatherboard' method without mechanical attachment. Covered by US patent 6,901,712, Canadian patent 2,413,550.

Features

-Combines benefits of residential water resistive barrier with commercial air barrier
-Meets industry standards for water resistive barrier and commercial air barrier
-Sheds water while allowing vapor to pass through – allowing walls to drain and substrates to dry
-Creates a continuous plane of air-tightness – improving building thermal performance
-Fully adhered to substrates, eliminating water migration
-Easy to apply with common hand tools

Henry Company, 909 N. Sepulveda, Ste. 650 El Segundo CA 90245
Tel: 800-486-1278 **Email:** techservices@henry.com
www.henry.com

REV: 08/18/2011

Uses

In residential and multi-family applications, **BlueskinVP™100** creates a water resistive barrier and air barrier when applied outside of the wall sheathing and behind the exterior wall cladding. Used for transitions, rough openings, fenestration and full-wall applications.

Storage

Store rolls on end, on original pallets or elevated platform. Protect from weather or store in an enclosed area not subject to heat over 120°F (49°C). In cold weather, it is recommended to warm rolls to 50°F (18°C) or above prior to application to assure adhesion to substrate.

Limitations

Membrane must be rolled after application to ensure adhesion to substrate and laps. Not designed for permanent exposure, protect installed membrane as soon as possible. Maximum exposure not to exceed 90 days. See Guide Specifications for further limitations. Excessive moisture in substrate or laps can inhibit adhesion. Do not expose the backside of the substrate to moisture or rain. Protect exposed back-up walls against wet weather conditions during and after application of membrane, including wall openings and construction activity above completed air barrier installation.

Surface Preparation

Acceptable substrates are plywood, OSB, wood, exterior-grade gypsum sheathing board such as DensGlass®, precast or cast-in-place concrete, concrete block, steel, aluminum and galvanized metal. All surfaces to receive **BlueskinVP™100** must be dry and clean of oil, dust, frost, bulk water and other contaminates that would be detrimental to adhesion of membrane. Strike masonry joints full-flush. Concrete surfaces must be smooth and without large voids, spalled areas or sharp protrusions. Concrete must be cured a minimum of 14 days. Curing compounds and release agents used in concrete construction must be resin based without oil or wax.

Approved adhesive-primers include **Blueskin Adhesive** or **Blueskin LVC Adhesive**. Aerosol **Blueskin Spray-Prep** is <u>not approved</u> with this product.

Conditions not typically requiring adhesive-primers:

- Application above 40°F (5°C) to clean & dry wood and sheathing boards such as: plywood and OSB. Ensure substrate and membrane temperatures are above 40°F (5°C)

Conditions requiring use of adhesive-primers:

- Metal, DensGlass® products, exterior grade gypsum board, Concrete, CMU and other masonry substrates

Note: if appropriate adhesion is not obtained due to conditions beyond the control of the installer, the adhesion can be aided by continuous application of adhesive-primer to the substrate and laps as per published BlueskinVP™ Installation Guidelines. Ensure all primed surfaces are covered in the same day.

Application

Refer to BlueskinVP™100 Guide Specification for detailed application information, see www.henry.com website. BlueskinVP™100 must be installed in a consecutive weatherboard method starting at bottom or base of wall and working up; providing minimum of 2" (5cm) side laps and 3" (7.6cm) end laps. Cut to manageable lengths, position membrane for alignment, remove protective poly-film and firmly apply pressure to assure adhesion. Eliminate all fishmouths, wrinkles or gaps, roll entire membrane surface (including seams) with a counter top or "J-roller" with adequate pressure [+5lbs] to ensure full contact and adhesion. Seal membrane terminations, heads of mechanical fasteners, masonry tie fasteners, around penetrations, duct work, electrical and other apparatus extending through the BlueskinVP™100 water resistive air barrier membrane and around the perimeter edge of membrane terminations at window and door frames with HE925 BES Sealant.

Cover rough openings and transitions with BlueskinVP™100 per Henry® details. Fenestration (window and doors) must be flashed per window/door manufacturers' recommendation, local building code requirements, ASTM 2112 and AAMA guidelines. Use pre-cut rolls of Blueskin® SA or SALT for sill pan flashings per Henry® published window flashing guidelines. For application of Blueskin SA or SALT over BlueskinVP™, the surface of BlueskinVP™ must be primed.

Insulation clips and brick-ties should be mechanically fastened through the membrane into solid backing and sealed with **Henry® HE925 BES Sealant**.

Limited Warranty

Product Warranty:
We, the manufacturer, warranty only that this product is free of defects, since many factors which affect the results obtained from this product - such as weather, workmanship, equipment utilized and prior condition of the substrate - are all beyond our control. We will replace at no charge any product proved to be defective within 12 months of purchase, provided it has been applied in accordance with our written directions for uses we recommended as suitable for this product. Proof of purchase must be provided. DISCLAIMER OF WARRANTIES: The Limited Warranty is IN LIEU OF any other warranties express or implied including but not limited to any implied warranty of MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, and we, the manufacturer, shall have no further liability of any kind including liability for consequential or incidental damages resulting from any defects or any delays caused by replacement or otherwise.

Assembly Warranty:
Assembly warranties are available for job specific applications when applied per Henry published systems guidelines found on www.henry.com or www.bakor.com. For application for extended warranties up to 10 years contact Henry Warranty Administration Department at Warranty@henry.com

STATEMENT OF RESPONSIBILITY

The technical and application information herein is based on the present state of our best scientific and practical knowledge. As the information herein is of a general nature, no assumption can be made as to a product's suitability for a particular use or application and no warranty as to its accuracy, reliability or completeness either expressed or implied is given other than those required by law. The user is responsible for checking the suitability of products for their intended use. Henry Company data sheets are updated on a regular basis; it is the user's responsibility to obtain and to confirm the most recent version. Information contained in this data sheet may change without notice.

BlueSkin SA Properties

TECHNICAL DATA SHEET

Blueskin® SA

Self-Adhesive Air/Vapour Barrier Membrane

Physical Properties

-Colour	Blue	-Low Temperature Flexibility @ -30°C (CGSB 37-GP-56M)	Pass
-Thickness	1.0 mm (40 mils)	-Water Vapour Transmission (ASTM E96)	1.6 ng/Pa.s.m^2 (0.03 perms)
-Application Temp	Minimum + 5°C	-Lap Peel Strength @ 4°C (ASTM D903 180° bend)	1750 N/m width
-Service Temp	Minus 40°C to 70°C	-Moisture absorption (ASTM D570-81)	0.1%
-Elongation (ASTM D412-modified)	200% minimum	-Air Leakage @ 75 Pa (ASTM E283-91)	0.003 L/s.m^2
-Tensile Strength (Membrane) (ASTM D412- modified)	3.4 MPa minimum	-Air Leakage After 3000 Pa Test (ASTM E330-90)	No change
-Tensile Strength (Film) (ASTM D882)	40 MPa minimum		
-Minimum Puncture Resistance – Membrane (ASTM E154)	178 N		
-Watertightness (CAN/CGSB-37.58-M86)	Pass		

Packaging

-Thickness	1.0 mm (40 mils)	-Gross Coverages	
-Roll length	22.86 m (75 ft.)	914 mm (36")	20.9 m^2 (225 ft^2)
-Roll width	914 mm (36"), 457 mm (18") 300 mm (12"), 225 mm (9") 150 mm (6"), 100 mm (4")	457 mm (18")	10.5 m^2 (112.5 ft^2)
		-Net Coverages*	
		914 mm (36")	19.7 m^2 (212 ft^2)
-Top Surface	Blue Cross-Laminated Polyethylene	457 mm (18")	9.3 m^2 (100 ft^2)
-Bottom Surface	Siliconized Release Film	*Based on 50 mm (2") laps both sides and end.	

Description

Blueskin® SA is a self-adhering membrane consisting of an SBS rubberized asphalt compound which is integrally laminated to a blue cross-laminated polyethylene film. **Blueskin® SA** is specifically designed to be self-adhered to a prepared substrate, providing an air/vapour/water barrier.

Features

- SBS modified membrane, flexible at low temperatures
- Impermeable to air, moisture vapour and water
- No flame required
- Thickness controlled at point of manufacture
- Excellent adhesion to prepared substrates of concrete, concrete block, primed steel, aluminum mill finish, anodized aluminum, galvanized metal, gypsum board and plywood
- Excellent compatibility with most Bakor adhesives and liquid air barrier membranes
- Self-sealing when penetrated with self-tapping screws

Storage

Store rolls on end, on original pallets or elevated platform. Protect from weather or store in an enclosed area not subject to heat over 49°C.

Henry Company Canada, 15 Wallsend Ave., Scarborough, ON M1E 3X6 **Tel:** 800-387-9598 **Fax:** 866-483-9266
www.bakor.com

Limitations

Not designed for permanent exposure. Good practice calls for covering as soon as possible. Not to be used in direct contact with flexible PVC/vinyl membranes or gaskets. Some sealants may discolor if in contact with the asphalt compound or may soften the asphalt compound. Contact sealant manufacturer for more information.

Uses

Blueskin® SA is designed for use as a self-adhered sheet air and vapour barrier. Its principal application is on walls of either masonry, concrete or gypsum board. It can also be used as a transition sheet in conjunction with **Bakor Liquid Membranes** where greater movement is anticipated, due to its high strength. **Blueskin® SA** is also used for tying into metal on curtain walls, windows and door frames.

Preparation

Acceptable substrates are precast concrete, cast-in place concrete, concrete block, primed steel, aluminum mill finish, anodized aluminum, galvanized metal, gypsum board including DensGlass Gold®.

All surfaces to receive **Blueskin® SA** must be clean of oil, dust and excess mortar. Strike masonry joints flush. Concrete surfaces must be smooth and without large voids, spalled areas or sharp protrusions. Concrete must be cured a minimum of 14 days and must be dry before **Blueskin® SA** is applied. Where curing compounds are used they must be clear resin based, without oil, wax or pigments. For best adhesion on Oriented Strand Board (OSB), install **Blueskin® SA** on smooth of OSB panel.

All surfaces to receive **Blueskin® SA** must be primed with **Blueskin® Primer**, applied by lambs wool roller, brush or spray equipment at the rate of 1 litre per 2-6 m^2 depending on porosity and texture of surface and allowed to dry for 30 minutes before **Blueskin® SA** is applied. Ensure that all primed surfaces receive **Blueskin® SA** in the same day. Alternatively, prime with **Aquatac™**. Allow to dry to a tacky film.

Application

Refer to **Blueskin® SA** Guide Specification for detailed application information. Material should be conditioned at room temperature for ease of application.

Blueskin® SA must be lapped a minimum of 50 mm on both sides and end laps. Position **Blueskin® SA** for alignment, remove protective film and press firmly in place. When **Blueskin® SA** is entirely in place, roll membrane including seams with a counter top roller to ensure full contact. When using **Blueskin® SA** with brick ties, position **Blueskin® SA**, press in place and cut for ties or projections. Seal around any openings and at leading edge at the end of the days work with **Air-Bloc 21, Air-Bloc 21 FR, Bakor 230-21, or POLYBITUME® 570-05**. **Blueskin® SA** applied to the underside of the substrate (i.e. ceilings) requires mechanical fastening through wood or galvanized metal strapping or have insulation mechanically fastened. Fastening must take place immediately after installation of **Blueskin® SA**. Space strapping on 450 mm centres, running perpendicular to the side laps.

Detail work must be carefully carried out to ensure continuous air tightness of **Blueskin® SA**. It is recommended that mechanical attachment be made to all window and door frames, or a properly designed sealant joint be provided.

Insulation Application over Membrane

The use of mechanical fasteners through **Blueskin® SA** along changes in plane, such as inside corners, may be required by some insulation manufacturers. Consult insulation manufacturer prior to installation of insulation.

Insulation Clips: Insulation clips should be mechanically fastened through **Blueskin® SA** into the substrate with a self-tapping screw. Apply number of insulation clips as recommended by the insulation manufacturer.

Insulation Adhesive: Bakor 230-21 Rigid Insulation Adhesive should be applied to insulation boards in a serpentine pattern to restrict movement of air behind the insulation. Alternatively, a full coat notched trowel application of **Bakor 230-21 Rigid Insulation Adhesive** may be applied to the back of the board. Press insulation firmly in place. **Air-Bloc 21** or **Air-Bloc 21 FR** are also acceptable as adhesives. <>

Henry Company Canada, 15 Wallsend Ave., Scarborough, ON M1E 3X6 **Tel:** 800-387-9598 **Fax:** 866-483-9266

www.bakor.com

Plasti·Fab
EPS PRODUCT SOLUTIONS
Better building ideas from PFB

BULLETIN NO.	212
ISSUED:	March 7, 2010
REPLACES:	January 13, 2010

Product Information Bulletin

PlastiSpan® HD Insulation Material Property Data Sheet
CAN/ULC-S701-05, Type 2

CAN/ULC-S701-05, ***Standard for Thermal Insulation, Polystyrene, Boards and Pipe Covering*** is the National Standard of Canada for moulded expanded polystyrene (EPS) insulation. The table below provides material properties for PlastiSpan HD insulation meeting CAN/ULC-S701, Type 2.

PlastiSpan HD Insulation Material Properties[1]	Test Method[2]	Units	Values
Thermal Resistance *Minimum RSI per 25 mm (R per inch)*	ASTM C518	m^2•°C/W (ft^2•h•°F/BTU)	0.70 (4.04)
Compressive Resistance *Minimum @ 10% Deformation*	ASTM D1621	kPa (psi)	110 (16)
Flexural Strength *Minimum*	ASTM C203	kPa (psi)	240 (35)
Water Vapour Permeance[3] *Maximum*	ASTM E96	ng/(Pa·s·m^2) (Perms)	200 (3.5)
Water Absorption[4] *Maximum*	ASTM D2842	% By volume	4.0
Dimensional Stability *Maximum*	ASTM D 2126 7 Days @ 70 ± 2°C	% Linear Change	1.5
Limiting Oxygen Index *Minimum*	ASTM D2863	%	24

Notes to Table:

1 PlastiSpan insulation properties are third party certified under a certification program administered by Intertek Testing Services and listed by the Canadian Construction Materials Centre (CCMC) under evaluation listing number 12425-L (Type 2).

2 The test methods used to determine material properties in the above table provide a means of comparing different types of cellular plastic thermal insulation. They are intended for use in specifications, product evaluations and quality control. They do not predict end-use product performance.

3 WVP values quoted are maximum values for 25-mm thick samples with natural skins intact. Lower values will result for thicker materials.

4 Water absorption % by volume in CAN/ULC-S701 is determined using ASTM D2842 which involves complete submersion under a head of water for 96 hours.

Quality, Service and Expertise

1-88-THINK EPS® www.plastifab.com

Appendix B - Edge Sealing

Small scale testing was undertaken in order to verify the effectiveness of the paint used in sealing the edges of the CLT. Small scrapes of the European spruce CLT samples were used, approximately 6” long, 1 1/2” wide, and 3 ½” thick. Four samples were used, three of which were painted on all six sides with three coats of Interlux Brightside one-part polyurethane finishing paint. The third sample was painted on the four cut edges, with a small border around the exposed faces of the CLT sample, in order to compare water uptake values with the completely covered samples. Of the three completely sealed samples, one was steamed for 2.5 hours, and weighed every half hour, one was submerged in room temperature blue water for 5 days, and weighed every 24 hours, and one was kept in an enclosed space over room temperature water for five days, and weighed every 24 hours. The fourth sample was also submerged for 5 days, in the blue water, in order to determine the depth of liquid penetration into the CLT face. Room temperature was around 25°C. The four samples, and their testing conditions, may be seen in Figures B.1 to B.4, with their mass over the course of testing as indicated in grams.

Figure B.1 25°C Submersion Test

Figure B.2 Enclosed 25°C 100% RH Test

Figure B.3 100°C Steam Test

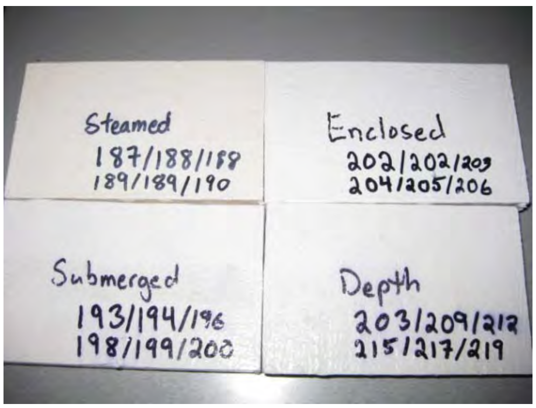


Figure B.4 Edge Sealing Test Mass Results

By plotting the mass of the sealed samples over time, the average rate of moisture uptake was obtained based on the line of best fit, as seen in Figure B.5. Using the values in Table B.1, the rate of water uptake, with paint, was found for each of the three testing scenarios.

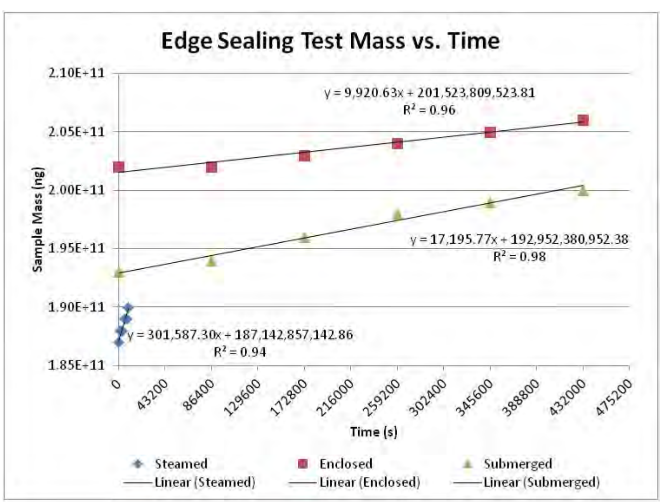


Figure B.5 Edge Sealing Test Mass vs. Time

Table B.1 Edge Sealing Liquid and Vapour Permeance

Sample	W (mm)	L (mm)	H (mm)	Surface Area (m^2)	Vapour Pressure (Pa)	Rate of Absorption (ng/s)	Water Uptake ($ng/Pa.s.m^2$)
Steamed	90	151	31	0.0421	101613	301587	70.5
Enclosed	90	151	33	0.0431	3161	9921	72.8
Submerged	90	152	31	0.0424	3161	17196	128.4

Based on the small scale testing, it appears as though the water uptake of the CLT with three coats of paint is around $100ng/Pa.s.m^2$. While this is significantly higher than materials such as polyethylene sheeting or vapour impermeable peel-and-stick, paint can be more reliably applied to wood without wrinkles where water may enter, and remains adhered while the wood expands during wetting.

Based on the permeance of the sealed submerged sample, the amount of moisture taken up through the sealed edges of the sample with exposed faces is approximately 7g. The additional 9g of water absorbed through the exposed faces, having a total area of 24mm by 250mm, leads to a combined liquid and vapour uptake rate of $1200ng/Pa.s.m^2$. Considering this rate is for uptake across the wood grain, and not at the end grain, the experiment shows that the three coats of paint reduces uptake to 10% or less of the unsealed value. Combined with the placement of sensors towards the centres of the panels in the full-scale experiment, painting the CLT panels appears to be a suitable method of sealing the edges before wetting. As seen in Figure B.6, in five days, the blue liquid water penetrated approximately 2 mm into the bare face of the sample, and the painted portion showed no penetration of dyed liquid.

Given the scale of the panels to be used in the test wall, approximately 600mm square, with the moisture content sensors located within 100mm of the centre of the panel, this sealing method should prevent any edged effects during the wetting and drying phases in the region being monitored.

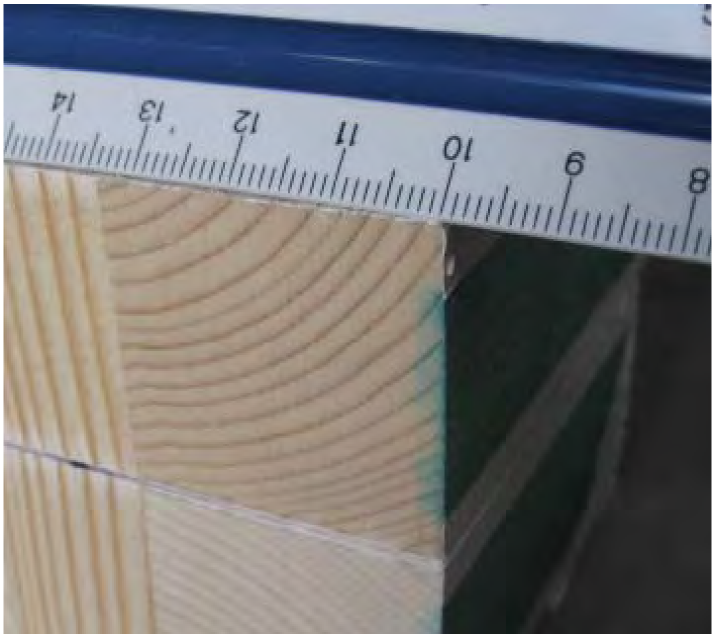
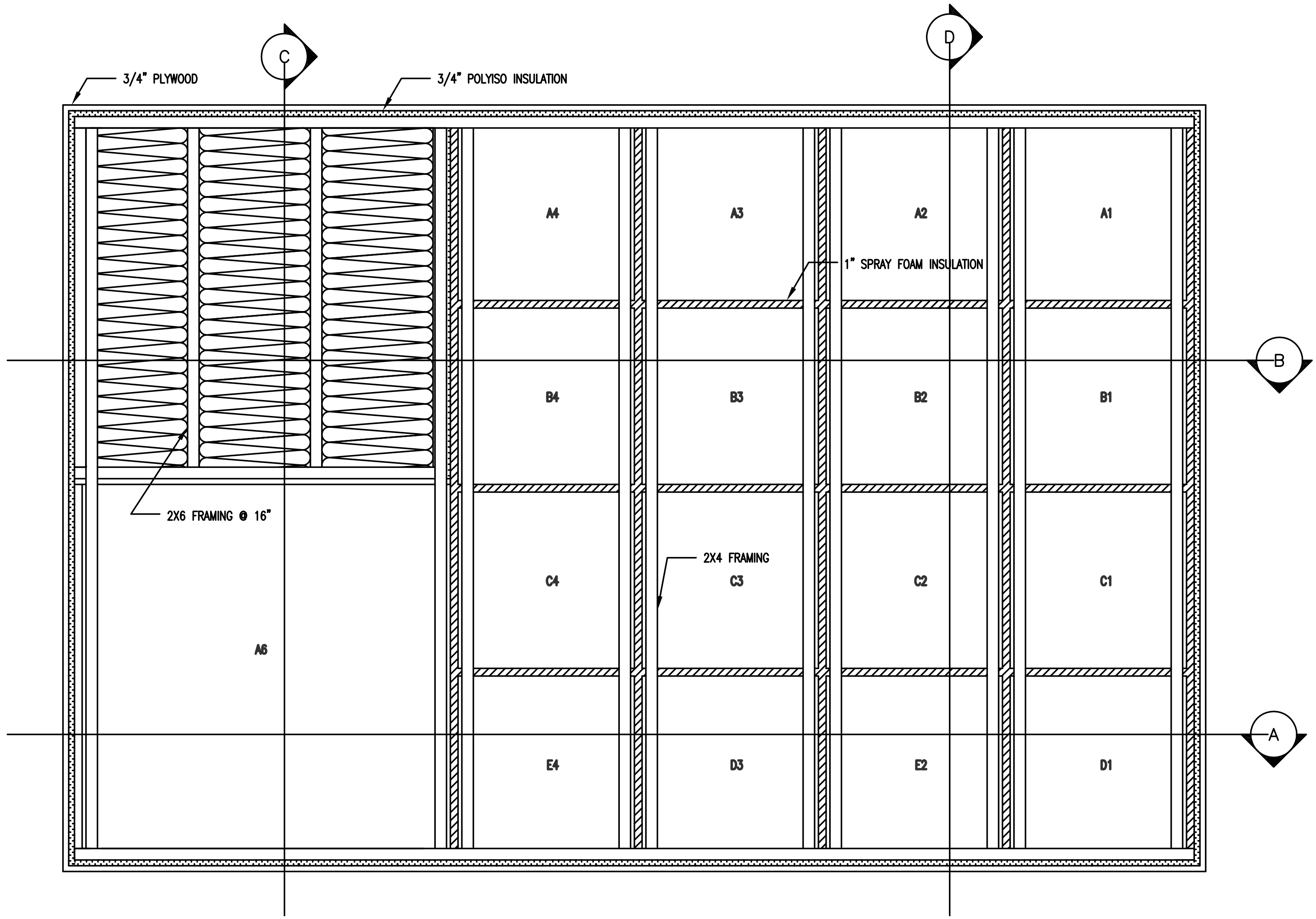


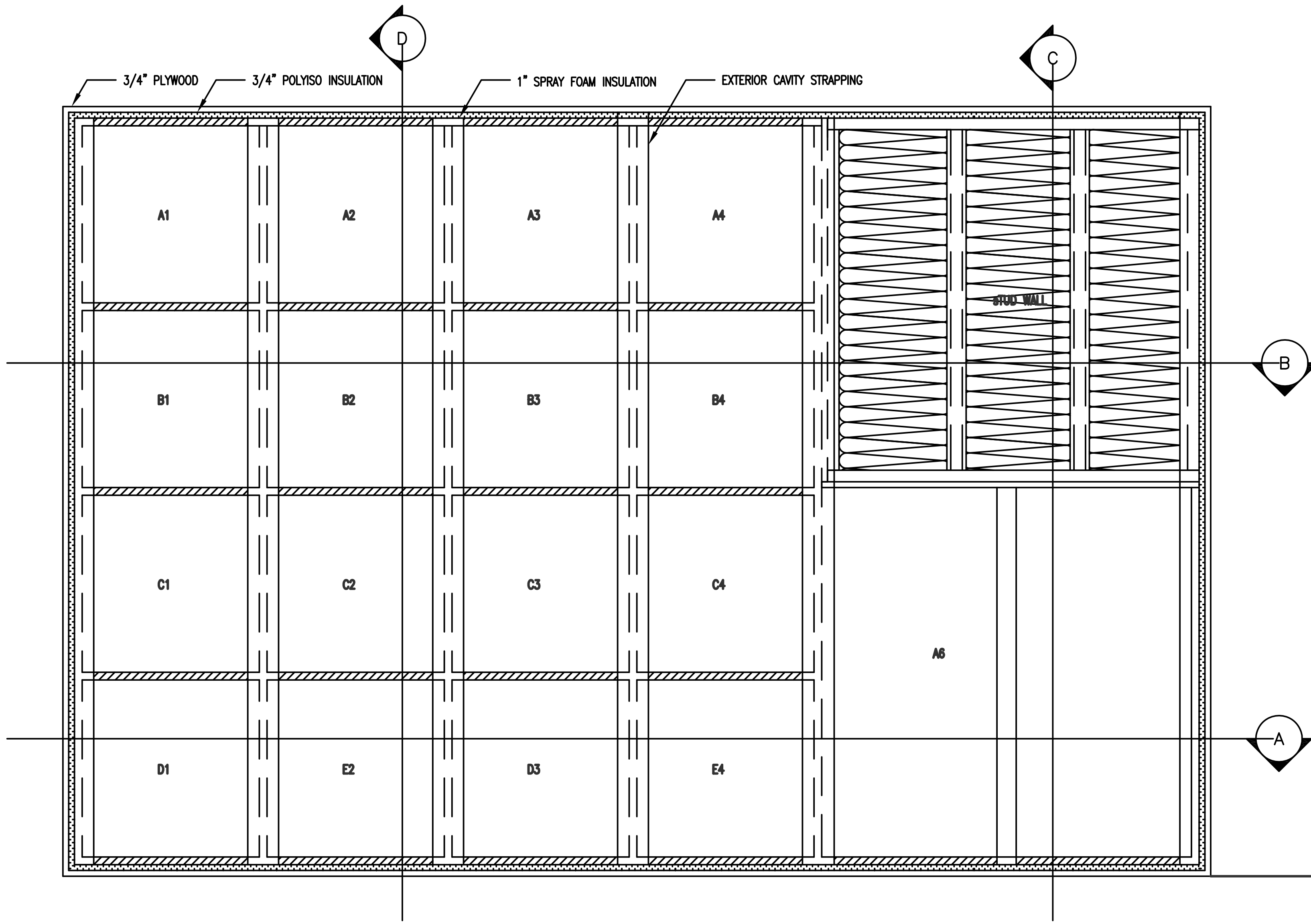
Figure B.6 Five Day Dye Penetration

Appendix C - Construction Drawings

Drawings to follow

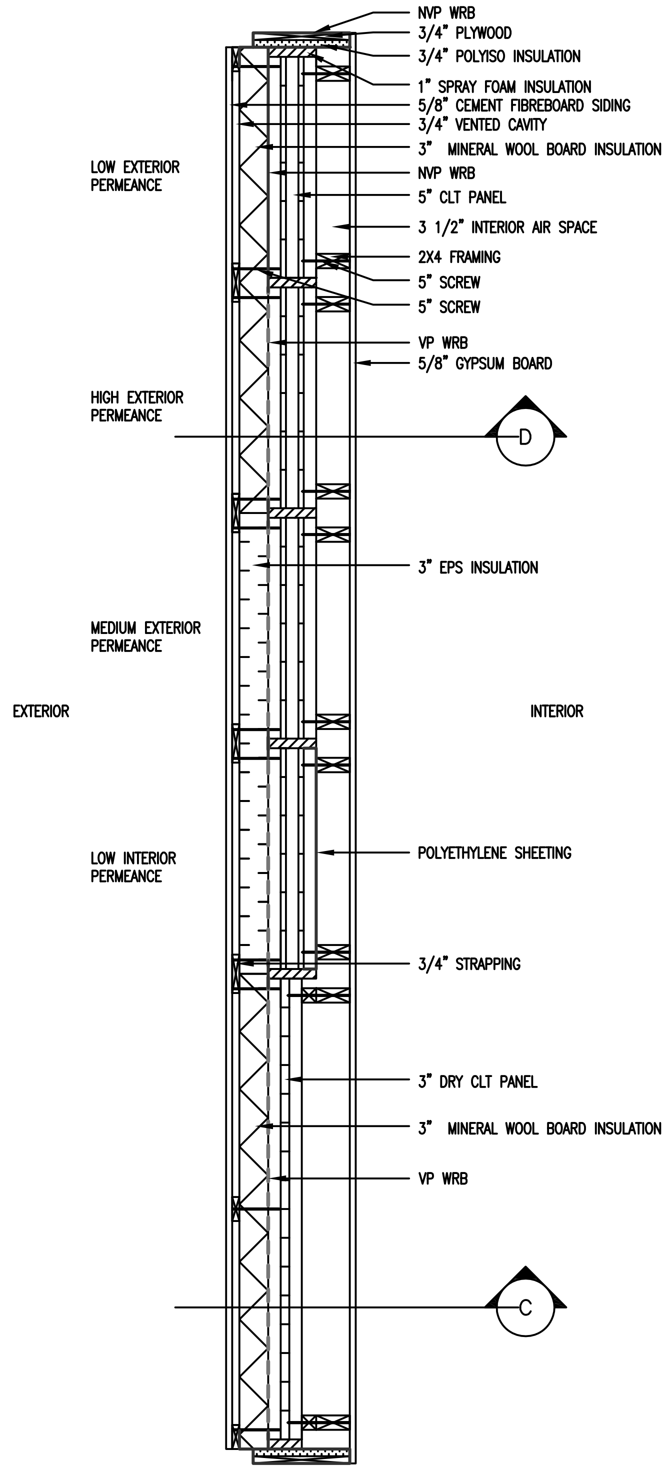


INTERIOR ELEVATION
20:1



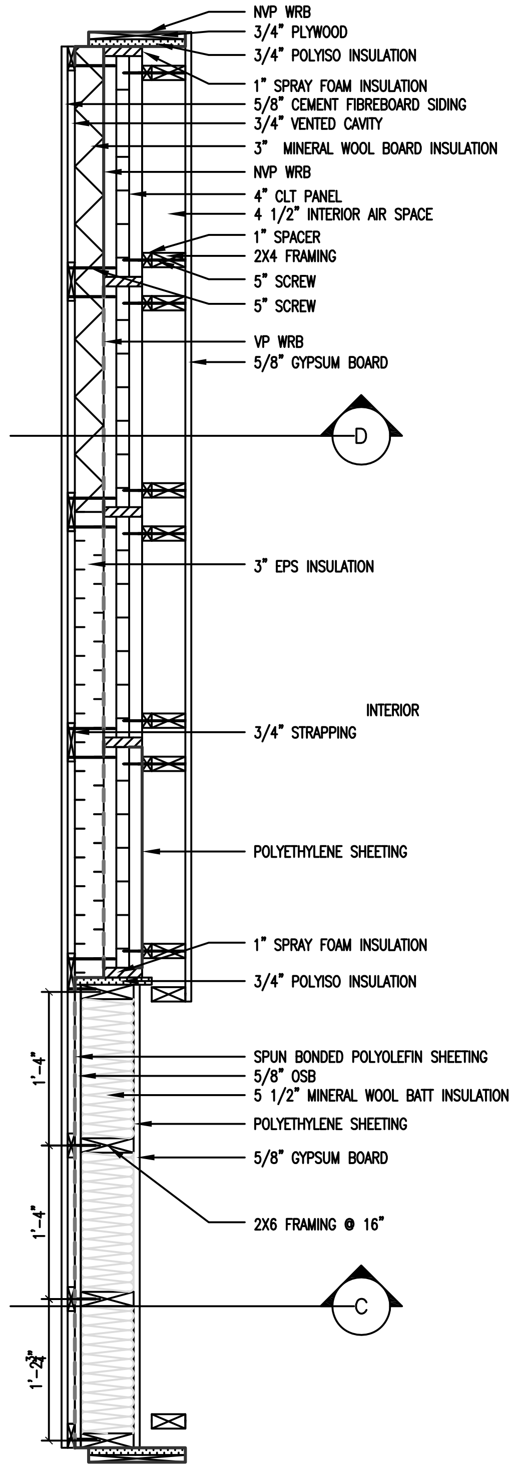
EXTERIOR ELEVATION
20:1

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT



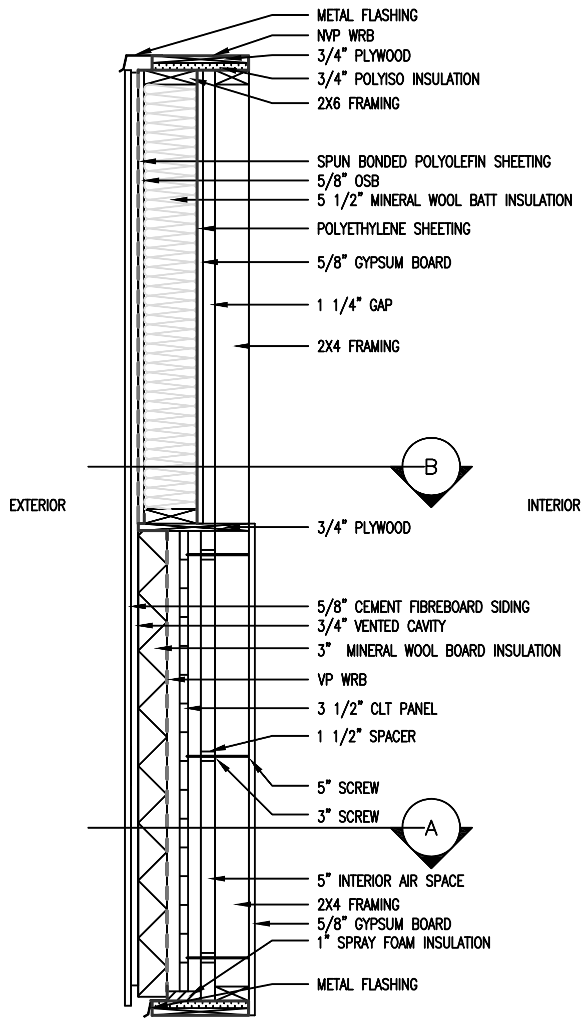
A SECTION – WESTERN SPF (C) PANELS, DRY CLT PANEL
20:1

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT



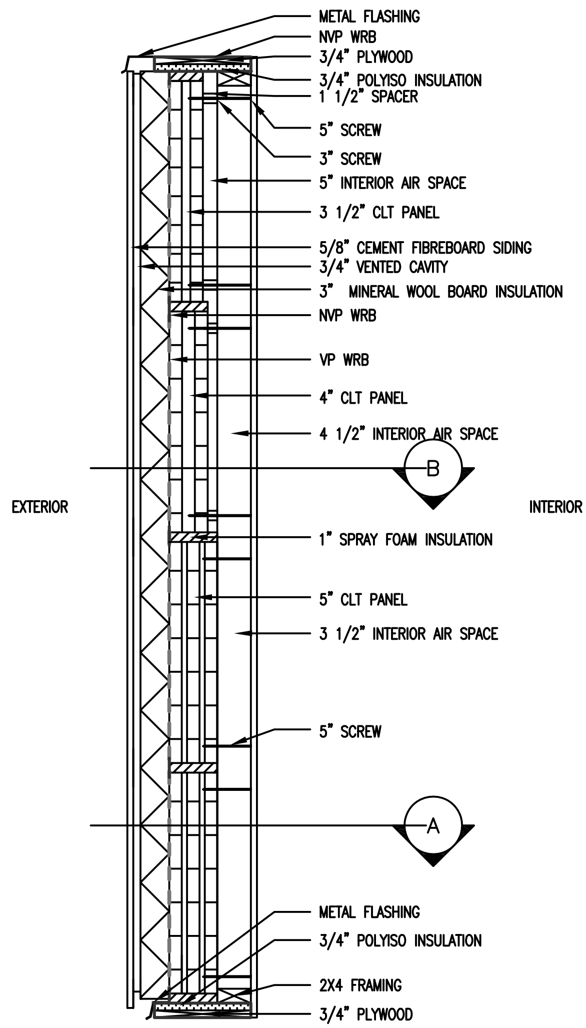
B SECTION – BLACK SPRUCE (B) PANELS, STUD WALL
20:1

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT



C SECTION – STUD WALL AND DRY CLT PANEL

20:1



D SECTION – HIGH EXTERIOR PERMEANCE PANELS
20:1

Appendix D - Heat Flux

A heat flux experiment was conducted alongside the hygrothermal testing. This included a dry 1200mm x 1200mm European spruce CLT panel in the high exterior permeance wall configuration, and a typical cavity wall with 2x6 studs at 16" apart, detailed in the construction drawings in Appendix C. Three heat flow sensors were used, one fastened in the centre of the interior face of the CLT panel, one fastened on the interior face of the gypsum board, cantered on a stud with full width cavities on either side, and one fastened on the interior face of the gypsum, centred on a full width cavity with a full width cavity to one side, and a partial width cavity to the other.

The heat flow sensors were model F-005-4 44.5mm square sensors with +/-5% accuracy provided by Concept Engineering. The self powered sensors produce a millivolt difference across two leads, which is multiplied by a manufacturer provided factor calibrated for each sensor to obtain a heat flow value in kW/m^2. An initial programming error which set the data logger sensitivity too low to measure the signal voltage was corrected and heat flux data was collected beginning in February.

THERM simulations of the walls result in the U values shown in Table D.1, where it is shown that the steady state U-values of the overall stud wall compared to the CLT wall assembly are virtually identical, differing by only 3%, and are about 0.3 W/m^{2}K.

Table D.1 Stud and CLT Wall THERM U-values

U-Value Location	THERM U-Value (W/m^{2}K)
Stud Wall, Stud	0.5380
Stud Wall, Cavity	0.2464
Stud Wall, Overall	0.2955
CLT Panel	0.3043

Figure D.1 shows the heat flux and exterior temperature data, using 2 hour running average values derived from the sensor data sampled every 15 minutes. From this data two observations may be made:

- The heat flux recorded on the CLT panel fluctuates much less than the values from the stud wall. This stability is an indication of thermal mass, and reduces peaks in heat loss, potentially lower the design requirements of the heating system.

- The heat flux through the stud is typically about twice the value of the heat flux through the insulated cavity of the stud wall. This relationship is in agreement with the ratio of the U-values found in THERM.

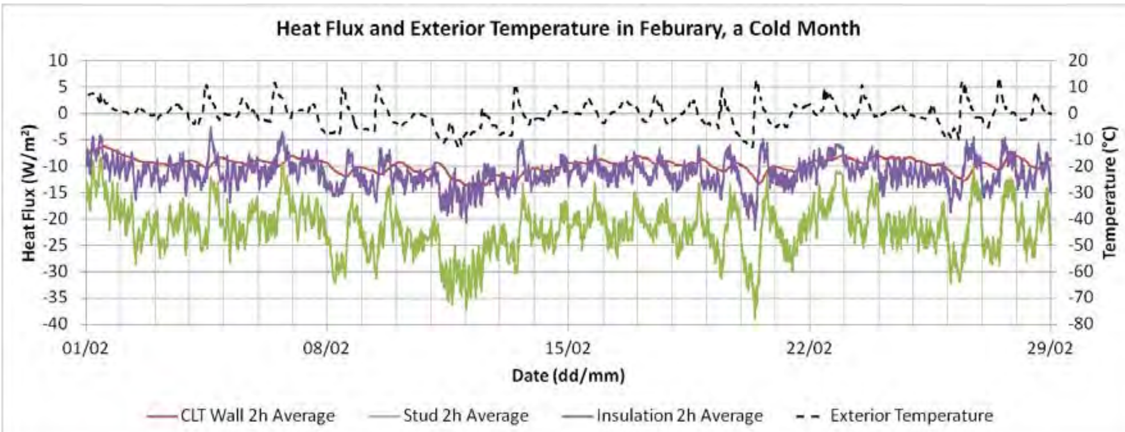


Figure D.0.1 Heat Flux and Exterior Temperature in Feburary, A Cold Month

This was the coldest time period recorded, and the values for heat flux, data logger panel (interior) temperature, and exterior temperature in this time period were used to determine the average measured U-values of the wall elements. For each element, the sum of the sampled heat flux values in February was divided by the sum of the sampled temperature differences. The composite stud wall U-value was calculated simple by using the weight average areas of the stud and the cavity, considering 1.5" of stud for every 16". The measured U values are shown in Table D.2. While all the measured U-values about twice as high as those calculated in THERM, it can be noted that while THERM predicted the stud wall would lose about 3% less heat than the CLT wall assembly, the measured values show the stud wall has in fact lost 25% more heat than the CLT wall.

Table D.2 Stud and CLT Wall Measured U-values

U-Value Location	Measured U-Value (W/m^2K)
Stud Wall, Stud	1.1082
Stud Wall, Cavity	0.5715
Stud Wall, Overall	0.6219
CLT Panel	0.4948

A more detailed view of the data collected during a clear week in March, shown in Figure D.2, allows an estimate of the time delay in peak flux through the CLT wall compared to the insulated portion of the stud wall. The peaks in negative heat flux, out of the CLT wall, is typically delayed about 3 hours compared to the peak in heat flux out through the insulated cavity. Reductions in heat flux, or possible heat gains though the wall are typically delayed about 6 hours compared to the insulated cavity.

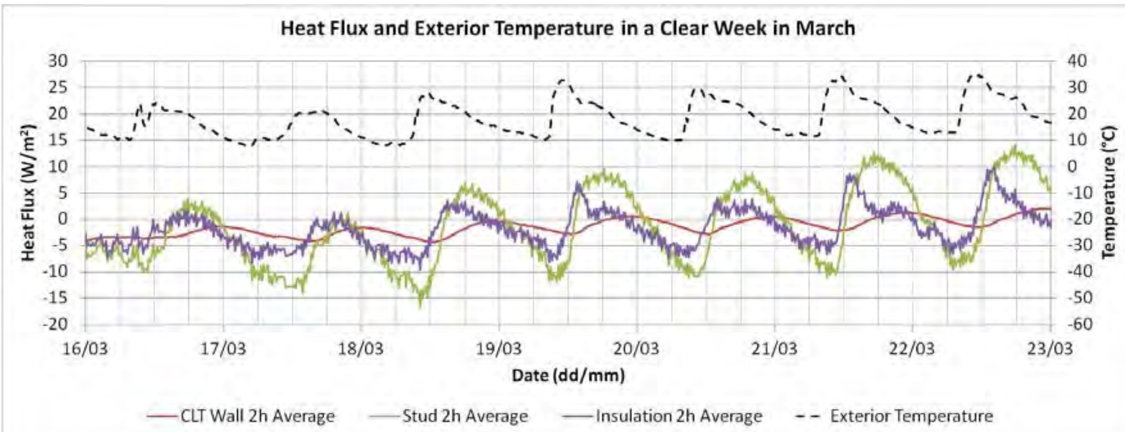
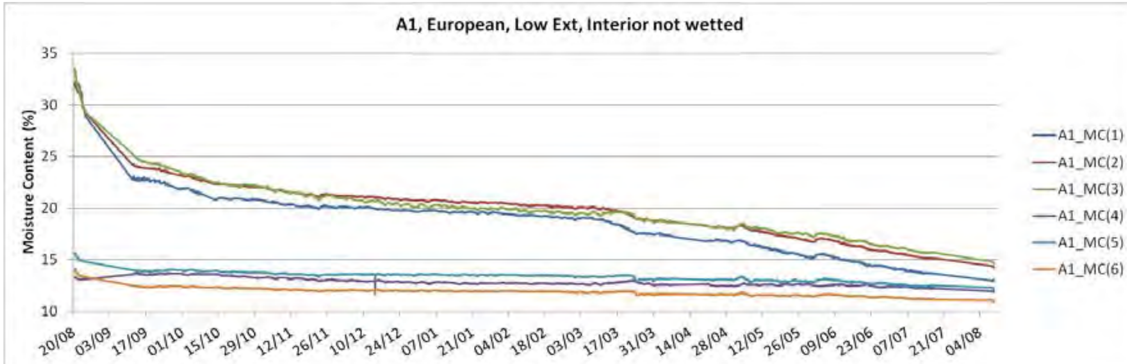
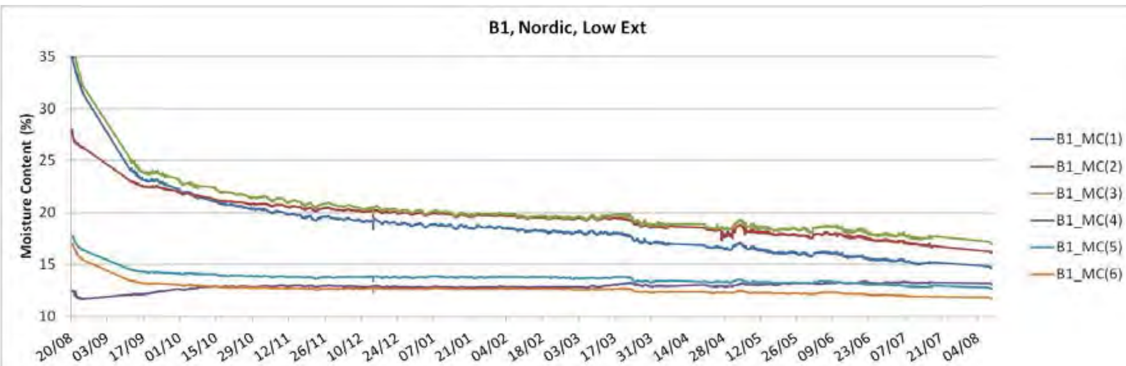
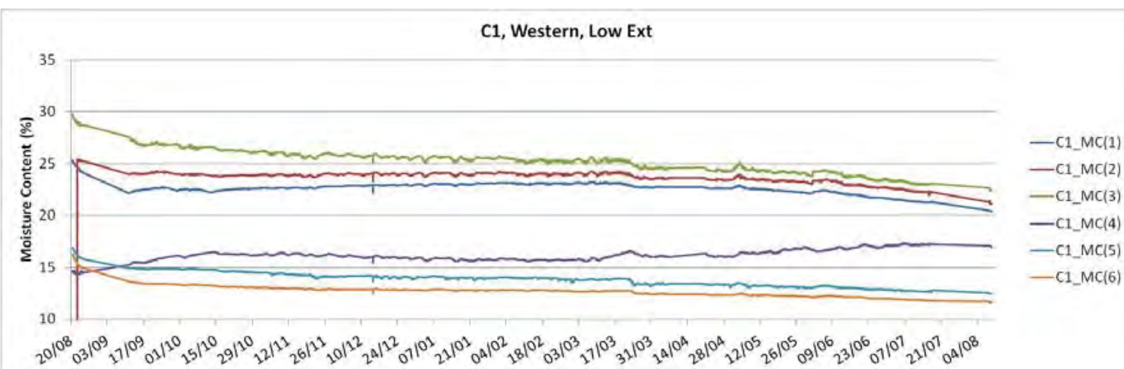


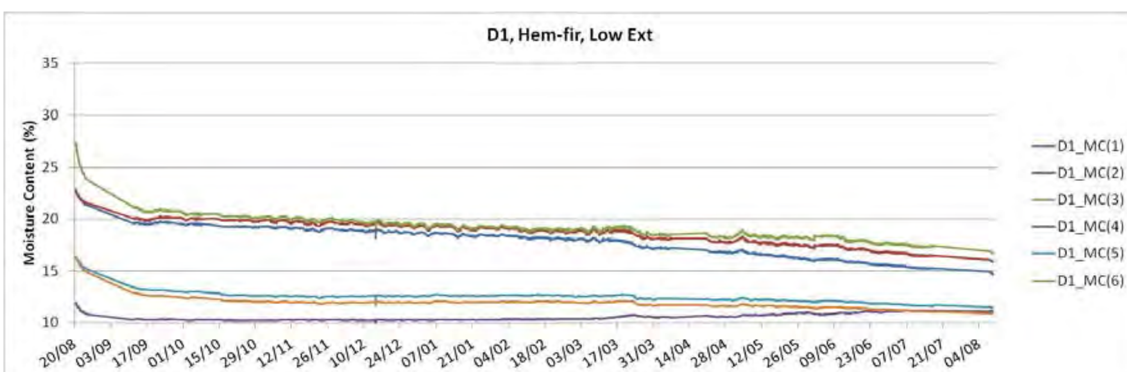
Figure D.0.2 Heat Flux and Exterior Temperature in a Clear Week in March

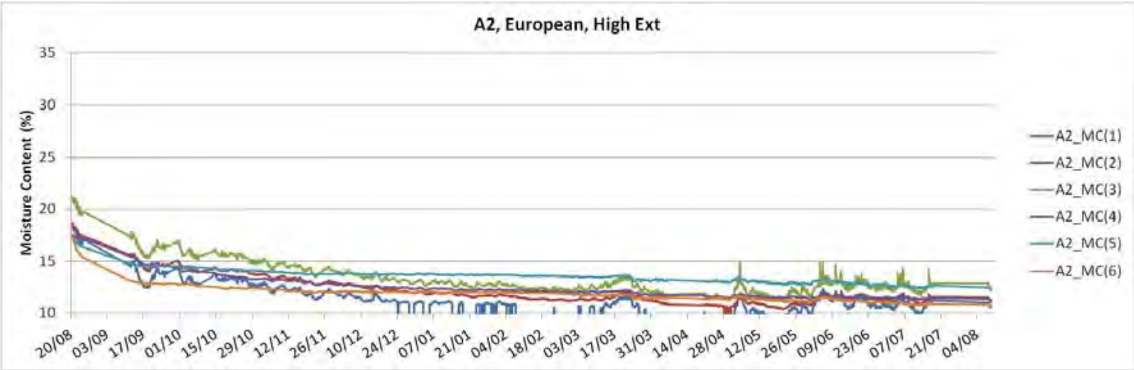
Appendix E - Complete Panel Moisture Content Data

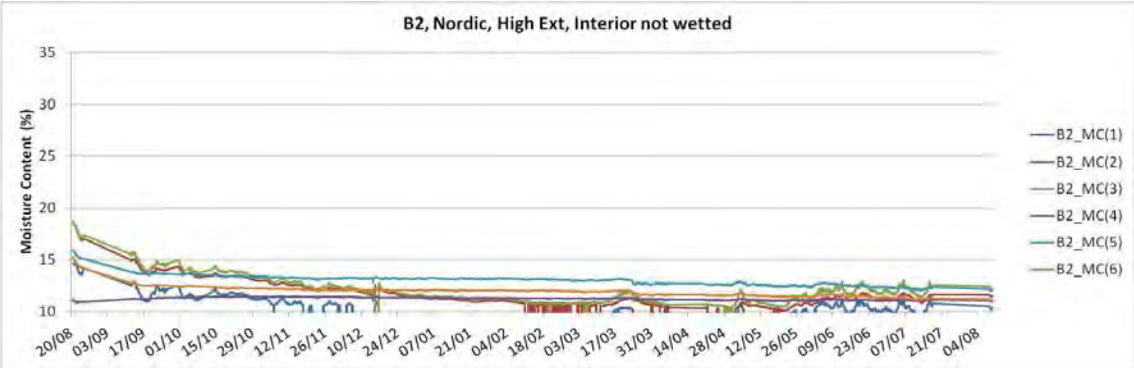


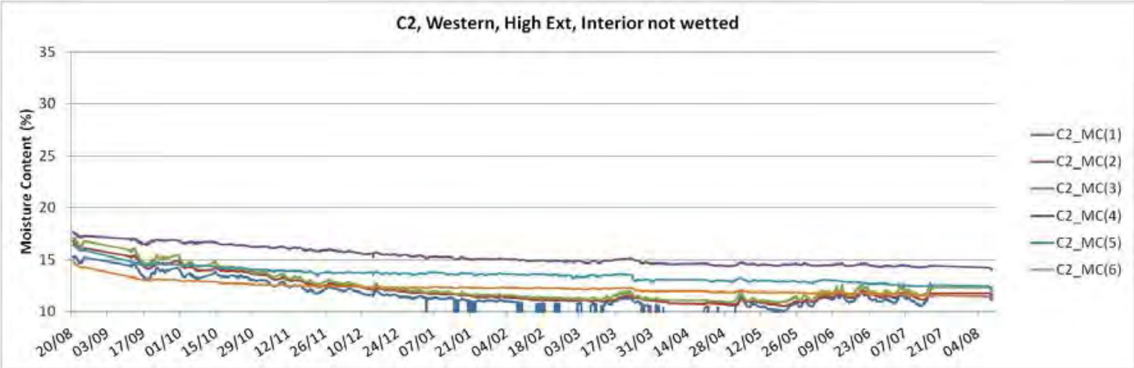


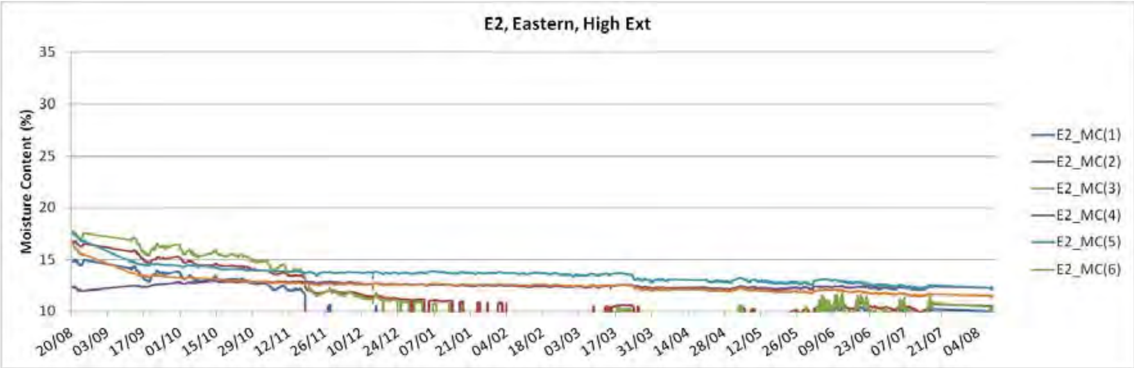


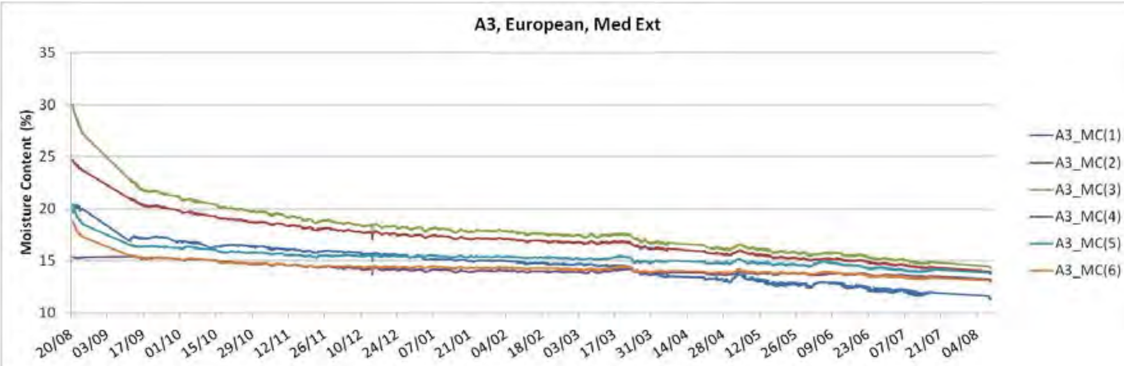


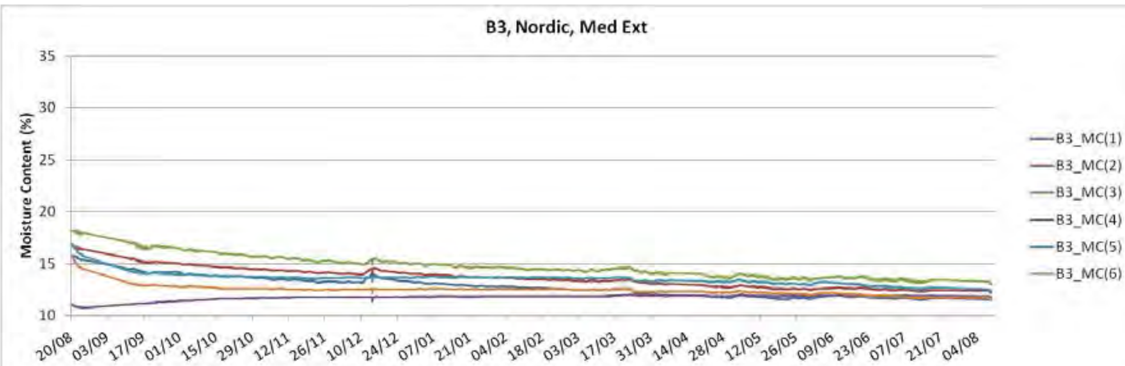

A2, European, High Ext
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
A2_MC(1)
A2_MC(2)
A2_MC(3)
A2_MC(4)
A2_MC(5)
A2_MC(6)

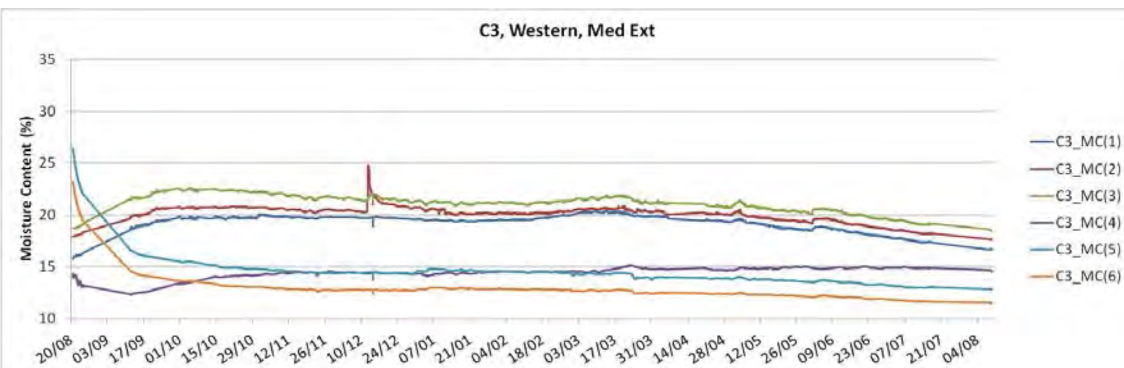

B2, Nordic, High Ext, Interior not wetted
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
B2_MC(1)
B2_MC(2)
B2_MC(3)
B2_MC(4)
B2_MC(5)
B2_MC(6)

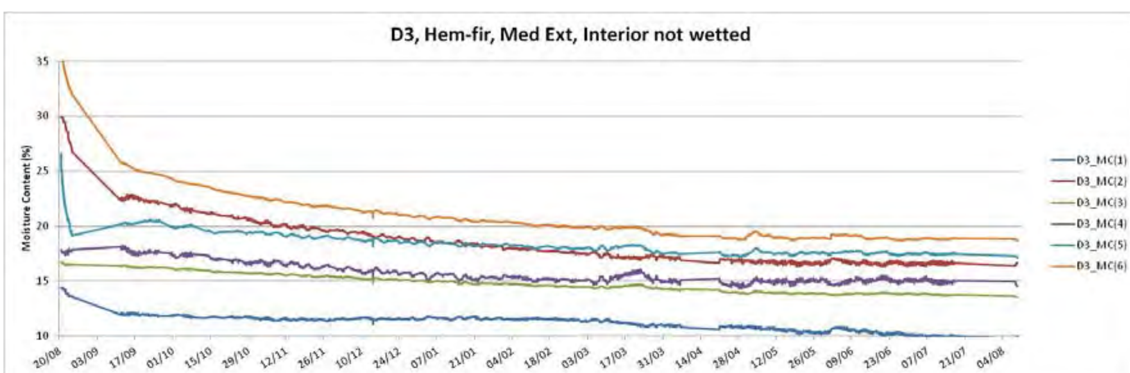

C2, Western, High Ext, Interior not wetted
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
C2_MC(1)
C2_MC(2)
C2_MC(3)
C2_MC(4)
C2_MC(5)
C2_MC(6)

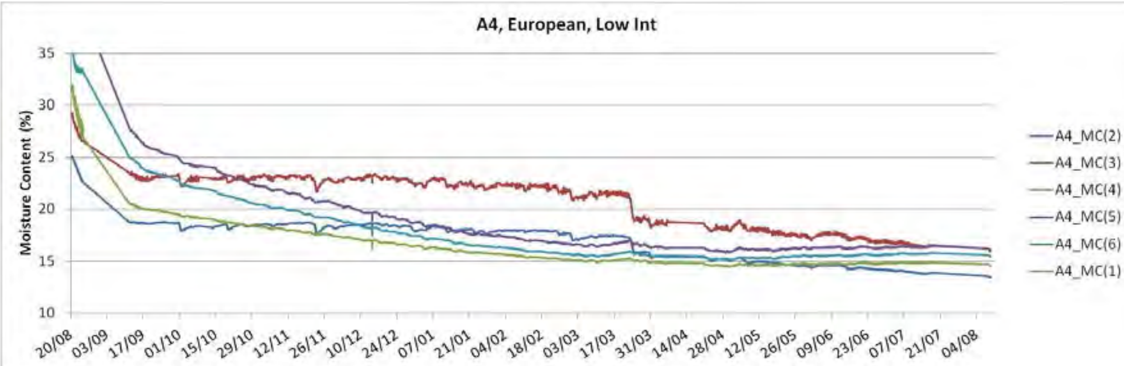

E2, Eastern, High Ext
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
E2_MC(1)
E2_MC(2)
E2_MC(3)
E2_MC(4)
E2_MC(5)
E2_MC(6)

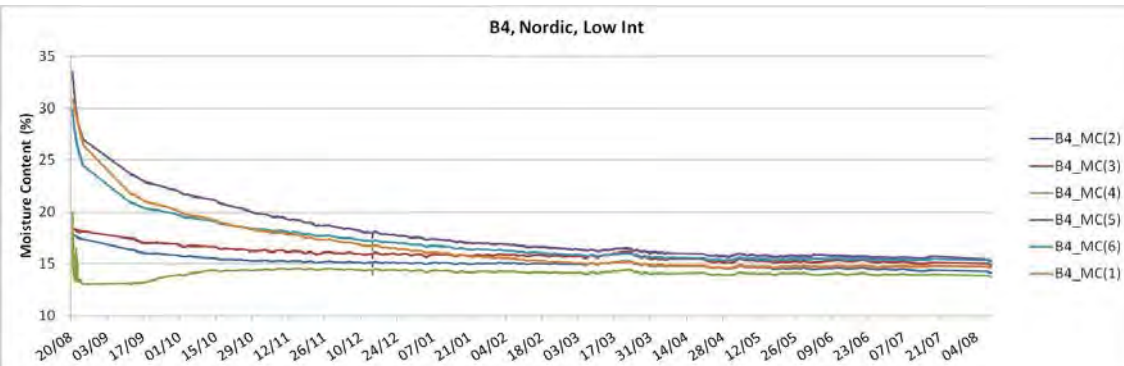

A3, European, Med Ext
Moisture Content (%)
35
30
25
20
15
10
20/08 03/09 17/09 01/10 15/10 29/10 12/11 26/11 10/12 24/12 07/01 21/01 04/02 18/02 03/03 17/03 31/03 14/04 28/04 12/05 26/05 09/06 23/06 07/07 21/07 04/08
A3_MC(1)
A3_MC(2)
A3_MC(3)
A3_MC(4)
A3_MC(5)
A3_MC(6)

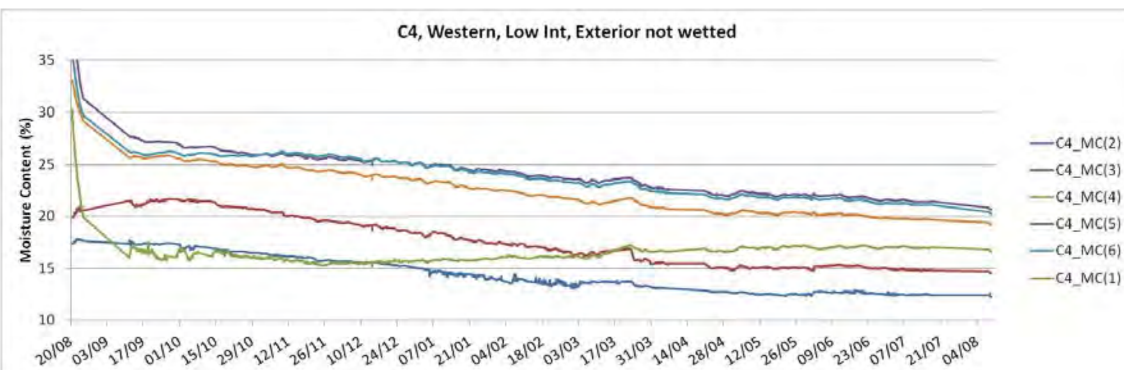

B3, Nordic, Med Ext
Moisture Content (%)
35
30
25
20
15
10
20/08 03/09 17/09 01/10 15/10 29/10 12/11 26/11 10/12 24/12 07/01 21/01 04/02 18/02 03/03 17/03 31/03 14/04 28/04 12/05 26/05 09/06 23/06 07/07 21/07 04/08
B3_MC(1)
B3_MC(2)
B3_MC(3)
B3_MC(4)
B3_MC(5)
B3_MC(6)

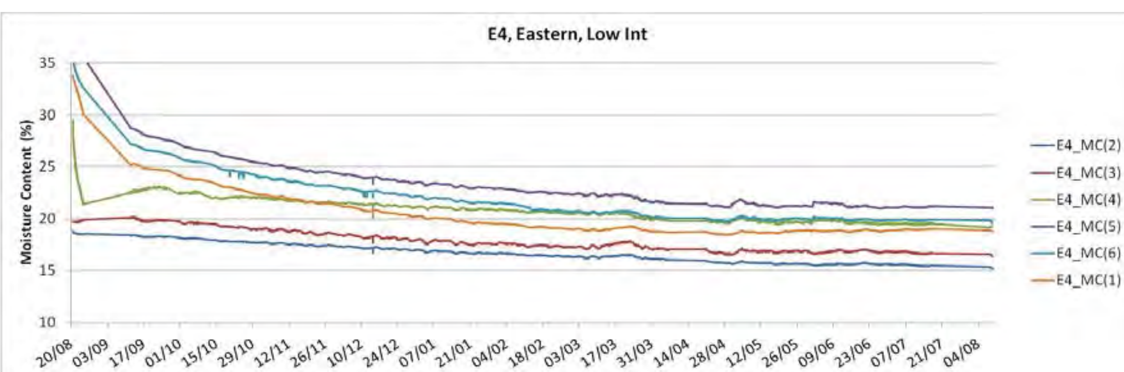

C3, Western, Med Ext
Moisture Content (%)
35
30
25
20
15
10
20/08 03/09 17/09 01/10 15/10 29/10 12/11 26/11 10/12 24/12 07/01 21/01 04/02 18/02 03/03 17/03 31/03 14/04 28/04 12/05 26/05 09/06 23/06 07/07 21/07 04/08
C3_MC(1)
C3_MC(2)
C3_MC(3)
C3_MC(4)
C3_MC(5)
C3_MC(6)

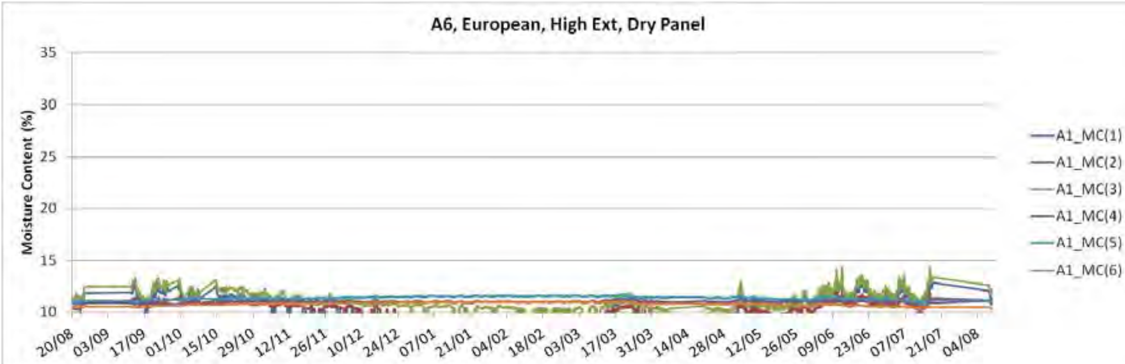

D3, Hem-fir, Med Ext, Interior not wetted
Moisture Content (%)
35
30
25
20
15
10
20/08 03/09 17/09 01/10 15/10 29/10 12/11 26/11 10/12 24/12 07/01 21/01 04/02 18/02 03/03 17/03 31/03 14/04 28/04 12/05 26/05 09/06 23/06 07/07 21/07 04/08
D3_MC(1)
D3_MC(2)
D3_MC(3)
D3_MC(4)
D3_MC(5)
D3_MC(6)


A4, European, Low Int
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
A4_MC(2)
A4_MC(3)
A4_MC(4)
A4_MC(5)
A4_MC(6)
A4_MC(1)

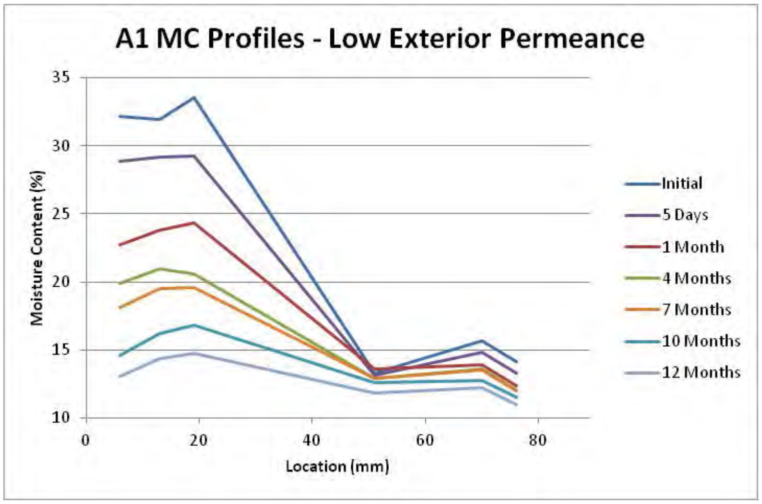

B4, Nordic, Low Int
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
B4_MC(2)
B4_MC(3)
B4_MC(4)
B4_MC(5)
B4_MC(6)
B4_MC(1)

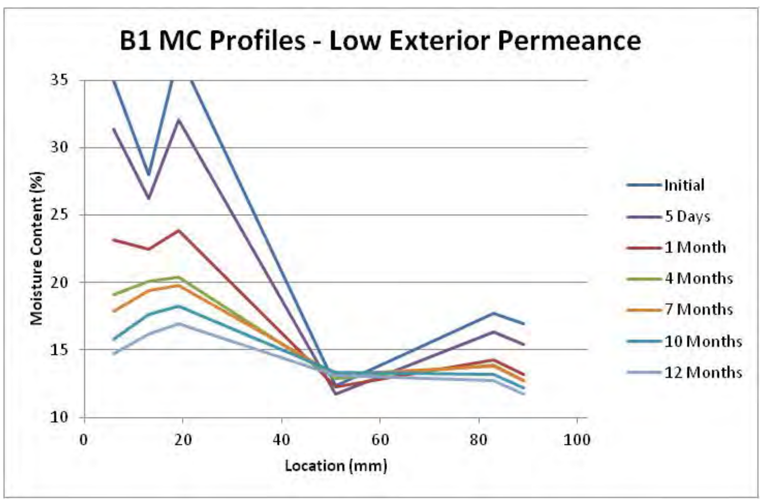

C4, Western, Low Int, Exterior not wetted
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
C4_MC(2)
C4_MC(3)
C4_MC(4)
C4_MC(5)
C4_MC(6)
C4_MC(1)

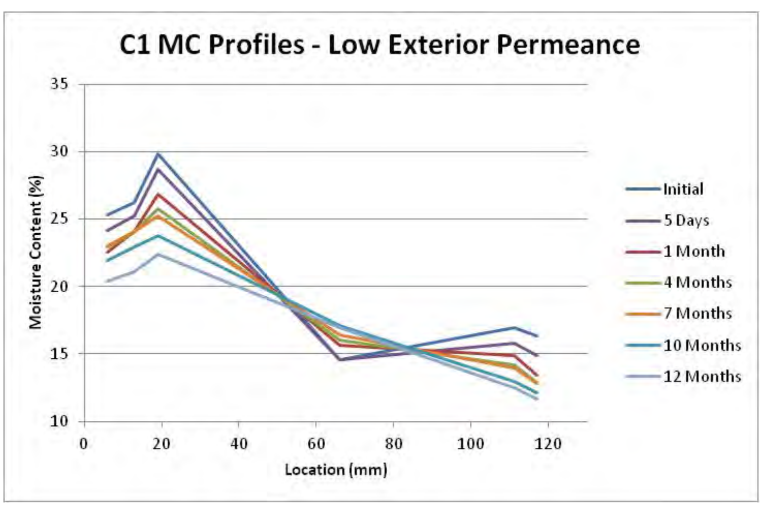

E4, Eastern, Low Int
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
E4_MC(2)
E4_MC(3)
E4_MC(4)
E4_MC(5)
E4_MC(6)
E4_MC(1)

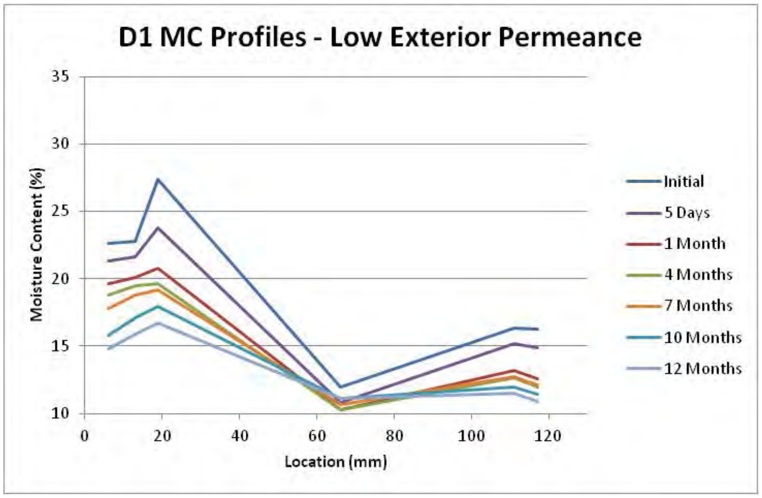

A6, European, High Ext, Dry Panel
Moisture Content (%)
35
30
25
20
15
10
20/08
03/09
17/09
01/10
15/10
29/10
12/11
26/11
10/12
24/12
07/01
21/01
04/02
18/02
03/03
17/03
31/03
14/04
28/04
12/05
26/05
09/06
23/06
07/07
21/07
04/08
A1_MC(1)
A1_MC(2)
A1_MC(3)
A1_MC(4)
A1_MC(5)
A1_MC(6)

Appendix F - Panel Moisture Content Profiles

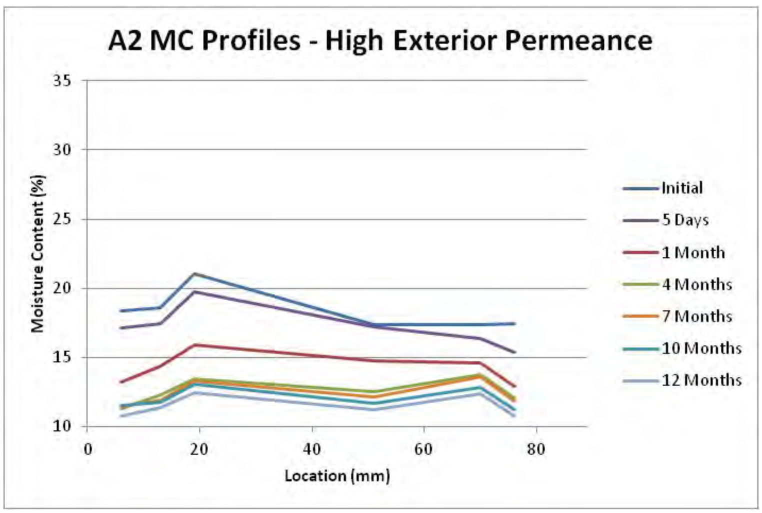




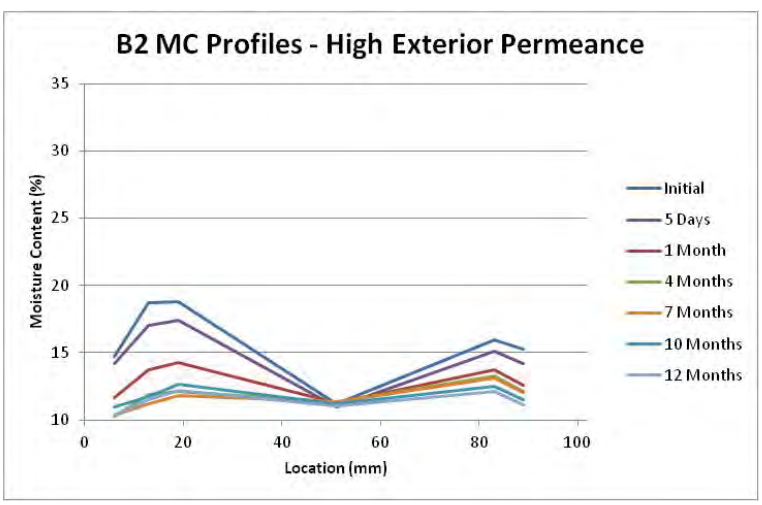




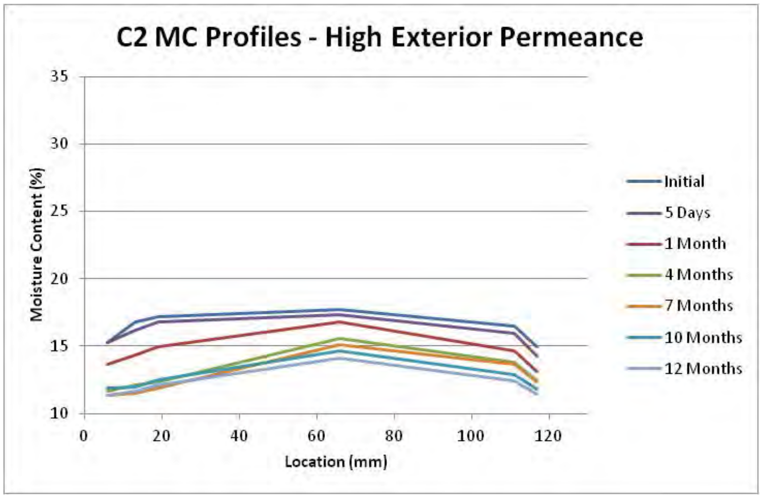
D1 MC Profiles - Low Exterior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

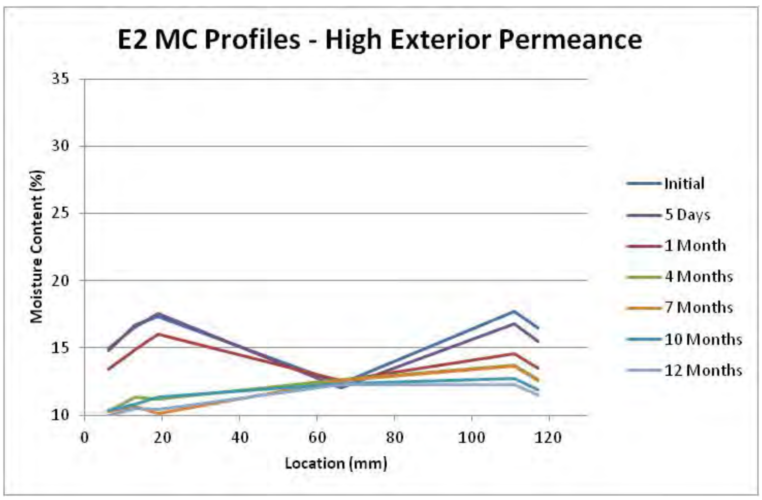


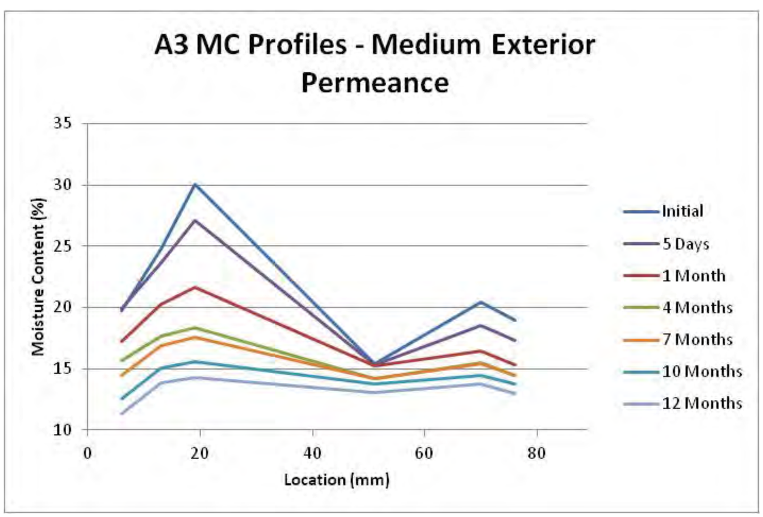
A2 MC Profiles - High Exterior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

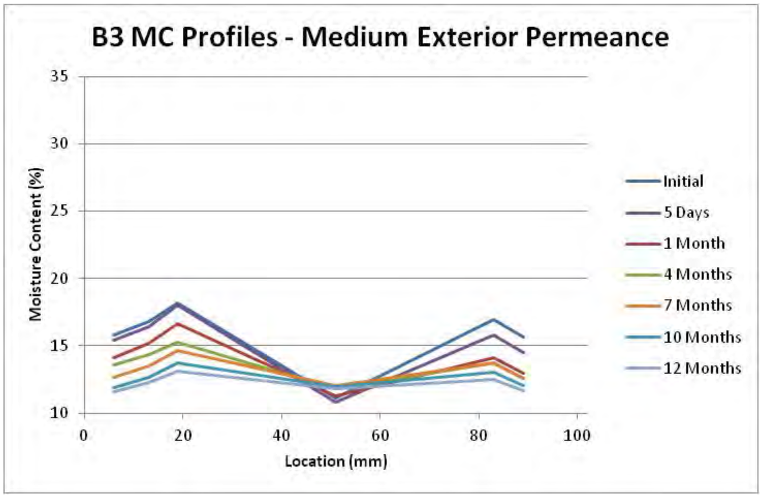


B2 MC Profiles - High Exterior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

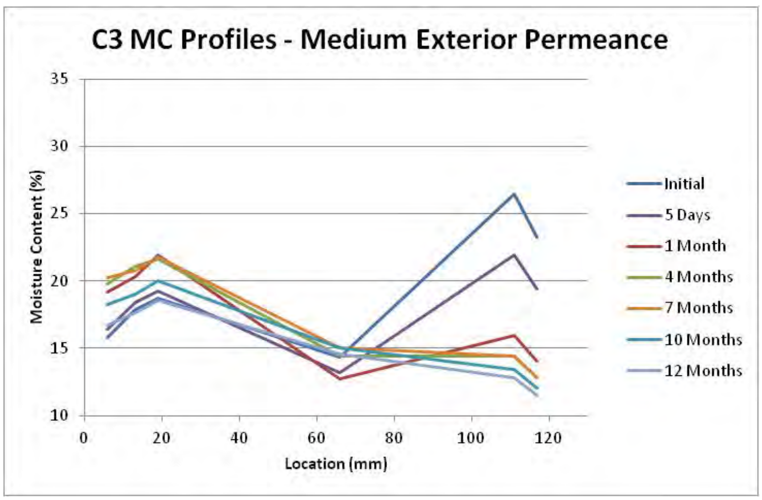

C2 MC Profiles - High Exterior Permeance
Moisture Content (%)
Location (mm)
35
30
25
20
15
10
0
20
40
60
80
100
120
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months


E2 MC Profiles - High Exterior Permeance
Moisture Content (%)
Location (mm)
35
30
25
20
15
10
0
20
40
60
80
100
120
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

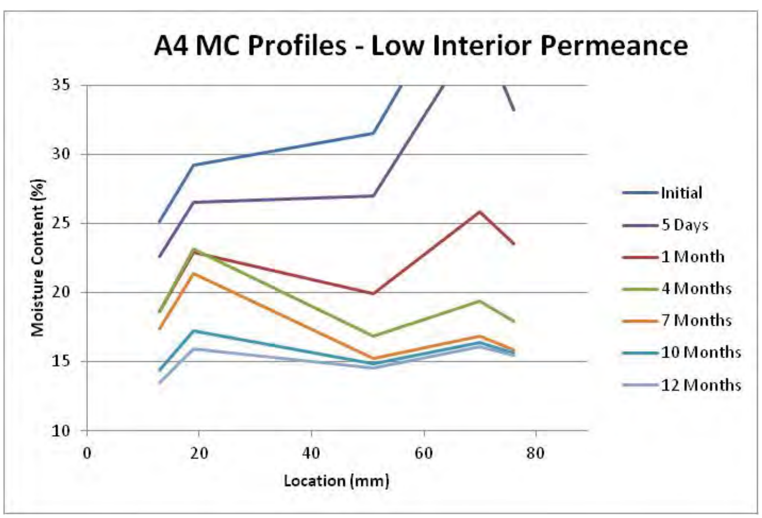

A3 MC Profiles - Medium Exterior Permeance
Moisture Content (%)
Location (mm)
35
30
25
20
15
10
0
20
40
60
80
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months



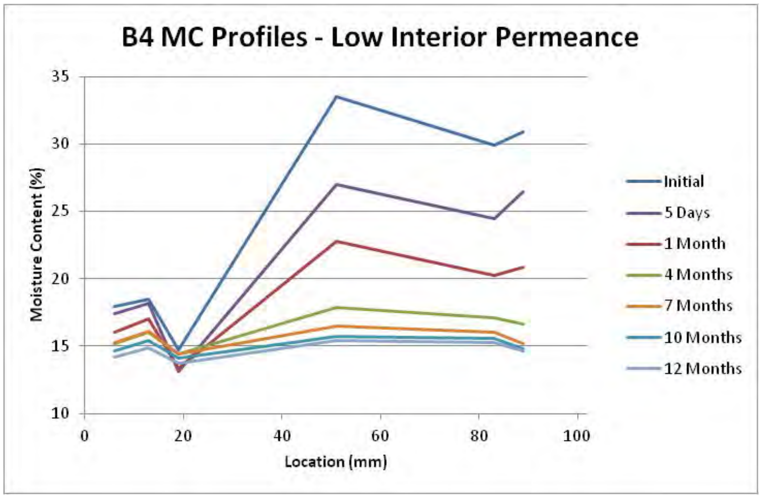
B3 MC Profiles - Medium Exterior Permeance
Moisture Content (%)
35
30
25
20
15
10
0
20
40
60
80
100
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

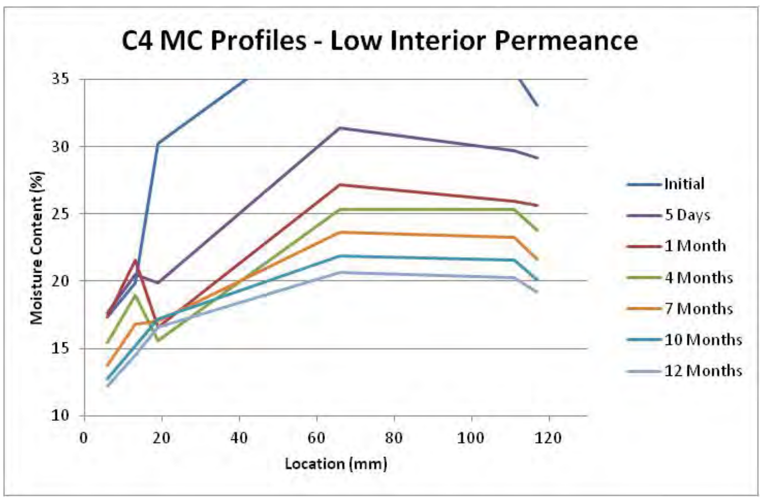


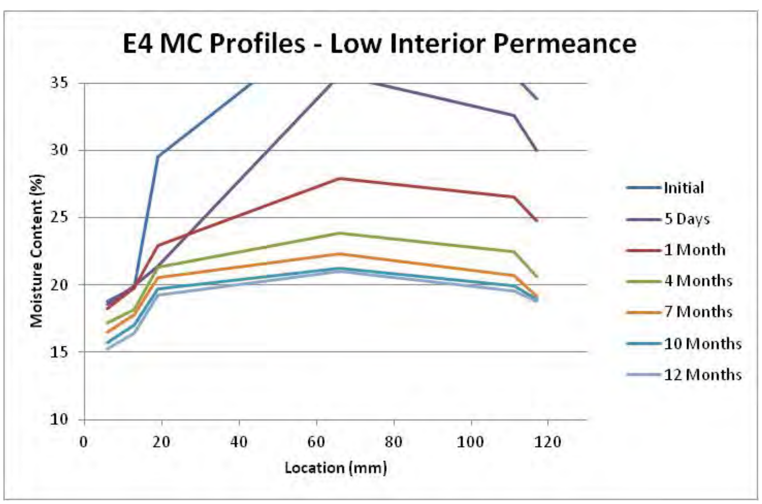
C3 MC Profiles - Medium Exterior Permeance
Moisture Content (%)
35
30
25
20
15
10
0
20
40
60
80
100
120
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

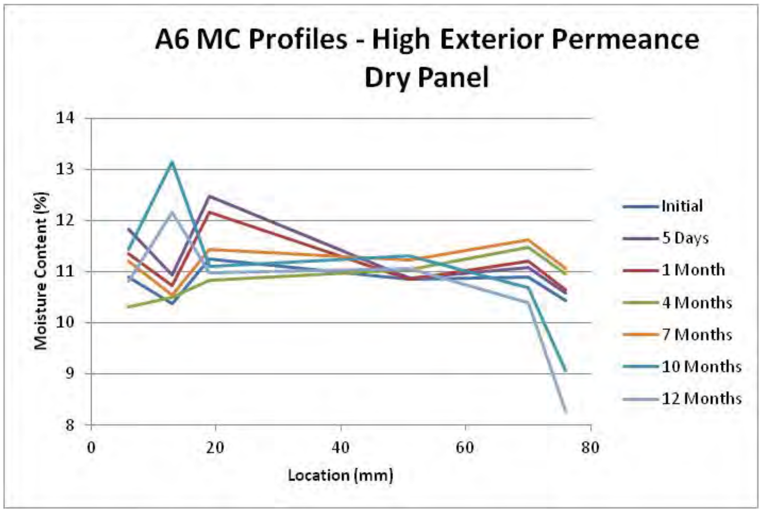


A4 MC Profiles - Low Interior Permeance
Moisture Content (%)
35
30
25
20
15
10
0
20
40
60
80
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months


B4 MC Profiles - Low Interior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months


C4 MC Profiles - Low Interior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months


E4 MC Profiles - Low Interior Permeance
Moisture Content (%)
Location (mm)
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months


A6 MC Profiles - High Exterior Permeance
Dry Panel
Moisture Content (%)
Location (mm)
14
13
12
11
10
9
8
0
20
40
60
80
Initial
5 Days
1 Month
4 Months
7 Months
10 Months
12 Months

Appendix G - Select Weather Data