AN INVESTIGATION OF THE MOISTURE SORPTION AND PERMEABILITY PROPERTIES OF MILL-FABRICATED ORIENTED STRANDBOARD

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Paul Christopher Timusk, 2008

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Abstract

An Investigation of the Moisture Sorption and Permeability

Properties of Mill-Fabricated Oriented Strandboard

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Paul Christopher Timusk

Civil Engineering

University of Toronto

This thesis brings the disciplines of Building Science and Wood Science together in the study of the moisture-related properties of oriented strand board (OSB). Using controlled mill-manufactured panels specifically made for this project, this research reveals how the sorption and permeance properties of OSB are affected by several variables including production parameters and physical panel properties, moisture- history, and relative humidity exposure. Since OSB varies in composition through its thickness, this study isolated and tested various core and surface components. Permeability and sorption properties of individual OSB layers, intact panel sections, and panel sections that had undergone cyclic wetting and drying or relative humidity cycling prior to testing, were evaluated.

After laboratory testing and analysis, a set of OSB permeance and sorption values were entered into the material database of a finite-element hygrothermal

computer modeling program. Relying on this data, a series of hygrothermal wall simulations were carried out using standard wall sections exposed to various climate conditions found throughout North America. These simulations revealed that the results vary widely depending upon the permeance and sorption values used. Thus the common practice of characterizing a range of OSB products with various moisture histories by using a single permeance or sorption value may not be wise.

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Δ = deflection (m)

P = load (N)

L = span between supports (m)

E = modulus of elasticity (Pa)

I = specimen section modulus (m^4)

b = specimen width (m)

d = specimen depth (m)

W = Heat of wetting at some moisture content m (cal/g)

W_0 = Total heat of wetting from oven dry moisture content 0 to moisture content m (cal/g)

Q_s = Differential heat of sorption (cal/g)

RH = Relative humidity (%)

p = vapour pressure (Pa)

p_o = vapour pressure at saturation (Pa)

γ = interfacial tension, water to air (surface tension) (0.07275 N/m)

M = mole mass of water (0.01802 kg/mole))

ρ = density of water (approx. 998 kg/m^3)

R = gas constant (8.314 J/(mol·K))

T = temperature (Kelvin)

Q = volume flow rate

Q_s = slip flow along a circular cross-section capillary

r = capillary radius

ΔP = pressure drop across capillary

l = capillary length

η = viscosity

$\bar{P}$ = mean gas pressure within capillary

P_0 = gas pressure where Q was measured

δ_l = factor depending on fraction of molecules undergoing diffuse reflection upon collision with capillary wall (Knudesn flow)

$\bar{V}$ = molecular mean thermal velocity

μ = permeability (ng/Pa·s·m)

M = permeance (ng/Pa·s·m^2)

w = mass of water vapour transmitted over time (ng)

x = flow path (m)

A = cross-sectional area of flow path, in square meters (m^2)

Δt = time interval, in seconds (s)

$(p_1 - p_2)$ = vapour-pressure difference across the material, pascals (Pa)

l = length of flow path, meters (m)

$\bar{\mu}$ = average permeability of material (ng/pa.s.m)

mc   = moisture content, kg water per kg oven dry wood (%)

α = statistical significance level as probability in % of falsely rejecting the null hypothesis

R^2 = regression analysis coefficient of determination

R   = thermal resistance imperial measure, (ft$^2\cdot$hr$\cdot^o$F / BTU)

RSI   = thermal resistance SI, (m$^2\cdot$K / W)

List of Acronyms

ANOVA: Analysis of Variance
APA: The Engineered Wood Association
ASTM: American Society for Testing and Materials
CSA: Canadian Standards Association
HSD: Honestly significant difference (Tukey's)
IB: Internal bond
MDI: Methylenediphenyl diisocyanate resins
MOE: Modulus of elasticity
MOR: Modulus of rupture
MSF: Million square feet
NMR: Nuclear magnetic resonance microimaging
NRC: National Research Council of Canada
OSB: Oriented Strandboard
PF: Phenol formaldehyde resin
PRS: Performance rated sheathing (grade of OSB for structural use)
RH: Relative humidity
RPM: Revolutions per minute
VDP: Vertical density profile

Chapter 1

Introduction

1.1 Background

Historically, the trial and error approach to building design served mankind well. In this slow and proven method, changes to materials and methods were tried on buildings, and then watched and evaluated for their performance. What worked was repeated, while what did not was discarded. The designs and methods that evolved were specific to a given region and climate, using materials that were

available locally.   This is explained by Neil Hutcheon, one of the forefathers of Building Science, in his Canadian Building Digest -48 titled "Requirements of Exterior Wall Systems", (Hutcheon, 1963).

After World War II things began to change more rapidly, and moisture-related problems in buildings became more frequent.   The timing coincided with the advent of vapour barriers, sheet goods such as plywood, and the increasing use of thermal insulation, all of which increased air tightness and indoor relative humidity.   Vapour barriers served to reduce moisture loss through vapour diffusion, while at the same time making buildings more air-tight.   Sheet goods such as plywood and gypsum board replaced board sheathing, increasing air tightness.   And thermal insulation, with some forms such as kraft-paper faced batt, also increased air tightness, while cooling down assemblies, reducing their ability to dry.

To make matters worse, soon thereafter, globalization and industrial prosperity brought new imported designs, an explosion of new building materials and the high efficiency furnace.   Designs such as flat roofs reduced or eliminated traditional overhangs, allowing walls to get wet.   The introduction of new and yet unproven materials complicated matters.   And the high efficiency furnace, much like electric heating, reduced ventilation rates by drawing combustion air from the outside.

The field of Building Science has caught up, so it is now possible to accurately predict the performance of any building enclosure design in any climate with real weather data.   What used to take years through trial and error, can now be simulated in a matter of minutes.   However, in order for these simulations to provide realistic and reliable results, one must have realistic and reliable material property data.   One such material in common use is oriented strandboard (OSB).

1.2 Oriented Strandboard (OSB)

Oriented strandboard (OSB) is a structural wood composite panel product, made from wood strands, bonded together with a synthetic resin under heat and pressure. It can be manufactured from either hardwoods, known as angiosperms or deciduous trees, or from softwoods, known as gymnosperms or coniferous trees, or from a mix of both. In North America, OSB is most commonly manufactured in the form of 4-foot (1220mm) by 8-foot (2440mm) sheets, and in a range of thicknesses from ¼" (6.5mm) up to 1.5" (38mm). Its primary use is in residential house construction as roof, wall and floor sheathing; other common uses include industrial packaging, rim joists, the webs of composite I-beams and the skins of structural insulated panels (SIPs).

The total quantity of OSB produced in North America, (U.S. and Canada) in 2005 was over 26 billion square feet (2.41 billion square meters) on a 3/8" (9.5mm) basis, of which Canadian production accounted for 43%, or 11,168 million square feet on a 3/8" basis (MSF 3/8") or (1,037 million square meters), and U.S. production for 57%, or 14,985 MSF (1,392 million m^2) 3/8". According to predictions by the Engineered Wood Association (the APA) (APA, 2006), based on public announcements and other data, new OSB capacity could add as much as 10,000 MSF (929 million m^2) 3/8" of new OSB production to North America by 2011, an increase of 38%, bringing total annual production capacity to over 36 billion square feet (3.344 billion square meters), 3/8" (APA, 2006). By contrast, the market share for plywood, a building product which competes with OSB in the same markets as floor, wall and roof sheathing, is declining. Plywood production in North America has decreased by over 4.5 billion square feet (418 million square meters) over the past five years, with a forecasted further reduction of 1.5 billion square feet (139 million square meters) over the next five years. These production losses are from a much smaller North American total production number of only 16,954 million square feet (1,575 million square meters) 3/8" in 2005, which is 65% of the total OSB production figure.

In 2005, Canada consumed a total of 1,248 MSF (116 million m^2) 3/8", (12.5%) of its total OSB production, and exported 9,920 MSF (922 million m^2) 3/8". The U.S. consumed 25,366 MSF (2,357 million m^2) 3/8", (169%) of its total production, importing 10,559 MSF (981 million m^2) 3/8", of which 9,813 MSF (912 million m^2) 3/8" (93%) came from Canada (APA, 2006).

In terms of the end use for OSB in North America in 2005, 19,593 MSF (1820 million m^2) 3/8" (73%) went in to the residential market, 4,825 MSF (448 million m^2) 3/8" (18%) to the remodelling market, 796 MSF (74 million m^2) 3/8" (3%) into the industrial market, and 1,547 MSF (144 million m^2) 3/8" (6%) into the non-residential market (APA, 2006). Accounting for 37% of the total global OSB production, these numbers illustrate that OSB is an important and growing part of the Canadian economy (APA, 2007).

1.3 OSB Construction and Moisture Performance Problems

Given the importance of the OSB industry, any perceived problems with the product, whether substantiated or not, must be addressed. The moisture related performance of OSB is such an issue, due partly to the recent Vancouver leaky condominium crisis, and an overall growing public awareness and concern with issues such as mould and indoor air quality.

Although, in general, North American wood frame houses perform very well in a wide range of extreme climates as illustrated by the vast number of wood frame houses across the country, they do occasionally experience moisture-related problems. The problems can range from mould and mildew proliferation, which can sometimes lead to occupant health problems, to the extreme case of buildings experiencing extensive structural damage. Given the widespread use of OSB, it is often unjustly blamed for many of the problems. A fundamental understanding of the moisture-related properties of OSB and how they relate to manufacturing is needed in order to protect and expand the industry, while

providing healthy, durable, energy efficient, environmentally responsible and affordable housing. A building scientist once said, "It is not building materials that fail, but rather the hands that design the buildings" (Timusk, 1990).

"Moisture is one of the most important factors affecting building performance and durability, especially in countries with cold climates. Understanding and predicting moisture movement within and through the building enclosure is crucial to the control and the avoidance of moisture-related problems…" (Straube, 1998).

The push towards improving the energy efficiency of buildings, driven by an increasing understanding that wasteful ways of humans are no longer sustainable, has been the major factor in the proliferation of moisture-related building enclosure problems. The unfortunate side effect of both reducing air leakage and improving thermal resistance, the two most significant approaches to improving energy efficiency, is a decrease in the drying ability of the building enclosure. This in turn has led to a proliferation of moisture-related building envelope failures.

It is the goal of the author to bring together the disciplines of wood science, building science, and the OSB manufacturing industry with this work. Various manufacturing variables were adjusted during a trial at an OSB mill to produce a range of panels for the study. The panels were then tested for their water vapour permeance and sorption properties. Finally, the results were used as material property data for the simulation and prediction of the moisture related performance of walls using hygrothermal modeling software.

1.4 Research Needs

The problem must be approached from both the building industry side as well as from the material manufacturing side. If the OSB industry understands how their manufacturing parameters affect the final moisture-related properties of OSB, they will be better able to design the material with the desired final properties. If the designers/builders understand the moisture-related properties of OSB as a building material, they will be better able to design better building systems which will avoid moisture-related problems.

As explained earlier, the traditional way in which designs or materials for building have been tested and evaluated for centuries was through trial and error. This method was suitable years ago when change was slow. However, the pace of change drastically increased over the last several decades for numerous reasons which include a drive to achieve energy efficiency, material efficiency, as well as an exponential rate of increase in the development of new technologies and materials. The old trial and error method of testing or evaluation is no longer feasible for the current rate of change.

Fortunately, at the same time that the field of Building Science has advanced, a very important Building Science tool has been developed. Long after Hutcheon wrote his paper on the "Requirements of Exterior Wall Systems", a computer program called WUFI was written. Programs such as WUFI (Warme und Feuchte Instationar – Transient Heat and Moisture, developed by IBP – Fraunhofer-Institut fur Bauphysik), (Kunzel, Karagiozis and Holm, 2001) and hygIRC (Developed by the National Research Council, Institute for Research in Construction), (NRC, 2000), allow one to simulate the performance of materials and designs, subject to the forces of various climates based on real climate data. Many years of exposure can be simulated and evaluated in mere minutes. The two key moisture-related hygroscopic material properties which need to be addressed for both traditional performance prediction methods such as steady-

state calculations, as well as hygrothermal modeling, are water vapour permeance and water vapour sorption.

Water Vapour Permeance

Water vapour permeance is defined as "the timed rate of water vapour transmission through a unit area of flat material or construction induced by unit vapour pressure difference between two specified surfaces, under specified temperature and humidity conditions" (ASTM E96-00). In other words, permeance is a measure of the water vapour flux through a given thickness of material, which can be by any combination of water vapour diffusion, surface diffusion (also known as slip flow), or capillary flow. Pure water vapour diffusion is driven by a vapour pressure or concentration gradient, while surface diffusion and capillary flow (through capillary suction) are driven by a relative humidity (RH) gradient. The S.I. unit of measure for permeance is nanograms per pascal-second-meter squared (ng / Pa$\cdot$s$\cdot$m^2). Permeability is the arithmetic product of permeance and thickness, and the units of measure are nanograms per pascal-second-meter (ng / Pa$\cdot$s$\cdot$m). Another commonly used measure of the same property (used by the WUFI hygrothermal modeling software) is water vapour diffusion resistance, and can be normalized by calculating an equivalent thickness of still air in meters.

The water vapour permeance of a building material is important to the moisture performance of any building assembly such as a wall or roof, in that it indicates the rate at which water vapour will pass through a material under given conditions. This in turn helps in the understanding of:

a) How large a difference in relative humidity or vapour pressure can be maintained from one side of an assembly to the other? (Can a building in a cold climate retain an acceptable indoor relative humidity level for the occupants?);

b) How quickly other materials in an assembly will experience a change in relative humidity, and moisture content;

c) Whether or not, and how fast moisture will accumulate in a material or assembly, and how long it will then take to dry out again.

Water Vapour Sorption

Sorption, the combined effect of absorption and adsorption, is a property which relates the amount of moisture which a material will store, in a specific relative humidity and temperature environment. It can be stated in terms of the resultant moisture content a material attains for a given relative humidity. The relationship is also commonly presented in the form of a curve called a "sorption isotherm", or "absorption isotherm", which shows the equilibrium moisture content at different relative humidities, from 0% to 100%.

The combined water vapour permeance and sorption properties of the component materials of a wall are the critical factors in determining whether or not deterioration will take place. For given interior and exterior climates, these material properties will affect the microclimates within the wall construction, and therefore the performance of the wall and the component materials. Performance in terms of durability will be indicated by the avoidance of mould growth, rot, corrosion of metal components, freeze-thaw damage as well as other moisture related deterioration mechanisms (specific values are discussed in Section 3.1).

When these moisture-related material properties of a material such as OSB are known, they can be used empirically, or in conjunction with hygrothermal modeling software, such as WUFI and hygIRC. The performance of a material or building assembly can then be predicted more reliably, allowing building systems to be designed with the desired moisture-related performance properties. This in turn will hopefully result in improved occupant health and building performance.

1.5 Rationale for Approach

Past studies on the moisture-related properties of OSB have looked at OSB simply as a standard, non-specific, off-the-shelf, homogeneous material, where the OSB for study has simply been purchased or provided by a manufacturer without the details of exactly how it was made (Kumaran, 2002). This approach may be sufficient at times, but often more details are necessary. By analogy one could imagine studying the strength of concrete or the performance of various concrete types, while ignoring details such as water to cement ratios, aggregate types, curing time, or whether or not any additives such as pozzolans or superplasticizers were used. This study aims to go a step further in OSB research, by examining how the manufacturing variables, the resulting material properties, and exposure to various moisture service conditions influence the final moisture-related properties of OSB, and ultimately the effect of the changes in the moisture-related properties on the performance of walls.

1.6 Objectives

The main objectives of this dissertation are as follows:

The first objective is to investigate the impact of selected OSB production parameters, post-manufacture treatments (surface sanding) and exposures (cyclic wetting and drying, and relative humidity cycling) on the moisture-related properties of commercially manufactured OSB. How the production parameters, treatments and exposures may be used to predict the moisture-related properties will also be investigated. As well, the difference in properties among the three component layers of OSB (top surface, core and bottom surface) will be measured.

The second objective is to investigate the impacts of the range of moisture-related properties on the modeled performance of selected common wall constructions subject to the Canadian climate.

A third objective is to develop a rapid test method for determining water vapour sorption properties. The development of such a rapid test may allow one to shorten the duration of sorption tests from several weeks to mere days.

1.7 Thesis Outline

Following the introduction and background presented in Chapter One, Chapter Two, *Wood and OSB,* outlines the structure of wood, from the microscopic and chemical level to the macroscopic level. A rationale for wood composite materials and OSB is presented next, followed by background on OSB. Chapter Three, titled *Moisture and Wood*, presents the background theory for the rest of this dissertation. The properties of water in its various forms are discussed, and then the storage and transport of water are discussed separately, as they are in the rest of this work, followed by previous work on the permeability and sorption properties of wood. In Chapter Four, titled *The OSB Manufacturing Process,* the relevant variables at each manufacturing step are discussed, with the aim of giving the reader some understanding of the process, and why the variables in this study were selected. Chapter Five, *Experimental Design*, outlines how the experimental aspects of this study were conducted, from panel manufacture through specimen preparation and laboratory testing. Chapter Six, *Results of Water Vapour Permeance and Sorption Testing,* presents the test results in two separate parts - first from the water vapour permeance testing, and second from the water vapour sorption testing. Chapter Seven, *Analysis and Discussion of Results,* is also divided into two sections - first dealing with water vapour permeance, and then with water vapour sorption. Chapter Eight, *Hygrothermal Modeling Analysis,* analyzes several different wall designs in three different North American climates, using the test results from this work as material data input for the WUFI hygrothermal computer analysis software. Chapter Nine, *Summary, Conclusions and Future Work*, presents conclusions on the water vapour permeance and sorption testing, as well as on the rapid sorption test method and hygrothermal modeling, and suggests areas where further work is needed.

Chapter 2

Wood and OSB

2. Introduction

This chapter discusses the structure and properties of wood and OSB. It starts with a discussion of the structure of wood, from chemical composition and microstructure, to the macrostructure. It then describes the general rationale for wood composite materials.

2.1 Wood and its Structure

Wood, the major component of most wood composite materials, is a truly amazing material. Wood is defined in the Concise Oxford Dictionary as "the hard fibrous material forming the main substance of the trunk or branches of a tree or shrub, used for fuel or timber". Thus, it is a natural material, unlike most other common building materials such as concrete or steel.

One of the most important differences wood exhibits from other materials is its inherent variability. It is estimated that there are over 20,000 different species of trees in existence, each with its own unique type of wood and associated characteristics (Wilson and White, 1986). Next, not even the wood from two trees of the same species, growing side by side, under the exact same site conditions is identical. Even two pieces of wood from the same tree will not be exactly the same. They all differ in structure and composition, and in this way wood is very different from many man-made materials such as plastic, concrete or steel. In order to find uniformity in wood, one must go even below the level of the cell structure to the molecular level.

2.1.1 Chemical Composition

What all wood does have in common is that it is all made from the same main chemical ingredients, which make up most of the cell wall: cellulose, hemicelluloses and lignin. These are polymeric molecules, built from monomers, and are present in differing amounts in different species. All cell walls also contain minor amounts of chemicals called extractives and some inorganic materials.

Cellulose

The main building block of wood is cellulose $(C_6H_{10}O_5)_n$, constituting approximately 40% to 50% of the dry wood substance by mass. It is a long linear-chained, high molecular weight molecule, composed of glucose monomers

($C_6H_{12}O_6$), in the anhydro form of D-glucose. This monomer is also known as hexose (6-carbon sugar), or β–glucose. These monomers are joined together via beta oxygen linkages, from the number one carbon atom on one glucose monomer to the number four carbon on the next, and thus can also be called β 1-4 glucane (Wilson and White, 1986). As two monomers join via two OH groups, a water molecule is released, and an oxygen joins the two remaining carbons (Raven et.al., 1987). Such a configuration of two monomers forms the basic repeating unit in the cellulose chain, and is called a cellobiose unit, and measures 1.03 nm in length (Panshin and De Zeeuw, 1980), (Sjostrom, 1981).

An individual cellulose chain as found in the cell wall can be up to 10,000 anhydro D-glucose monomers long (called the degree of polymerization), translating to 5150 nm or 5.1 µm in length (Panshin and De Zeeuw, 1980).
The very reactive OH groups on each glucose molecule project from either side of the cellulose chain, bind to OH groups on adjacent or parallel chains, forming hydrogen bonds. This cross-linking of parallel cellulose chains forms the crystalline bundles, which in turn form the cellulose microfibres and the bulk of the material of the cell wall.

Hemicellulose
Hemicellulose, accounting for from 20% to 35% of the total dry mass of the cell wall material (Panshin and De Zeeuw, 1980), is unlike cellulose in that it forms low molecular weight, branched polymer molecules. It is composed of different types of pentose and hexose monomers (Wood Handbook, 2002).

Lignin
Lignin, which accounts for approximately 23% to 33% by mass of dry wood substance in softwoods and 16% to 25% in hardwoods (Wood Handbook, 2002), is a very large, amorphous three-dimensional polymeric molecule. It behaves somewhat like a glue throughout the cell wall, giving the structure rigidity. However lignin also exhibits thermoplastic properties, essential to explaining

much of why wood behaves as it does when processed into various composites under heat and pressure. Lignin is quite insoluble, with low hygroscopicity (Panshin and De Zeeuw, 1980).

The basic structure of lignin, which is very complex, is generally thought to be composed of phenylpropane units, in which the "phenol ring may be substituted by as many as three methoxy groups". The addition of one methoxy group to the phenol ring produces a guaiacyl unit, and the addition of two methoxy groups results in a syringyl unit (Panshin and De Zeeuw, 1980).

Extractives

Extractives, one of two groups of compounds called extraneous materials, typically compose from 3% to 30% of the dry wood substance by mass, but have been reported as high as 35% in quebracho wood (*Schinopsis lorentzii Engl.*), (Panshin and De Zeeuw, 1980). They consist of a wide range of organic compounds, which as the name suggests, can be extracted by various means and with various solvents. Extractives impart such characteristics to wood as its color, decay resistance, smell and flammability, but more importantly in the context of this study, they can also affect permeability and hygroscopicity. Waxes, fats and sugars are some common extractive types, but a few of the more important groups are the polyphenols, tannins, and the oleoresins, from which turpentine, tall oil and rosin are made (Illston, Dinwoodie and Smith, 1979).

Inorganic Extraneous Materials

The inorganic group of extraneous materials in wood typically comprise from 0.1 to 1% of the oven dry mass of wood depending on the source and species. Approximately 70% by mass of this group is calcium, potassium and magnesium, which are of the alkali earth group of elements (Panshin and De Zeeuw, 1980). When wood is burned, the ash which remains is composed of these inorganic materials. Examples of the properties of wood related to these compounds are

the rate at which tools dull when working the wood, and the color of the flame when wood is burned.

2.1.2 Physical Structure

Just as the chemical composition of wood can vary from species to species, and even within a single tree, so can the physical structure. However, in general terms the structure of wood is like a bundle of drinking straws, with the axial or longitudinal direction of the straws parallel to the axial or longitudinal direction of the trunk of a tree.

The straws of the softwood or coniferous tree are called tracheid cells, and in the hardwoods they are primarily tracheids and vessels. The softwood tracheid is typically from 1.5 to 5.0 mm in length, depending on the species and location in the tree, and from 15 to 80 μm (0.015 to 0.080 mm) in diameter, thus often in the order of 100 times longer than wide, again depending on species and location of the cell within the tree (Wilson and White, 1986). In the hardwoods, the vessels, which are composed of numerous stacked vessel elements, vary in diameter from around 20 to 400 μm (0.020 to 0.400 mm). With respect to length, an individual vessel may be as long as several meters, but will more commonly measure around 200mm, which even at that will be composed of several hundred individual vessel elements (Wilson and White, 1986). The tracheids of hardwoods which are different from softwood tracheids, are of two types: the vasicentric tracheids, which occur with vessel cells; and the vascular tracheids, which are similar to vessel elements.

2.1.3 Variability and Strength-Affecting Characteristics

Above the chemical and cellular level of wood structure and variation in wood, are larger-scale, more significant, naturally occurring strength-affecting variations commonly referred to as "defects". These include knots, sloping grain, reaction wood, pitch pockets, and localized variations in density.

Why is wood stronger and stiffer in the parallel to grain direction than in the direction perpendicular to grain? Wood is an anisotropic material, unlike most plastic or steel, meaning that the physical and mechanical properties of wood are different in each direction. This difference in properties between the various directions is due to the structure of wood, which is composed of wood cells of different types and arrangements. Trees are classified into two main groups, the softwoods or gymnosperms (cone-bearing species) and the hardwoods or angiosperms. It should be pointed out here that hardwoods are not necessarily harder than softwoods, as the name would indicate. One of the softest and lowest density species in the world is a hardwood called Balsa (*Ochroma pyramidalis Urb.*), which is softer that most softwood species.

2.2 Wood Composite Materials

Wood composite materials are a "composite" of wood and non-wood materials. They have been described as "particles of variable length and thickness bonded together with a matrix to provide an artefact that possesses a measure of cohesive strength" by Dinwoodie (Dinwoodie, 1997). Wood composites exist in a whole range of complexities and products, from glue-lam (glued laminated timber) where boards are simply glued together, one on top of another, to melamine paper overlaid fibre board.

One logical classification system for wood composite materials is by element size, as suggested by Maloney (Maloney, 1986). Accordingly, a glulam beam consisting of large pieces of lumber laminated together with glue would be at one extreme, while paper or medium density fibreboard (MDF), which are composed of tiny wood fibres would be at the other. OSB falls somewhere toward the latter end of the list, between parallel strand lumber and waferboard.

There are many benefits to wood composite materials over unprocessed wood in its natural form. The most important of these are:

- The potential for the elimination or randomization of naturally occurring defects;
- The ability to design or engineer properties;
- The potential for using small, defective or otherwise unusable trees and recycled material;
- The ability to produce an almost unlimited range of shapes and sizes;
- The ability to integrate non-wood or synthetic materials into the composite;
- The potential to engineer the properties of the composite in each direction.

2.2.1 Elimination or Randomization of Defects

The inherent variability of wood as a result of being a natural material, is one of the main reasons for the development of wood composite materials. In order for an engineer or designer to be able to use a material effectively, meaning efficiently and safely, they must be able to predict its physical and mechanical properties with a small margin of error. Wood composite materials allow for the minimization of this inherent variability, resulting in a more uniform and predictable building material, with improved strength properties.

By reducing a large wood element or log into smaller size elements, one has the ability to cut out and remove many of the naturally occurring defects in the process. For example, when lumber is finger-jointed, knots can be detected and cut out of the longer lengths, and then the knot-free pieces can be joined together producing a long, uniform knot-free length. In OSB production, long logs are cut or "bucked" into shorter lengths, and sections with rot, knots or large crooks can be eliminated. Many of the remaining defects are removed further on in the process by means of screens.

Small defects or strength reducing characteristics which are not removed, such as areas of juvenile wood or pitch pockets, can be randomized. By being distributed randomly throughout the product, the effect of defects can be minimized.

Drying shrinkage often presents another range of problems with solid wood and can result in checking, cracking and splitting, warping, twisting, and cupping. In solid beams, end checking is a common occurrence, which decreases shear strength. In the manufacture of wood composites, the wood elements are almost always dried before being processed and assembled, thus producing a far more stable final product. By pre-drying to moisture content conditions much closer to the final service conditions, most of the dimensional changes will have already taken place, and the moisture content gradients which cause the internal stresses and cracking are eliminated. By gluing the elements together and alternating grain directions such as in plywood and OSB, the product is further stabilized, since longitudinal shrinkage is more than an order of magnitude less than tangential or radial.

2.2.2 Ability to Design or Engineer Properties

By virtue of breaking large wood elements down into smaller elements, and then re-assembling them using adhesives and other process variables such as heat and pressure, the possibility arises to design or engineer the physical and mechanical properties of the final product. The range of possible new wood - based materials is virtually unlimited.

2.2.3 Element Alignment

One of the first factors which must be considered is the alignment of the grain direction, because wood is much stronger in tension parallel to the grain than across the grain. For example, the average tensile strengths of Eastern white pine (*Pinus strobus*) parallel to grain is 73,100 kPa vs. 2,100 kPa perpendicular to grain (Forest Products Laboratory, 2002). By manipulating the grain direction

of the individual wood elements, mechanical properties can be preferentially altered to suit the end use. However, in order to be manipulated in a designed way, the elements in case must have an aspect ratio, i.e. their length and width and thickness dimensions cannot all be the same. For example, in the case of parallel strand lumber such as Parallam^{TM}, made by Weyerhaeuser TJM, the long, slender wood elements are all aligned in the machine direction (axial direction of the product). Because the grain of the component strands and hence long axis of the wood cells lies in the same direction, maximum tensile strength is achieved in the axial direction. Maximum bending strength and stiffness are in the planes perpendicular to the axial direction. Such products are designed primarily for use as long span beams, and maximize the material performance. In the case of OSB, by aligning the top and bottom surface elements in the machine direction, and the core perpendicular, in the cross-machine direction, maximum bending strength and stiffness are obtained in the machine direction. Thus when OSB panels are used for flooring or roofing, they are laid with the long 8-foot (2438 mm) direction across or perpendicular to the joists. Depending on the proportion of strands in each layer, the ratio of the properties is also varied.

2.2.4 Use of Small or Otherwise Unusable Trees

Feed-stock element size is often a limiting factor in products such as lumber or plywood. Such products require large diameter, relatively straight whole logs. Composites made from smaller wood elements can often utilize such wood that would be otherwise unsuitable. Small diameter trees, trees with short useable lengths, or even tops and branches can be made into small element composites such as OSB. Even smaller feed-stock sources, such as lumber off-cuts or edgings can be used by some composite products, such as particleboard or fibreboard, where the composite elements are even smaller and the process allows for their handling.

2.2.5 Large Composite Sizes

The dimensions of solid sawn lumber are limited by the size of the tree. For anything longer or wider than the tree, larger members must somehow be assembled from the wood elements which are available. These are wood composites, and can be produced in virtually any dimensions desired. And as the remaining old growth trees are depleted or what remain are placed under protection, the dimensions in which solid sawn lumber is commonly available are becoming smaller. This trend is becoming increasingly evident in applications such as floor joists, which are being replaced by wood composite I-beams, and in longer span beams, which are increasingly made of parallel strand lumber, such as Parallam.

2.2.6 Integration of Wood and Non-Wood Materials

The final benefit of wood composite materials over wood in its natural form is the ability to integrate various non-wood materials into the structure. Virtually all wood composite materials from glulam to particleboard, including OSB include some form of binder or adhesive to adhere the individual elements together. Further materials can be incorporated for improving various properties such as resin impregnated paper overlays to create very smooth surfaces, or glass or Kevlar fibre mats to improve strength, abrasion resistance or water resistance.

2.3 OSB Background

Oriented strandboard (OSB) is an engineered wood composite panel product, made by gluing together small wood elements called "strands" under heat and pressure. It's most common use is in residential house construction, which currently consumes approximately 60% of all OSB produced (Schuler and Adair, 2003) for wall, roof, or floor sheathing, but it is also used for many other applications such as for the web of wood composite I-joists, the skins of structural insulated panels (SIPs), for industrial packaging, and increasingly for wall studs. OSB is commercially available in a range of thickness from 6.4mm (1/4") to over

50mm (2") and it most commonly comes in sheets measuring 1219mm x 2438mm (4' x 8').

OSB evolved from another mat formed panel product called waferboard, which was first commercially produced by MacMillan Bloedel in Hudson Bay, Saskatchewan in 1963 (NRC, 2000). This product was also commonly referred to as "chipboard", and the commercial trade name was "Aspenite". Waferboard is composed of small, roughly rectangular wood elements measuring approximately 50mm by 50mm (2" by 2"), and 0.6mm (0.025") in thickness. These elements or wafers are randomly oriented in terms of grain direction and glued together with a water resistant phenol formaldehyde resin under heat and pressure, to produce a panel.

The innovation which differentiates OSB from waferboard is the orientation of the wood elements. It is sometimes debated as to who invented OSB, but consensus seems to be with Mr. Al Owen, the former owner of Pellican Spruce Mills in Alberta, which was bought in 1987 by Weyerhaeuser. The thin wood elements in OSB are called "strands", and they have a definite aspect ratio to them in terms of length and width. OSB Strands are commonly approximately 100mm to 140mm (4" to 5.5") in length, and strand width varies from just a few millimetres (called splinters) up to almost equivalent to the length, depending on where the strand fractures along the grain during stranding. The grain of the wood in the strands always runs in the direction of the strand length. This geometric strand property in which the length is greater than the width, called "aspect ratio", is the main difference separating OSB strands and waferboard "wafers", and is what allows the strands and hence the grain direction to be oriented (hence the name "Oriented Strandboard"). Waferboard, on the other hand, is manufactured with the wood elements randomly arranged in terms of grain direction (no orientation). Some OSB, designated OS-1 grade, is made with a random core. OS-2 grade, as manufactured for this study, has the core oriented perpendicular to the top and bottom surfaces. The result of the ability to

align the grain direction is the ability to preferentially design the mechanical properties of strength and stiffness of OSB in each direction, and hence the designation as an engineered wood composite product. The minimum strength and stiffness values in accordance to CSA 0437.0 for Grade 0-2 (Structural Use Panels) are listed below in Table 2.1.

Typical OSB is composed of three separately oriented layers of strands. The top and bottom surface layers are oriented with the long strand axis and grain direction parallel to the length of the panel (known as the machine direction), and the center or core layer is oriented 90° to the top layers, with the long strand axis parallel to the width of the panel (known as the cross-machine direction). The ratio of the thicknesses of these layers (known in the industry as the "differential") determines the ratio of panel flexural strength (modulus of rupture (MOR)) and stiffness, (modulus of elasticity (MOE)) in the machine direction to the cross-machine direction.

Table 2.1: Minimum OSB Strength and Stiffness Values, Dry, at Time of Shipping, in Accordance to CSA 0437.0 for Grade 0-2 (Structural Use Panels).

Orientation	MOE (MPa)	MOE (psi)	MOR ((MPa)	MOR (psi)
Machine Direction (Parallel to long direction)	5500	800,000	29.0	4200
Cross- Machine Direction (Perpendicular to long direction)	1500	225,000	12.4	1800

The vertical density profile (VDP), which is a measure of panel density through the thickness of the panel, is another factor to consider in the design of an OSB product. In general, the higher the extreme fibre density, or the steeper the VDP, the stiffer the panel. The relationship between flexural stiffness and depth of a rectangular cross-section specimen under a three-point loading configuration is given by the following relationship:

$$\Delta = \frac{PL^3}{48EI} \quad \text{and} \quad I = \frac{1}{12}bd^3 \qquad \qquad \text{Equation [1]}$$

where Δ = deflection (mm)
     P = load (N)
     L = span between supports (mm)
     E = modulus of elasticity
     I = specimen section modulus
     b = specimen width
     d = specimen depth

The implication is that due to the cubic relationship between stiffness and specimen depth, the farther a section or strand is from the neutral axis, the greater it's contribution to stiffness or modulus of elasticity. Hence, if one wished to design a panel with the stiffness in both the machine and cross-machine directions approaching equality, the amount of cross-machine direction strand needed in the core would greatly exceed the amount of surface strands in the machine direction.

The second factor of panel vertical density profile further complicates matters if one were to attempt to manufacture the aforementioned panel design. As illustrated in Figure 2.1, the density of OSB varies greatly through the thickness of a panel. This vertical density profile is the result of several factors, which include how the mat is pressed into a panel during manufacture (the pressing cycle), the press platen temperature, the resin types, the species of wood, and the moisture content distribution within the mat. It will later be shown that the moisture-related properties of OSB are dependent on the density of the panel. Dai et al. (2002) have conducted extensive studies on the effects of critical manufacturing variables which can be used to optimize the "vertical density profile…a critical property in wood composites, which affects almost every physical and mechanical property of resultant products".
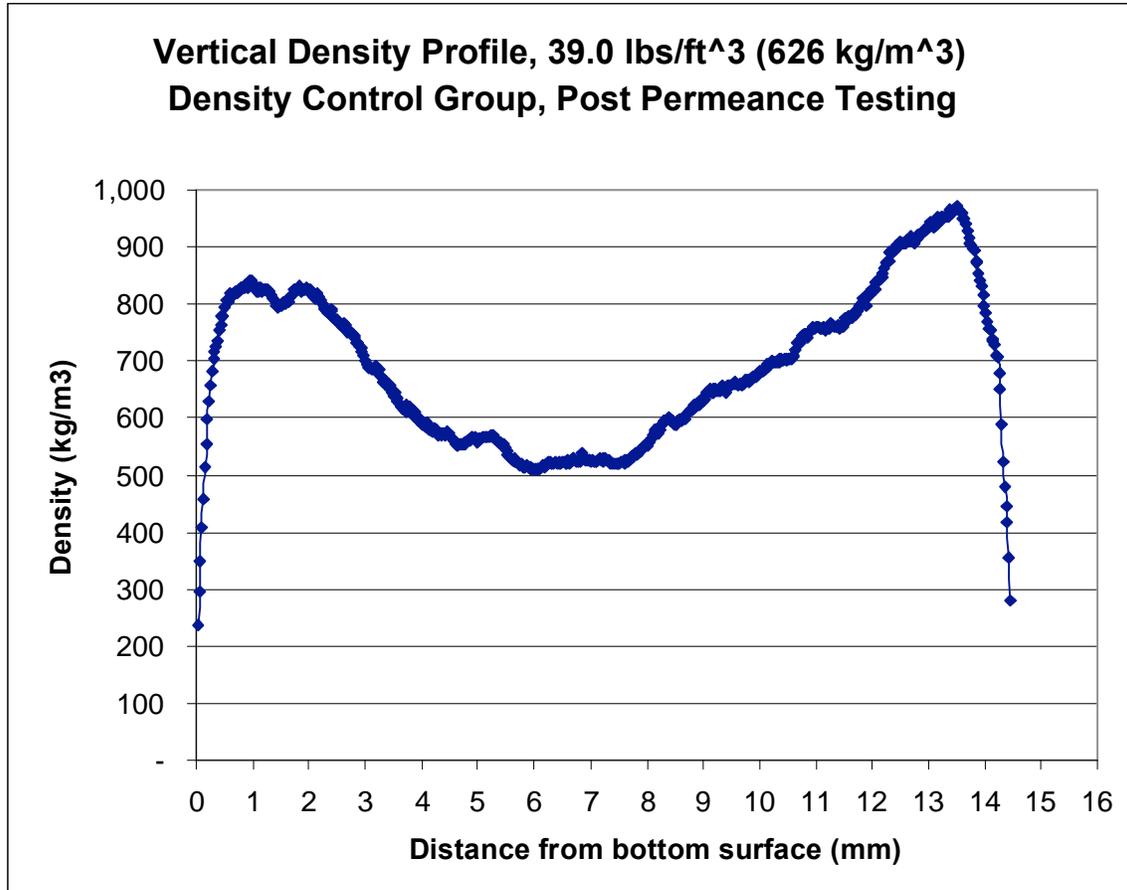
Figure 2.1: Vertical Density Profile of 39.0 lbs/ft^3 Unit Weight (626 kg/m^3 Density) Control Group OSB Panel, Post Permeance Testing by X-ray Densitometer.

The x-ray densiometer measurements used to create Figure 2.1 were conducted in the UofT Faculty of Forestry laboratory by the author. A brief description of the x-ray densiometry equipment and measurement technique is provided in Section 5.5.2.

Chapter 3

Moisture and Wood

3. Introduction

Moisture is one of the most important factors affecting building envelope performance, including durability, since it is involved in almost every material deterioration mechanism (Straube and Burnett, 2001). These deterioration mechanisms include the growth of microorganisms such as mould and decay fungi, corrosion of metals, dissolution, freeze-thaw of masonry, swelling/

shrinkage, and staining. In order to better predict the performance of building envelopes and design for durability, the interactions between moisture and the component building materials must first be understood.

3.1 Water, Storage and Transport

Susceptibility to moisture-related damage is dependent on the wetting, storage and drying properties of a material or assembly. If a material is hydrophobic or non-wettable such as vinyl siding or wax as shown in Figure 3.2, it will not get wet or store any moisture, and all the moisture-related problems are avoided. However, if the material is hygroscopic, meaning that it has an affinity for water vapour in the air, or is wettable, meaning that it has an affinity for liquid water, such as wood, brick or concrete, then moisture related damage is possible.

If a material is wettable or hydrophilic (opposite of hydrophobic), and capillary active, meaning that it has internal surface area for water molecules to be adsorbed, and small interconnected passages or capillaries for moisture to gain access, then it has some water storage potential. The potential for damage depends on (a) what relative humidity the material is at and thus the energy level of the moisture (which relates for example to the availability of the moisture for microorganism uptake), and (b) for how long it stays wet. If a material has few and relatively large capillaries, such as in well fired brick, capillary water will not appear until at high relative humidities. Also, if the capillaries are not interconnected and are inaccessible, they may not be accessible to moisture. The temperature range in which a material gets wet is another factor important for assessing the potential for moisture-related damage. For example, mould fungi need a temperature range between -7 and +55°C, whereas decay fungi need a temperature range between -5 and +45°C (Viitanen, 1996). Finally, if the material or assembly is able to dry quickly, it may then be able to dry out before damage occurs. It may also be able to lose some moisture between wetting events, possibly avoiding reaching a critical moisture level where damage occurs.

The combined water vapour permeance and sorption properties of a material or assembly determine the wetting, storage and drying properties, and thus are the critical factors in determining whether or not deterioration can take place. For a given set of environmental conditions, they will influence whether a material will be able to sustain the growth of microorganisms such as mould or deteriorating fungi, or become susceptible to other deterioration mechanisms, such as freeze-thaw, spalling, corrosion, or dissolution.

3.2 Water and Moisture

3.2.1 The Water Molecule

A water molecule consists of two hydrogen atoms bonded covalently with an atom of oxygen, as shown in Figure 3.1. In a covalent bond, electrons are shared between atoms, rather than as in an ionic bond, where one atom gives up electrons to another. The single electrons on each hydrogen atom are drawn to the oxygen atom, which only has six electrons in its outer valence shell. The result of the electron sharing is that the oxygen atom gains two electrons to complete its outer shell to eight electrons, its lowest energy state, while each hydrogen atom in turn shares one of the oxygen electrons, in turn giving each hydrogen two electrons in their outer valence shell, again the lowest energy state.

The shape of the water molecule is bent or angular (Figure 3.1). One might predict that the angle between the two hydrogen atoms and the two unbonded lone electron pairs might be 109.5^o. Such a spacing between the four electron clouds would be equal and thus the water molecule would be at its lowest energy state. However, experimental measurements using x-ray diffraction have shown that the angle between the two hydrogen atoms is 104.5^o, not 109.5^o. This is explained by the unbonded electron pairs having clouds, which are larger or

more negative that the clouds associated with the hydrogen atoms, and the larger more negative clouds distort the bond angle and molecular shape by pushing the hydrogen atoms closer together (Toon and Ellis, 1978).
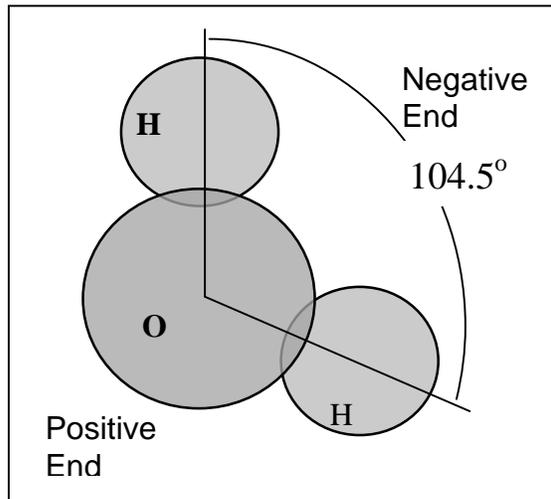
Figure 3.1: The Geometry of a Water molecule.

The electrons in a water molecule are shared unequally, in that they are held by the oxygen atom more strongly than by the hydrogen atoms. This is because oxygen has a higher electronegativity, or "electron attracting" power than hydrogen. In other words, the oxygen atom with only six electrons in its outer shell has a stronger demand for two more electrons to complete it's outer shell, thus attaining a lower energy state. The result of the electron sharing is that the hydrogen atoms end up with a partial positive charge, because their electrons have been pulled towards the oxygen, while the oxygen atom ends up with a partial negative charge. This charge imbalance on the molecule produces a dipole moment. One end of the water molecule (the end with the hydrogens) is more positively charged, while the oxygen end is more negatively charged (Figure 3.1). As a result, water is a polar molecule.

The fact that one end of the water molecule is slightly positively charged (the hydrogen end) compared to the other, results in an attractive intermolecular force between two such molecules with electric charges of opposite polarity. When

two such molecules join, the bond is called a hydrogen bond. In the case of a hydrogen bond between two water molecules, one of the hydrogen atoms with a slight positive charge is attracted to one of the negatively charged oxygen atoms. Each water molecule has the potential to bond with four other water molecules, two on the hydrogen atoms, and two on the oxygen atom, with the two free electron pairs.

Surface tension is an important phenomenon, which affects the properties of water, and it also occurs on the surfaces of other liquids and solids. When a water molecule is submerged and surrounded by other water molecules, it is pulled evenly in all directions. In each direction there are other water molecules with which to hydrogen bond. But when a water molecule is on the surface of the water, then on the surface side it no longer has other water molecules to bond with. This results in the re-orientation of bonds, with the end result of an overall increase of bond density in the surface plane. Surface tension is demonstrated when a droplet of water is placed on a non-soluble or hydrophobic surface as illustrated in Figure 3.2. Because the water remains in the form of a relatively round sphere, it is being held in that shape by surface tension forces.

Figure 3.2:   Water Drop on a Hydrophobic (left) and Hydrophilic (right) Surface.

The effect of surface tension is again seen when two water droplets come together and instantly join, forming one large spherical droplet. Surface tension can also be explained in terms of energy. Acknowledging that, according to the

second law of thermodynamics, all systems in the universe tend towards or try to achieve a state of maximum entropy and minimum enthalpy, the latter state of minimum enthalpy means the lowest energy form. Since the water molecules on the surface have unfulfilled hydrogen bonding potentials which face up into the air, these molecules are not at their lowest energy state. Thus the body of water attempts to assume a shape where the surface area is minimized, which in the case of a droplet is a sphere, and in the case of water in a cup is a flat surface. However, in the case of water in a cup, or more obviously in a small diameter capillary, how is the meniscus explained? This is again the result of surface tension, but in combination with something called adsorbed water, which must be explained before explaining the meniscus.

Water can exist in many forms or states. The most common forms of water are liquid, gas known as water vapour, and solid as ice or snow.

Another common form of water is the adsorbed state. It is also referred to as "sorbed", "hygroscopic" or "bound" water (Skaar, 1988). In the adsorbed state, water is similar to liquid water in that it has condensed from the vapour form to a lower energy state, yet it is different in that it is more tightly held to a surface and at an even lower energy than liquid water. An example is the meniscus, or upwards concave curvature at the edges of liquid water which is in contact with a non-hydrophobic surface, and is the result of surface tension, combined with a thin layer of adsorbed water pulling upwards.

3.3 Storage

3.3.1 Water Vapour

The composition of dry air by volume at ground level is approximately 78% nitrogen, 21% oxygen, small amounts of argon, carbon dioxide and other gases. Moist air can contain up to 4% water vapour by mass (Hutcheon and Handegord, 1995).   The amount of water vapour in the air at any given time can be measured in terms of humidity ratio (kg water vapour per kg dry air), or vapour pressure (Pa) or relative humidity (%) for a given temperature.

Water in the vapour or gas state, is in the highest energy state commonly found. Any given gas molecule at room temperature and pressure experiences approximately four billion collisions every second (Hutcheon and Handegord, 1995). The energy required to evaporate, or change from the liquid to the vapour state, otherwise known as the latent heat of vaporization, is 2500 kJ/kg. Conversely, when water condenses from the vapour state back to the liquid state, it gives off the same 2500 kJ/kg of energy as the latent heat of condensation. Due to the high kinetic energy level of water vapour molecules, their density is also low.   The molecular spacing in the vapour form varies considerably with temperature, and for saturated water vapour in the range from $0^{o}C$ to $140^{o}C$ measures from 1830 nm to 248 nm, or from 60 to 8 times greater than in the liquid form (Skaar, 1988). Thus, the amount of water stored in wood as water vapour at any given time is low as compared to the liquid water and adsorbed water states.

3.3.2 Adsorbed water

Adsorbed water is in a state somewhat similar to liquid water, but different in that it is more tightly held to a surface, and lower in energy. For water molecules going from the liquid to the adsorbed state, energy is given off (the latent heat of adsorption). Water can begin to exist in the adsorbed state on non-hydrophobic surfaces at relative humidity levels of approximately 5%, as found by T.C.

Powers (1965).   With respect to wood, water in the adsorbed state can only be found within the cell wall or on the lumen facing surface, as opposed to within the cell lumen, illustrated in Figure 3.8 (Skaar, 1988).   At any given time on such a surface, there is a constant exchange of molecules between water vapour molecules in the air and the water molecules on the surface in the adsorbed state.   Molecules bump into the surface and become adsorbed; at the same time other molecules which acquire the kinetic energy necessary to break away from attractive forces of the surface become airborne again and enter back into the vapour state.   When a state of equilibrium is reached between the surface and the air, the rate of water vapour molecules landing onto the surface is equal to the rate at which adsorbed molecules are leaving the surface and entering the vapour state.

As relative humidity increases, the number of adsorbed water molecule layers also increases on any hydrophilic material, as shown in Table 3.1. At 10% RH, the adsorbed film is around one water molecule thick, and not until around 50% relative humidity does the adsorbed film grow to two molecules thick (Powers, 1965).

The heat of adsorption is directly related to the adsorbed film thickness.   For cement paste, the first molecular layer of adsorbed water releases 3700 kJ/kg, the second adsorbed layer 2972 kJ/kg, and the fifth layer 2500 kJ/kg, which is equivalent to the latent heat of vaporization for water (Powers, 1968). This again illustrates that the first layers are most tightly held and lowest energy, and subsequent layers less tightly held and higher energy until the fifth layer at which the water molecules behave as liquid water, known as capillary water or free water in wood.   In Table 3.1, Powers shows the average thickness of such an adsorbed layer over a flat surface of cement paste, in both angstrom units and in the number or fraction of adsorbed molecule layers, and in Figure 3.3 graphically, including the adsorption energy associated with the adsorbed layers.

Table 3.1: Estimated Average Thickness of Adsorbed Film in Cement Paste at Different Relative Humidities (Powers, 1965).

Relative Humidity (%)	Thickness		
	$\overset{0}{A}$	nm	Molecular Diameters
5	2.00	0.200	0.76
10	2.45	0.245	0.95
15	2.80	0.280	1.06
20	3.05	0.305	1.16
30	3.40	0.340	1.30
40	4.25	0.425	1.62
50	5.15	0.515	1.96
100	13.00	1.300	5.00

Diameter of adsorbed water molecule = 2.63 $\overset{0}{A}$

10 $\overset{0}{A}$ = 1 nm
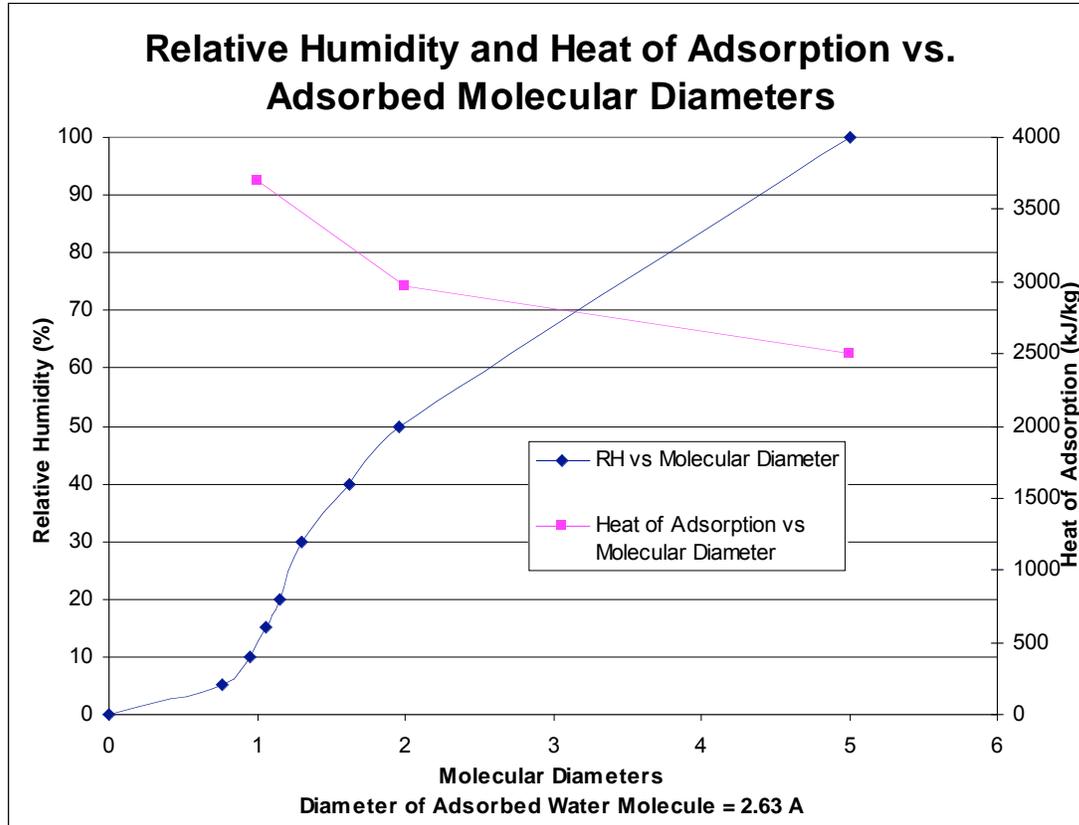
Figure 3.3: Relative Humidity and Heat of Adsorption vs. Molecular Diameters of Adsorbed Water. Data from "Properties of Fresh Concrete", Powers, 1968,

Although these data are for cement paste, the behaviour of adsorbed water on wood surfaces would be very similar, as both are hygroscopic materials with very large internal surface areas. The volume of water which can be held in the adsorbed state, depends on the ambient relative humidity above the surface, and also on the total surface area available. In wood, the point where free or capillary water can begin to exist within the cell lumen is at the fiber saturation point, when the cell wall is fully saturated but the cell lumen remains empty (Figure 3.8).

When looked at on a per-mass of water sorbed basis rather than on a molecular layer thickness basis, the differential heat of sorption (Q_s) is the amount of energy released per unit mass of water sorbed at a given moisture content, commonly measured in calories per gram of water sorbed. The heat of sorption

starts off high at very low moisture content, as the first water molecules attach to the surface of the material, and decreases quickly up to the fiber saturation point moisture content for wood, when the cell wall is fully saturated and the differential heat of sorption becomes zero, just as in Figure 3.3. It is thus "a measure of the excess binding energy of the water molecules to the wood substrate over that between the water molecules in the liquid state", which would be measured beyond the fiber saturation point (Skaar, 1988). The total area under the curve from oven dry to fiber saturation is the total heat of wetting (W_0). The total heat of wetting is the heat energy given off per gram of oven dry wood soaked in an excess of liquid water sufficient to raise its moisture content above the fiber saturation point, and has units of energy per oven dry mass of wood. It is proportional to the total number of sorption sites available for the sorption of water (Skaar, 1988). If the heat of wetting at an arbitrary moisture content m between the oven dry and fiber saturation moisture contents is simply called the heat of wetting (W), then the difference between total heat of wetting (W_0) and the heat of wetting at (W) some moisture content (m) is called the integral heat of sorption ($W_0 - W$), and the relationship between them and the differential heat of sorption (Q_s) is as follows (Skaar, 1988):

$$W_0 - W = \int_0^m Q_s dm \hspace{4cm} \text{Equation [2]}$$

Where: W = Heat of wetting at some moisture content m

                 W_0 = Total heat of wetting from oven dry moisture content 0 to moisture content m

                 Q_s = Differential heat of sorption

According to Stamm (1964) the differential heat of sorption at zero moisture content $(Q_s)_0$ is very similar for a range of cellulosic materials including wood,

cotton, and viscous rayon, ranging from 265 to 330 (with a mean of 290) calories per gram of water, and is due to the hydrogen bonding of water molecules to OH groups on the wood surface. Skaar (1988) notes that due to this fact, "the nature of the initial bond between water and dry cellulosic materials is essentially the same for all such materials". He also points out that although curves of the differential heat of sorption (Q_s) plotted against moisture content vary among such materials, when the differential heat of sorption (Q_s) is plotted against relative humidity, the curves for different wood species become very similar.

Comparing the figures for cement paste from Powers, when the latent heat of vaporization (2500 kJ/kg) is subtracted from the heat of adsorption for the first adsorbed layer (3700 kJ/kg), the difference (1200 kJ/kg) is the differential heat of sorption at the zero moisture content or oven dry state $(Q_s)_0$. Since 1 calorie = 0.004184 kJ, then $(Q_s)_0$ for cement paste becomes 286.8 cal/g. This value for cement paste is almost identical to the mean value of 290 cal/g as reported by Stamm (1964) for a range of cellulosic materials.

3.3.3 Capillary Water

Capillary water, also known as liquid water, free water or bulk water, is defined by Powers (1965) as "localized accumulations of water that cannot be accounted for in terms of adsorption." In other words, it is water which is in a lower energy state than water vapour, but higher energy than in the adsorbed or solid forms, and can thus also be defined in terms of energy.

For capillary water to occur, several conditions must be satisfied. First, according to Powers, capillary water can exist only when the tensile stress in the surface of the adsorbed film becomes equal to the surface tension of liquid water. This can theoretically only begin to occur at around 50% RH, when the third adsorbed molecular layer begins to appear, as illustrated in Table 3.1. At this point, the distance between the outermost water molecules and the substrate or

adsorbate surface becomes large enough to reduce the attractive forces between them, to the point where the surface tension in the adsorbed layer becomes equal to that of free or bulk water. A second condition necessary for a meniscus to form, behind which capillary water can exist, is that the capillary be sufficiently small.

The relationship between the vapour pressure p over the meniscus in a capillary, to the saturation vapour pressure p_o (and thus relative humidity) and the radius of curvature of the meniscus r is described by the Kelvin equation:

$$\log_e {p}\Big/{p_o} = -\frac{2\gamma M}{r\rho RT}$$
Equation [2]

Where p = vapour pressure over meniscus (Pa)

p_o = vapour pressure at saturation (Pa)

γ = interfacial tension, water to air (surface tension)
(0.07275 N/m)

M = mole mass of water (0.01802 (kg/mol))

ρ = density of water (approx. 998 kg/m^3)

R = gas constant (8.314 J/(mol·K))

T = temperature (Kelvin)

A third condition, not explicit in the Kelvin equation, but which limits the lower relative humidity at which the meniscus can form and thus capillary water can exist, is the cohesive strength of water (approximately 1000 atm) (Powers, 1965). When capillary tension in the bulk water behind the meniscus exceeds its cohesive strength, the meniscus and the water behind it can no longer exist.

When these conditions are all satisfied, a meniscus can form with capillary water behind it. The volume of water held becomes then related to both the surface area (adsorbed water) as well as the capillary volume (capillary water).

Also according to the Kelvin equation, the smaller the capillary, the smaller the radius and the lower the vapour pressure or relative humidity at which capillary water can exist, down to 50% RH, below which it can no longer exist.   According to Skaar (1988), the Kelvin equation is valid to radii as small as $0.01\mu m$, which is much less than the radius of the smallest wood cell cavity (lumen), and corresponds to a relative humidity of approximately 90% calculated by the Kelvin equation.

As mentioned, it is a matter of debate regarding the exact number of adsorbed layers of water molecules, and at which point water is considered to no longer be in the adsorbed state, but in the capillary or free water state. This is generally thought to be around the five molecular layer thickness level. In terms of energy, it occurs when the energy of the outer most water layer is that of liquid (free or capillary) water.

When the relative humidity is increased to around 50%, capillary water begins to appear. This may at first appear contrary to what was just stated above, in that at 50% RH there were only two molecular layers of adsorbed water on a surface, and that not until beyond five molecular layers of adsorbed water can water be considered to be free water. This is the case for flat surfaces, but a complication arises in the tiny capillaries. Hydrostatic tensile forces arise, which interact with the hydrogen bonding forces between the surface and the adsorbed layers. The result is the appearance of capillary or non-adsorbed water in the small capillaries at approximately 50% RH. It first appears in the smallest capillaries, of 15 angstrom units (1.5 nm) minimum radius, and then with increasing RH in larger and larger capillaries. T.C. Powers shows again in the paper *Mechanisms of Shrinkage and Reversible Creep of Hardened Cement Paste, 1965*, in Table 3.2: "Computed Inscribed Diameters of Capillary Cavities Able to Contain

Spherical Bubbles at Given Humidities", the relation between the relative humidity (%) and the radius of the meniscus and of the capillary size for the meniscus to exist in equilibrium with that relative humidity. The same relationship and almost identical chart is presented by Skaar (1988) titled "Relationship of Activity (h), Capillary Pressure (P_o - P) and Capillary Meniscus Radius at 27°C".

Table 3.2: Relationship Between Relative Humidity, Hydrostatic Tension, Nucleation Radius and Required Radius of Spherical Cavity (Powers, 1965).

Relative humidity	Hydrostatic tension		Nucleation radius		Required radius of spherical cavity	
(%)	(atm)	MPa	($\overset{0}{A}$)	Nm	($\overset{0}{A}$)	nm
98	28	2.8	346	34.6	351	35.1
96	57	5.8	170	17.0	175	17.5
92	116	11.8	84	8.4	89	8.9
85	226	22.9	43	4.3	48	4.8
70	495	50.2	20	2.0	25	2.5
50	963	97.6	10	1.0	15	1.5
45	1100	111.5	*	*	*	*
40	1200	121.6	*	*	*	*

*: Meniscus cannot exist.

Diameter of adsorbed water molecule = 2.63 $\overset{0}{A}$

1 nm = 10 $\overset{0}{A}$

The column titled Hydrostatic Tension, in atmospheres, is a measure of the capillary tension of the water behind the meniscus. If one end of the capillary is in equilibrium with a lower relative humidity than the other end, water will attempt to flow from the high RH end towards the low RH end to eliminate the difference in capillary tensions. It is this mechanism which drives the capillary transport in capillary active materials.

3.3.4 Sorption Isotherm

The relationship between the moisture content (mc) of a capillary active material and the relative humidity (RH) of the environment surrounding it at a given temperature, is described by a curve called a sorption isotherm. The term "sorption" implies both adsorption (wetting) and desorption (drying), however this study deals specifically with adsorption for reasons of constraints described in Section 7.2, so desorption was not measured. Figure 3.4 is an example of a typical sorption isotherm (specifically adsorption, because was wetting only) for OSB, measured by the author. As the relative humidity of the atmosphere surrounding the material rises, the moisture content within the material also rises, whether it is in the vapour, adsorbed or capillary water state.
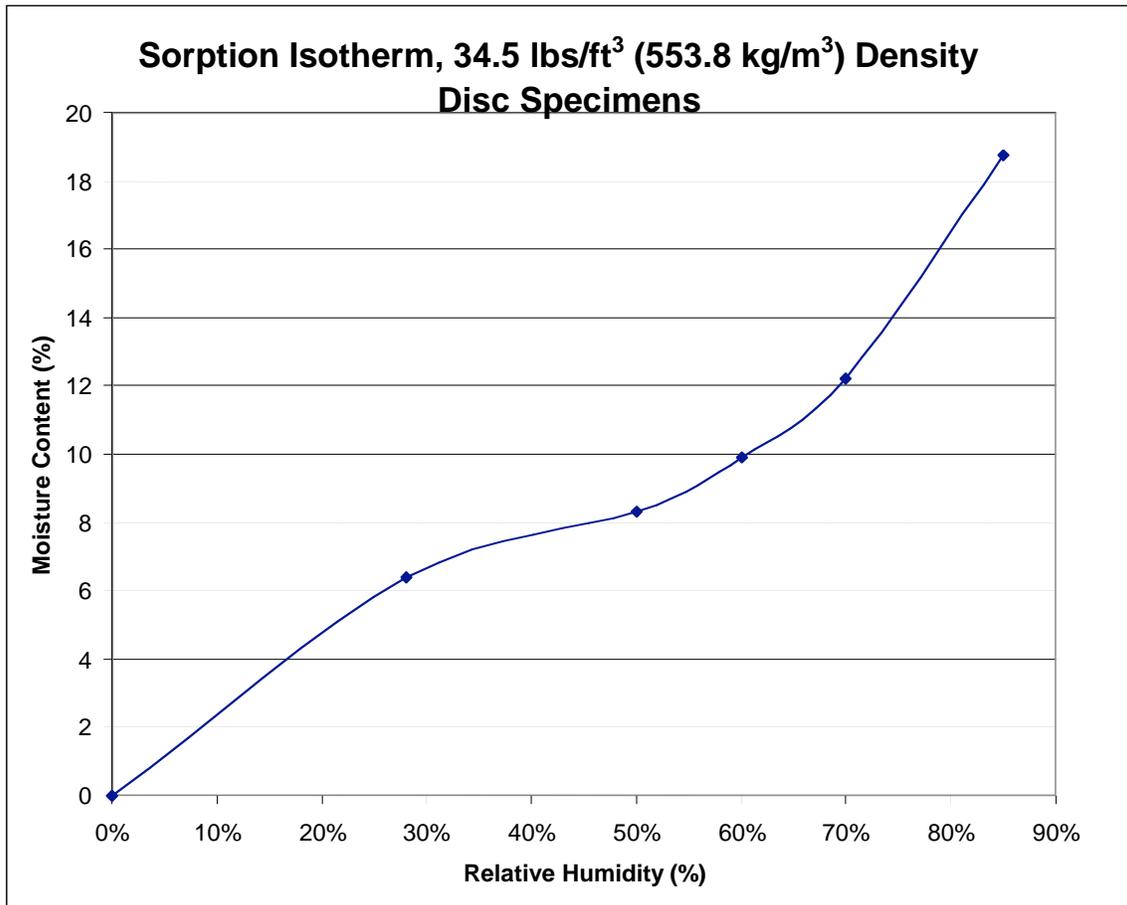
Figure 3.4: Typical Sorption Isotherm for a Hygroscopic Material (OSB).

The characteristic shape of the sorption isotherm is unique to different materials, and depends on their internal structure. It can be explained in terms of the various states in which the moisture is being held at the different corresponding relative humidities. The general shape of the sorption isotherm curve for wood and wood composite materials is one where the slope is steep from approximately 0 to 15 or 20% RH, then levels off somewhat until about 50% RH, where it gets steeper again, increasing until 100% RH or saturation.

The first portion between 0 and 50% RH is due to the accumulation of water in the adsorbed state. The first adsorbed layer exhibits the greatest affinity to the surface of the material, and subsequent layers have lower energy and are less tightly held, as the distance increases from the surface. The adsorbed layer thicknesses for increasing relative humidity levels are illustrated in Table 3.2. This explains the decreasing slope of the curve until approximately 50% RH.

At 50% RH we can begin to see the appearance of capillary water, so the slope of the curve begins to increase again with RH, increasing first as small capillaries begin to fill, and then increasingly larger and larger capillaries fill. This part of the curve tells much about the size distribution of capillaries within the material. A material such as well fired brick has very few small capillaries, and thus the curve remains flat until approximately 80% RH, when the RH is sufficiently high enough that even large capillaries begin to fill. Wood on the other hand, shows an increase in slope from approximately 50% onwards, indicating that it has some capillaries tiny enough to support capillary water at the first instance possible, and then a distribution of diameters to allow the slope to keep climbing, as larger and larger capillaries in the cell wall structure begin to fill. If wood contained only tiny capillaries, one would expect the curve to climb quickly at 50%, but then begin to level off again before 100% as all of them became full. A material with two or more discrete size distributions of capillaries might exhibit a curve with several distinct areas of slope increase followed by areas of levelling. The exponentially increasing slope of the sorption isotherm at the high relative

humidity end of the curve is also related to the cubic relationship between pore radius and volume of capillary water.

The hollow centres of wood cells known as cell lumens or cavities, measure from approximately 1 to 100 µm in radius, but the tapered ends may be as small as 0.1 µm, corresponding to a relative humidity of 99% for capillary water condensation according to the Kelvin equation (Skaar, 1988). When the cell walls are fully saturated with water, but the cell lumens or cavities remain empty, a point known as the fiber saturation point is reached.

Many different sorption isotherm equations exist for predicting the relationship between relative humidity and moisture content for organic materials (77 according to Skaar). One of the more commonly used is the BET (Brunauer-Emmett-Teller) theory, first proposed by Brunauer in 1938 (Skaar, 1988). It is thought to work fairly well below 40% RH, but not so well above this RH (Skaar, 1988). The model assumes that there is but one adsorbed layer possible, and that subsequent layers behave as capillary water. The model was improved on to better represent the relationship above 40% by Brunauer et al. (1983), by allowing up to n layers, with the best fit for wood occurring when n is between 6 and 8 (Skaar, 1988).

3.3.5 Water Storage in Wood

Wood is a hygroscopic material, meaning that it has an affinity for polar liquids such as water, in liquid, vapour and adsorbed forms. As described in Section 2.1.1, cellulose, the major constituent of wood, consists of individual glucose monomer molecules. These glucose molecules forming the cellulose chains, contain polar and very reactive hydroxyl (OH) groups, which have a strong affinity for other polar molecules such as other parallel cellulose chains, or water. These hydrogen bonds formed between OH groups and water molecules explain the very strong affinity of wood for water, and why the adsorbed water molecules closest to the surface of the cellulose are so tightly held as seen in the low RH

range of the sorption isotherm curve where the curve is very steep at first, then levels off. The first layer of adsorbed water closest to the wood surface is most tightly held and has the highest energy, and subsequent layers are less tightly held and have lower energy.

The relationship between wood density and the amount of water it will absorb is generally thought to be that higher density results in higher amounts of moisture for a given volume. This relationship may apply at lower relative humidities, but appears to reverse at the higher relative humidities, over about 75%, as shown in the results and discussed in this study. At the lower humidity levels, water is held mostly in the adsorbed state. The higher the internal surface area of the material, the more water can be adsorbed. In wood, it is the cell wall material which holds water associated with free OH radicals, mainly in the amorphous part of the wood (the hemicellulose), which is the most hygroscopic of the cell-wall constituents (Skaar, 1988). As the relative humidity rises, water begins to condense in the smallest capillaries first, and then progressively in larger and larger capillaries (Table 3.2). At higher relative humidities, the relationship appears to reverse, where lower density materials begin to hold more water (higher moisture content), as lower density corresponds with a larger capillary volume for the water to occupy (less wood mass, more void space). This is discussed in detail in Section 6.2.3, "Density vs. Sorption". Another type of capillary exists in wood, called a "transient capillary". These are capillaries which appear due to swelling during adsorption, and disappear again upon desorption.

Clay brick has been included as an illustration of an extreme case, as it has a low internal surface area for adsorbed water, but has larger capillaries, which begin to store condensed water at the over 80% relative humidity range. In this sense it is similar to a very low density wood material. Shown in Figure 3.5 are theoretical curves drawn by the author. These curves illustrate the sorption isotherms (volumetric moisture content vs. relative humidity) for three different density materials: a high density wood, a low density wood, and clay brick.

Experimentally, it is difficult to determine the relationship at high RH ranges with a high degree of accuracy, as condensation begins to occur very rapidly, capillaries become saturated, and any slight temperature change can result in drastic moisture content changes.
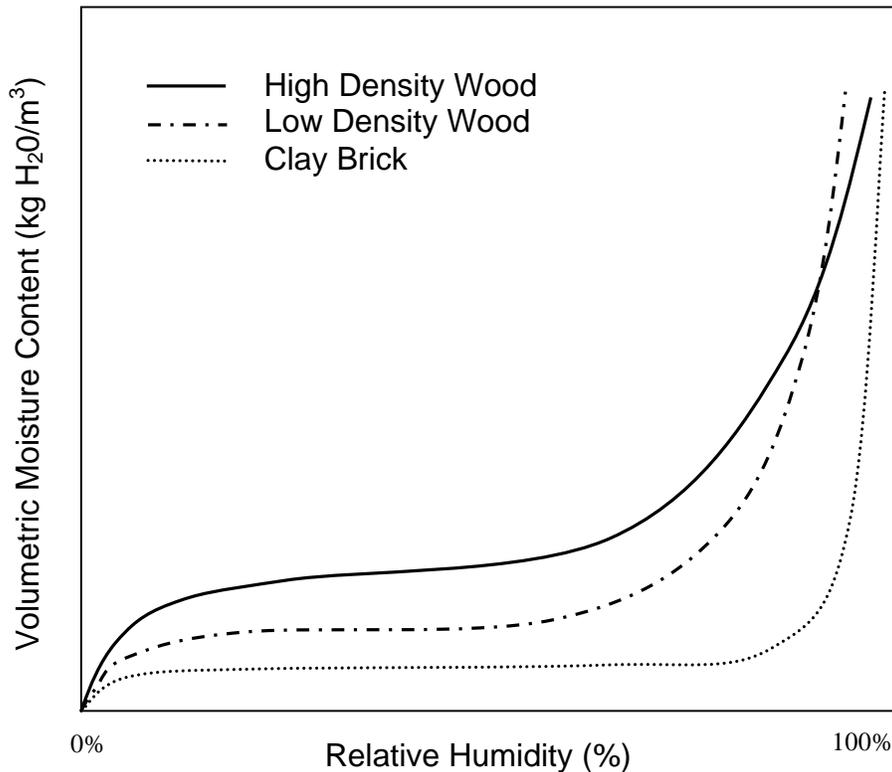
Figure 3.5: Schematic Representations of Relative Humidity vs. Volumetric Moisture Content for Different Density Materials (by Author).

This effect of density vs. moisture content, with the higher density material absorbing more moisture at lower humidities, and a reversal with lower density material absorbing more moisture at higher humidities will be seen again, specifically with respect to OSB, through examination of the experimental results from this study in Chapters six and seven.

3.3.6 Mould / Fungal Growth

For reasons of occupant health as well as the durability of wood frame buildings, there must be an understanding of the requirements of microorganisms for

growth. In general, all microorganisms require sufficient moisture to be available, temperature within a range which is neither too low nor too high, and a source of food such as most wood and wood composite materials on which to feed and grow. The final requirement for establishment and growth is sufficient duration under the conditions conducive to growth, which becomes more complicated, as under ideal conditions, the time will be shorter than under marginal conditions.

The microorganisms of concern fall into two general categories: mould fungi and decay fungi.

"Mould fungi are a heterogeneous and not particularly well defined group of fungi", and most of them belong to Ascomycotina (Viitanen, 1996). They can grow on numerous materials, including wood, paper, textiles, brick, concrete and even glass, provided there is some organic material, such as dust, on the surface. In general, the conditions necessary for their growth are relative humidities above 75 to 80%, and temperatures in the range of -7°C and $+55^{o}$C (Viitanen, 1996).

Decay fungi are generally classified into three types, which are brown rot, soft rot and white rot. According to Viitanen, the most common of the three types found in buildings with excessive moisture levels or water damage are the brown rot fungi, most of which belong to Basidiomycetes, and some to Ascomycetes (Viitanen, 1996). Conditions necessary for their growth are temperatures within the range of -5 to $+45^{o}$C and relative humidities above 94 to 98%, depending on the temperature (Viitanen).

The specific thresholds of temperature and moisture content for growth of microorganisms is varied in the literature, but the general consensus seems to be that to err on the safe side, wood is kept below a relative humidity of 75 to 80% (Time, 1998). However, to put relative humidity in terms of the resultant moisture content, depends on the type of wood or wood based material and its particular

sorption isotherm. Viitanen mentions that near the fibre saturation point (approximately 30% moisture content), the wood cell wall is in the most swollen state, resulting in the highest cell wall porosity, which then allows the enzymes and compounds produced by fungi to diffuse easily (Viitanen, 1996).

3.4 Transport of Moisture

Wood, in the form of a living tree, has been "designed" with the ability to transport materials in the form of water and dissolved substances, first from the leaves down to the roots for storage during the growth season, and then from the roots back up for growth during the spring. Thus products made from wood, including OSB, have some built-in or inherent ability to transport moisture. The ability of the composite to transport moisture depends on the arrangement of the elements, their continuity, densification during processing, and any chemical treatments or additions of materials, such as waxes and resins.

3.4.1 Permeability Defined

Permeability, simply defined, is the rate of flow of a fluid through a porous material across a unit area through a unit thickness under a pressure gradient. In SI units, vapour permeability is measured in ng/pa.s.m, (nanograms per pascal · second · meter). It can be visualized as the flow in ng through a $1m^2$ face x 1m thick cube of a given material, under 1Pa vapour pressure difference, as illustrated in Figure 3.6.
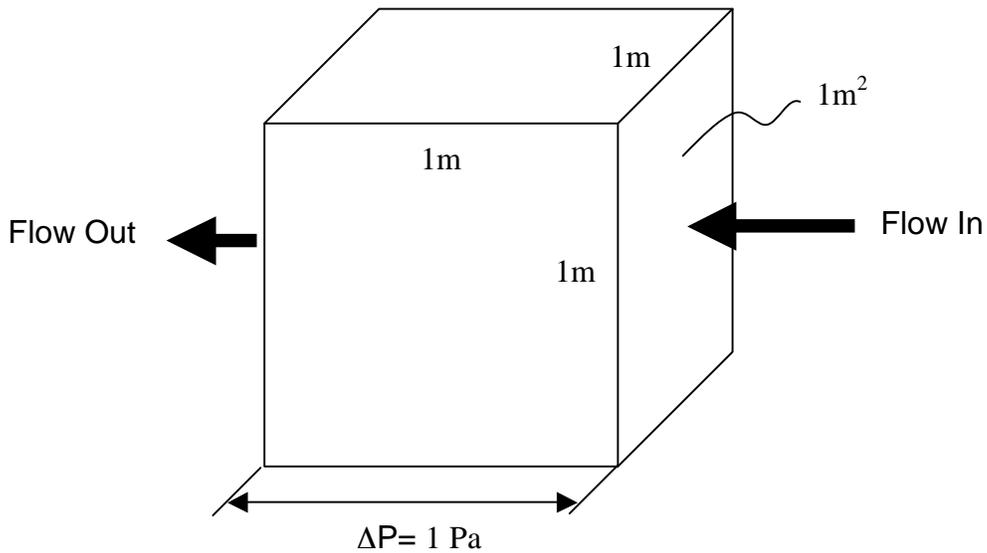
Figure 3.6 Illustration of Permeability, in ng/Pa·s·m (by Author).

3.4.2 Permeability in Wood

Wood exhibits a very large range of permeabilities, depending upon species, location in the tree, moisture content, drying history and direction of flow. When considering both the range of species as well as the flow direction, the range of permeabilities is reported to be in the order of 10,000,000 (Illston et al., 1979). For example, maximum permeability values in hardwoods are reported to be as much as 10 times higher than maximum values for softwoods (Pashin and De Zeeuw, 1980). With respect to the anisotropic nature of wood, the direction of flow is of even greater importance, where permeability in the longitudinal direction may be from 1000 to 100,000 times greater than permeability for the same species in the transverse (radial or tangential) direction (Panshin and De Zeeuw, 1980).

In general terms, the structure of wood has been said to be like a bundle of drinking straws, with the axial or longitudinal direction of the straws parallel to the axial or longitudinal direction of the trunk of a tree. The straws of the softwood or coniferous tree are tracheid cells measuring from 15 to 80 μm (0.015 to 0.080

mm) in diameter, and in the hardwoods they are primarily tracheids, varying in diameter from around 10 to 40 µm (0.01 to 0.04 mm), and vessels (or vessel elements) varying in diameter from around 20 to 400 µm (0.02 to 0.40 mm), (Wilson and White, 1986).

Within the conifers (softwoods), it is believed that the primary flow path in both the longitudinal and tangential directions is through the pits in the cell walls (Figures 3.7 and 3.8). This is because both the longitudinal tracheid cells, which constitute over 90% of the volume of conifers, and parenchyma cells, have closed ends (Panshin and De Zeeuw, 1980). Pits are openings which occur in the cell walls, where the primary cell wall is thinner than elsewhere, and where the secondary cell wall does not exist. The basic pit structure consists of the pit cavity through the thicker secondary cell wall, and the pit membrane made of the very thin remaining primary cell wall and true middle lamella. The thin pit membrane consists of an inner disc, called the torus, supported and attached to the pit border by a network of microfibrillar bundles oriented radially, which is called the margo. During formation, the torus becomes thickened by the deposition of material which encrusts it. At the same time, the margo becomes thinner due to enzymatic action, reducing it to a network of defined and separated microfibril bundles, each 0.1 to 1 micrometer in diameter, with openings between one another measuring up to 0.2 micrometers wide allowing for the passage of fluids and materials (Panshin and De Zeeuw, 1980).
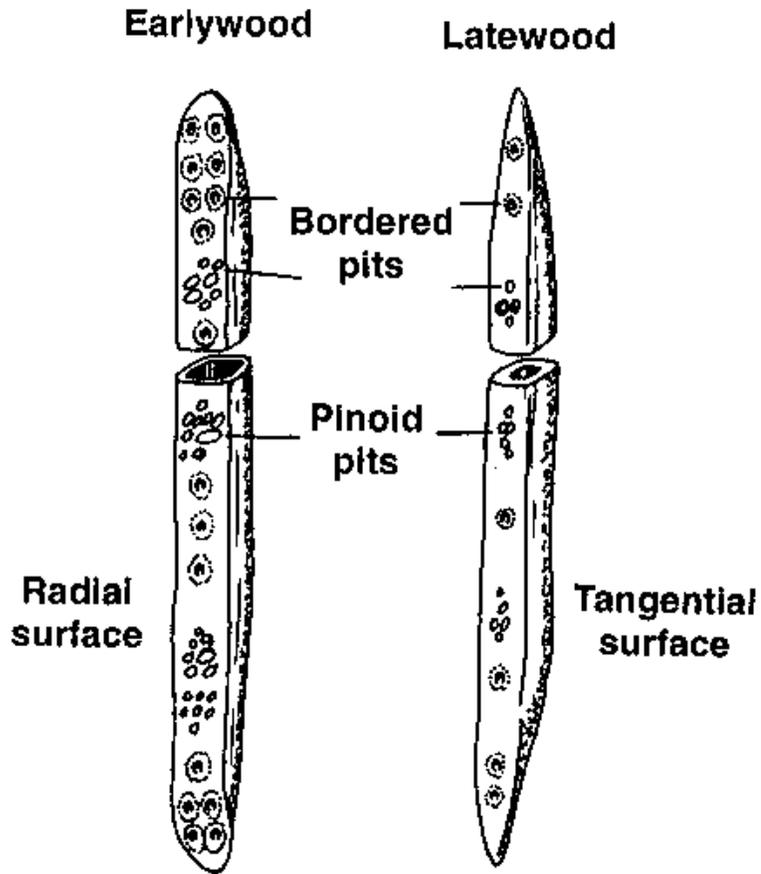
Figure 3.7: Softwood (Pine) Tracheid Cell, with Pits (Koch, 1972).
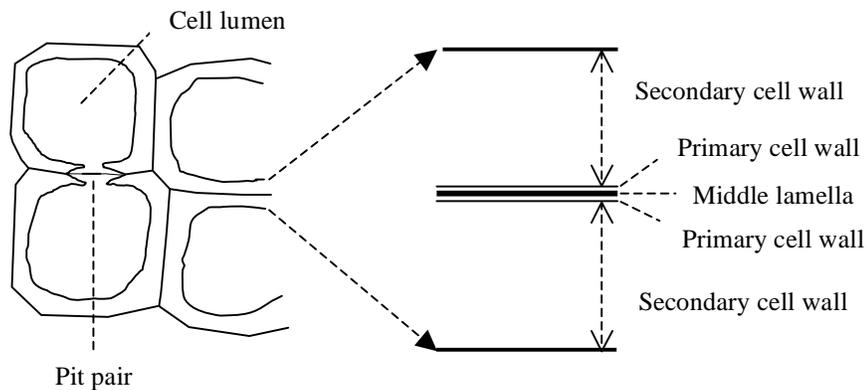
Figure 3.8: Cross-section Showing Cell Wall Structure, and Pit Pair "(by author).

Pits in common or adjacent walls of cells next to one another almost always occur in pairs, opposite to one another. Two such pits form what is called a pit-

pair, allowing flow between the two cells. There are three types of pits: the simple pit, which occurs between two parenchyma cells; the half bordered pit, which occurs between a parenchyma cell and an axial (longitudinal) tracheid; and the bordered pit, which occurs between two axial tracheids (Wilson and White, 1986). Simple pits are characterized by their more or less parallel pit cavity walls. The differentiating feature of the bordered pit is the concave shape of the opposite pit cavity walls, where the opening in the secondary cell wall closest to the lumen of each connected cell is smaller in diameter than at the midpoint between the two cells in the middle of the pit cavity. The half bordered pit is simply a combination of the two aforementioned pits, with the bordered end of the pit chamber (at the tracheid cell) constricted, and the other end (at the parenchyma cell) not (Wilson and White, 1986). There is also variation in pit sizes among the various wood species.

According to Wilson and White, the pit pairs are the major pathway for flow between adjacent tracheid cell lumens (Wilson and White, 1986). It was believed (Illston et al. 1979) that the pits or the size of the pits alone, was the determining factor in permeability. This led to the following equation, assuming a cylindrical shaped capillary:

$$\frac{QP_o}{\Delta P} = \frac{\pi r^4 \bar{P}}{8\eta l} + \frac{2\pi r^3 \delta_l \bar{V}}{3l}$$

Equation [3]

Where:
- Q = volume flow rate
- r = capillary radius
- ΔP = pressure drop across capillary
- l = capillary length
- η = viscosity

- $\bar{P}$ = mean gas pressure within capillary
- P_0 = gas pressure where Q was measured
- δ_l = factor depending on fraction of molecules undergoing diffuse reflection upon collision with capillary wall (Knudesn flow)

- $\bar{V}$ = molecular mean thermal velocity

which is a combination of the Poiseuille equation for laminar flow of both gas and liquid (derived from Darcy's law):

$$Q = \frac{\pi r^4 \Delta P}{8 \eta l} \cdot \frac{\bar{P}}{P_0}$$
Equation [5]

and the equation for slip flow along a circular cross-section capillary:

$$Q_s = \frac{2 \pi r^3 \delta_l V}{3l}$$
Equation [6]

where flow is proportional to a power function of radius, and because the pits are the smallest openings in the flow path. However, Petty and Puritch (1970) showed that at least 40% of the flow resistance in the longitudinal direction was due to the cell cavity or lumen. It should be noted however that there is a great deal of variation in types of pits, their sizes, shapes (they are not necessarily circular in opening), and whether or not they are open to flow, blocked (occluded), or partially open.

The major path for flow in hardwoods is through the tubular shaped vessel cells, know as vessel elements. The ends of these vessel elements contain openings called perforations. When two vessel elements are joined end to end, the pair of perforated vessel ends is known as a perforation plate, whereas the actual opening from one vessel to the other is known as a vessel perforation (Panshin and De Zeeuw, 1980). Transverse movement is through pitting, especially between fibres, and two adjacent pits are called a pit-pair. Transverse movement can also be through ray cells in the radial direction, mostly at low relative humidity levels (Perre and Turner, 2001).

3.4.3 Effect of Moisture Content on Permeability

The permeability (μ) or permeance (M) of hygroscopic, or capillary active materials including wood increases with increasing relative humidity or moisture content. Some examples of common building materials which exhibit this characteristic are illustrated in Table 3.3.

Table 3.3: Permeance Values (ng/pa·s·m^2) for Water Vapour Transmission at 23°C (from Table 5.5 in Hutcheon and Handegord, 1995)

Material	Dry Cup M (50 - 0%) RH	Wet Cup M (100 - 50%) RH	*Inverted Wet Cup (liq. Water - 50%)
Tar-infused sheathing paper	375	1770	4050
12.5mm wood fibreboard	2470	2520	Not available
Asbestos cement board	285	480	Not available
Polyethylene film (0.10mm)	5	4	Not available

*(Liquid water transport not vapour diffusion for inverted wet cup)

Siau, referring to the work of Stamm (1959) on determining the longitudinal permeabilities of *Picea sitchensis* specimens, explains the increase in permeability observed with increasing moisture content by a lower bonding energy between bound water molecules and sorption sites in the wood at higher moisture contents (Siau, 1983). Siau hypothesizes that this bonding energy should approach zero at the fibre saturation point, beyond which the addition of more water will be stored as free water in the cell lumens and thus will not be interacting with the cell wall material.

3.4.4 Moisture Transport Mechanisms and Permeability

The difference in rates in the hygroscopic or capillary active materials is also due to the different transport mechanisms at work at any given relative humidity. It should be noted here that the permeability values listed do not differentiate between the different transport mechanisms (water vapour diffusion, surface diffusion and capillary flow), but rather are the combination of all transport

mechanisms which may be at work at the relative humidity level stated. In some cases they may even be operating in opposite directions at the same time.

3.4.4.1 Vapour Diffusion

At the low end of the relative humidity scale, water vapour diffusion driven by a vapour pressure gradient will be the primary transport mechanism at work, along with some limited adsorbed flow due to a relative humidity gradient. But since the first molecular layers of adsorbed water are most tightly held, surface diffusion is not significant. The relative humidity is too low for any liquid or free water to appear in even the smallest capillary pores. Because water vapour diffusion is a slow or inefficient transport mechanism, the permeability is low at this RH level. The density of water molecules in the vapour state is very low as compared to in the liquid state, so the net amount of transport by the mechanism is limited. Of course, as the amount of voids or flow paths increases, the relative amount of vapour diffusion increases, such that a high porosity material such as glass fibre batt insulation will have a higher permeability than a lower porosity material, even though the transport is only by vapour diffusion. The other factor determining the rate of vapour diffusion is the vapour pressure or water vapour molecule concentration gradient across the material. The most commonly used equation for the calculation of water vapour flow is a form of Fick's law (Hutcheon, 1995; Hunter, 1995):

$$w = -\mu \frac{dp}{dx}$$

Equation [7]

where

w = mass of water vapour transmitted over time

p = vapour pressure

x = flow path

μ = permeability of material

A steady state form of this differential equation is as follows:

$$W = \bar{\mu} A \Delta t \frac{(p_1 - p_2)}{l}$$

Equation [8]

Where:

W = total mass of water vapour transmitted, in nanograms (ng)

A = cross-sectional area of flow path, in square meters (m^2)

Δt = time interval, in seconds (s)

$(p_1 - p_2)$ = vapour-pressure difference across the material, pascals (Pa)

l = length of flow path, meters (m)

$\bar{\mu}$ = average permeability of material, over the vapour pressure gradient involved, in nanograms per pascal second meter (ng/pa.s.m)

3.4.4.2 Adsorbed Flow (Surface Diffusion)

As the relative humidity is increased, the amount of adsorbed water on all of the internal surfaces of the hygroscopic material begins to increase. At 10% RH, the adsorbed film is around one water molecule thick, and not until around 50% relative humidity does the adsorbed film grow to two molecules thick (See Section 3.3.2).

The adsorbed layers of water molecules can contribute to transport in response to a relative humidity gradient through the mechanism of adsorbed flow, also known as slip flow. The flow is always in the direction of the relative humidity gradient, from high to low. The process works on the principle of the second law of thermodynamics, where the water molecules attempt to achieve the lowest energy state possible (minimum enthalpy) and at the same time to spread themselves out (maximum entropy). The adsorbed water molecules attempt to distribute themselves so that they are as close as possible to the surface or substrate. The first adsorbed layer is most tightly held and with the highest binding energy, and thus in the lowest energy state. Each subsequent layer is

farther away from the surface, less tightly held / lower binding energy, and in a higher energy state. Adsorbed flow occurs along the material in the direction of the relative humidity gradient, from high to low. The molecules at the high RH end can be envisioned as being in two, three or more molecular layers thick, depending on the magnitude of the relative humidity, and in fewer layers the further along one moves down the gradient towards the low relative humidity end. Along the way, between the two ends, there will be a "slope", albeit only a few water molecules high. This "slope" is what the molecules move down, driven by the attraction to be as close as possible to the surface, minimizing their energy, and at the same time spreading themselves out (maximizing their entropy). Furthermore, as relative humidity increases, so does the mobility of the outermost layer of adsorbed water as it becomes less tightly held. For a more detailed discussion, see Skaar, 1988.

3.4.4.3 Capillary Flow

As mentioned in Section 3.3, it a matter of debate in terms of the exact number of adsorbed layers of water molecules, and at which point water is considered to no longer be in the adsorbed state, but in the capillary or free water state. This is generally thought to be at around the five to eight molecular lthickness for wood.

As free water begins to appear and increases in amount beyond the 50% relative humidity level, so does the associated transport mechanism of capillary flow. Capillary flow is the most efficient of the three transport mechanisms, and as it begins and increases, the rate of increase in permeability also increases, (shown by the increasing slope of the permeability vs. relative humidity curves). Coupled with capillary flow, the vapour diffusion and adsorbed flow mechanisms can still occur in all of the larger capillaries which are not yet full of free water.

3.4.4.4 Combined Vapour Diffusion, Adsorbed and Capillary Flow

Having discussed the three transport mechanisms independently (water vapour diffusion, adsorbed flow and capillary flow), they often occur all at the same time, and not necessarily all in the same direction. An experiment was devised by J.A. Paxton and N.B. Hutcheon to demonstrate the different mechanisms (Paxton and Hutcheon, 1952). The experiments discussed in this work were all performed under isothermal conditions, but when a temperature gradient is introduced, the magnitude of each process becomes different and the net effect is more complicated than for the isothermal case. The experiment consisted of a sealed vessel full of evenly distributed moist sawdust. When a temperature gradient was applied across the vessel, with one end at 16°C and the other at 38°C, the moisture re-distributed itself. At the colder end, the moisture content in the sawdust became significantly higher than at the warm end. The experiment was performed at two different starting moisture content levels in the sawdust, once below 50% RH and then once above 50% RH. In the first case, once equilibrium was achieved, no vapour pressure gradient was found across the chamber, which in turn indicated that no capillary flow took place either, which would have been necessary to balance the vapour diffusion. However, in the second higher relative humidity test, once equilibrium was established, a vapour pressure gradient was found to exist in the direction from the warm to the cold side. This vapour pressure gradient and vapour diffusion flow was balanced by wicking, or capillary flow and surface diffusion in the opposite direction, from the cold, high moisture content face towards the warm, lower moisture content face. This experiment reinforces the fact that vapour diffusion is driven by a vapour pressure (otherwise known as water vapour concentration) gradient, while wicking or capillary flow is driven by a relative humidity gradient.

3.5 Previous Work on the Permeability and Sorption Properties of Wood

The study of the permeability and sorption properties of wood is by no means a new area. The field is of importance to many industries and fields, such as pulp and paper making, the kiln drying of lumber and veneer, the preservation of historical artefacts and the durability and performance of buildings.

An article by McBain in London titled "The sorption of gases and vapours by solids" was written in 1932. This was one of the earliest articles found.

Other early work in the area was by J.F. Siau, who published a book in 1983 titled "Transport Processes in Wood".

Work more specific to buildings and building materials was underway in Sweden in the 1940's. A 1946 National Research Council of Canada (NRC) Technical Translation (#747) of a paper written by C.H. Johansson and G. Persson is titled "Moisture Absorption Curves for Building Materials" (Johansson and Persson, 1946). In it the researchers used various saturated salt solutions to control the relative humidity in a chamber maintained at 25°C to determine the sorption isotherm curves for a range of building materials, including various types of brick, solid wood, concrete, wood wool boards, and wood fibre boards. The preface by Neil B. Hutcheon as the Assistant Director of NRC emphasises the importance of the sorption properties of building materials to Canadian construction practice from the perspective of damage to structural and finish components due to swelling. Interestingly, no mention is made of biological concerns such as mould, mildew or rot.

A recent large scale project was conducted by the NRC titled the MEWS (Moisture Management in Exterior Wall Systems) Consortium Project (Kumaran et al., 2002). The overall objective of the project was "to predict the hygrothermal responses of several wall assemblies that are exposed to North American climate

loads, and a range of water leakage loads". They tested an array of building materials for a range of properties including water vapour permeance and sorption, and then used the data with the IRC (Institute for Research in Construction) hygrothermal computer model "hygIRC" to simulate the walls in a series of climates. Among the materials selected for study, were seven OSB products, either purchased for the study, or supplied by project partner manufacturers. These were then pre-tested and four OSB products were selected for study. Their bulk densities ranged from 575 to 725 kg/m^3, and the thickness ranged from 10 to 11.5 mm[1]. Their test method used involved mixing known volumes of 0% to 100% air to attain relative humidities in increments of 10% all the way to 100%, it is most probable that they used a mechanical system rather than saturated salt solutions to control relative humidity. They did use gravimetric measurements to determine the overall rate of moisture transfer rates, so the method was a modified ASTM E-96 cup method for permeance/permeability testing.

Alvarez (1998) also used a non-cup test method designated the "ASHRAE FDC" (forced direct control) method for investigations on the nonisothermal diffusion of moisture through OSB. The system controls relative humidity levels by the direct removal and injection of distilled water. Alvarez states that although several nonisothermal diffusion models for porous materials based on "gradients of water-vapour pressure, chemical potential of water, moisture concentration and activated moisture molecules" exist, none are universally accepted.

The report also mentions that the European Union is in the process of developing a new CEN [1]standard 89 N 336 for permeance and permeability testing based on ISO standards (which has not yet been published), and that the ASTM E 96 standard is also currently being revised to E 96/E 96M-05.

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[1] The range of OSB bulk densities (oven dry mass / equilibrium volume) of virgin panels (not altered by soaking or RH-cycling) tested by the author were from 497 to 643 kg/m3 (values are compared in Results and Discussion section).

Simpson and Lui (1991) studied the effect of moisture content on the isothermal diffusion coefficient for aspen (*Populus sp.),* comparing experimental adsorption results to a mathematical model.   They found the coefficient increased exponentially with moisture content between the studied range of 0 to 18% moisture content at 43°C, as did Avramidis and Siau (1987) when studying diffusion in the radial direction for western white pine (*Pinus monticola).*

A recent study used nuclear magnetic resonance (NMR) microimaging to investigate the absorption of liquid water in specimens of OSB and solid wood (Van Houts et al. 2004). Small specimens were encased in silicone on all sides except those for the introduction of moisture, and then placed inside the special small scale NMR machine chamber. Then liquid water was introduced into the chamber to soak the specimen, and then removed for imaging. The results were for free water only, as bound water and solid wood were not visible due to the rapid rate of decay of the signal. Visible as streaks parallel to the strand orientation direction, they observed that the primary path for liquid water movement was through inter-strand voids.   Liquid water penetration was observed both through the edges of specimens, parallel to the strands, and through voids in the surfaces, perpendicular to the strands.

With respect to the effects of moisture exposure and specifically cyclic exposure on wood and wood composite materials, very little work has been done (Time, 1998). According to Time, only three such studies have been conducted, and those only on solid wood. Time investigated among other things, the effects of cyclic exposure of solid spruce (*Picea abies*) specimens to different relative humidities on the sorption isotherms. He states that "a repetitive pattern in moisture content change is found in both weekly and daily changes" where "the same level of moisture content is reached in both absorption and desorption every cycle".

A study was conducted by Nofal and Kumaran (1999) at the NRC Institute for Research in Construction, who were also co-authors of the large NRC MEWS study, titled "Behaviour of Engineered Wood Materials Under the Effect of Wetting and Drying Cycles". Their experiments investigated the effects of repeated cycles of water soaking and drying on the moisture content, rate of moisture uptake and thickness swell of OSB. The authors point out that the moisture-related properties currently used by most hygrothermal computer models are those of virgin materials, and that "these properties do not accurately reflect the actual conditions to which construction materials would be subject within the wall assembly over its service life", and therefore that "it is important to evaluate the evolution in material properties due to various cyclic moisture loads". Their experiments were conducted on three unspecified commercially available OSB products. Among their main findings were that the rate of moisture uptake increased drastically after the first wetting / drying cycle, that moisture uptake continued to increase with each cycle up to ten cycles, and that the rate of moisture uptake increased drastically with more cycles. The results were for soaking in liquid water only, and the authors did not conduct any experiments with water vapour cycles.

Chapter 4

The OSB Manufacturing Process

4. Introduction

This chapter describes the OSB manufacturing process in detail, step by step, with a discussion of each variable involved and the associated impacts. The first goal here is to provide the reader with an appreciation for the complexity of the process. The second goal is to provide an understanding of why the variables chosen for this study were selected, by identifying the various manufacturing parameters involved, the extent to which they are controllable, and the extent to

which OSB properties vary as a direct result. This investigation will later attempt to determine the relationship between some of these panel manufacturing variables and the moisture-related properties of the final OSB product, and then the end effect on the performance of the panels in the walls of buildings. This analysis could also provide guidance with respect to which variables might be investigated in future work. For further details on the OSB manufacturing process, Noffsinger (2004) has modeled some aspects of the OSB manufacturing process in his Ph.D. dissertation "Modeling the Oriented Strandboard Manufacturing Process and the Oriented Strandboard Continuous Rotary Drying System". The manufacturing process as described below is represented pictorially in Figure 4.1 "Flow of OSB process at Ainsworth 100 Mile House mill (Ainsworth Lumber Company, 2000)", at the end of this chapter.

4.1 The OSB Mill

The commercial OSB panels for this study were manufactured at the Ainsworth Lumber Company Ltd. OSB mill located in 100 Mile House, BC in March of 2002. This mill was built in 1994, and was the first OSB mill of the Ainsworth Lumber Company. It is built around a 12-opening, 9 foot (2743mm) wide by 24 foot (7315mm) long press, designed with the flexibility to produce both domestic 4' x 8' panels (1220 mm x 2440 mm), and 3 x 6 (914 mm x 1829 mm) panels for the Japanese market. The species mix at the time of manufacture was approximately 60% Aspen (*Populus tremuloides)*, 30% Lodgepole Pine (*Pinus contorta Dougl.*), 9% Birch (*Betula papyrifera*), 1% peeler cores [2]- (SPF).

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[2] Peeler cores are small diameter cylindrical wood elements left over from the veneer making process. They are the material which remains after the veneer making lathe has peeled all the veneer possible from a log, and the diameter becomes too small. SPF refers to the combined species group of spruce, pine and fir.

4.2 The Log Yard

The wood (with the exception of the peeler cores) comes to the mill as tree-length logs by either rail or logging truck. The branches and tops have been removed, but the bark remains on. The logs are then stored in the log yard, out doors and unsheltered, until the time when they are used. Organization of the log yard is a critical aspect of OSB production, essential to managing the wood inventory in such a way as to ensure both a consistent species mix going into the mill at all times, as well as inventory control in terms of the time the logs spend in the log yard and thus moisture content of wood. If wood is allowed to sit too long in the yard, it will dry out to the point where stranding becomes difficult, yielding an excess of fines and splinters. The presence of such splinters negatively affects both wood recovery and panel quality.   Hence the incoming logs are arranged, stored and managed in terms of species and time spent in the log yard.

The piles of logs of different moisture content and species are brought by a wheeled loader from the log yard to the back, or in-feed area of the mill, as called for by the "but'n top loader" operator, whose role it is to ensure a consistent wood mix to the mill at all times. The logs are placed in an area of temporary storage next to a but'n'top loader machine, from which the operator further fine-tunes the log mix by selecting individual logs one at a time from the piles of different log types, and placing them onto the log deck which then leads into the mill. After this stage in the process, the wood mix can no longer be altered.
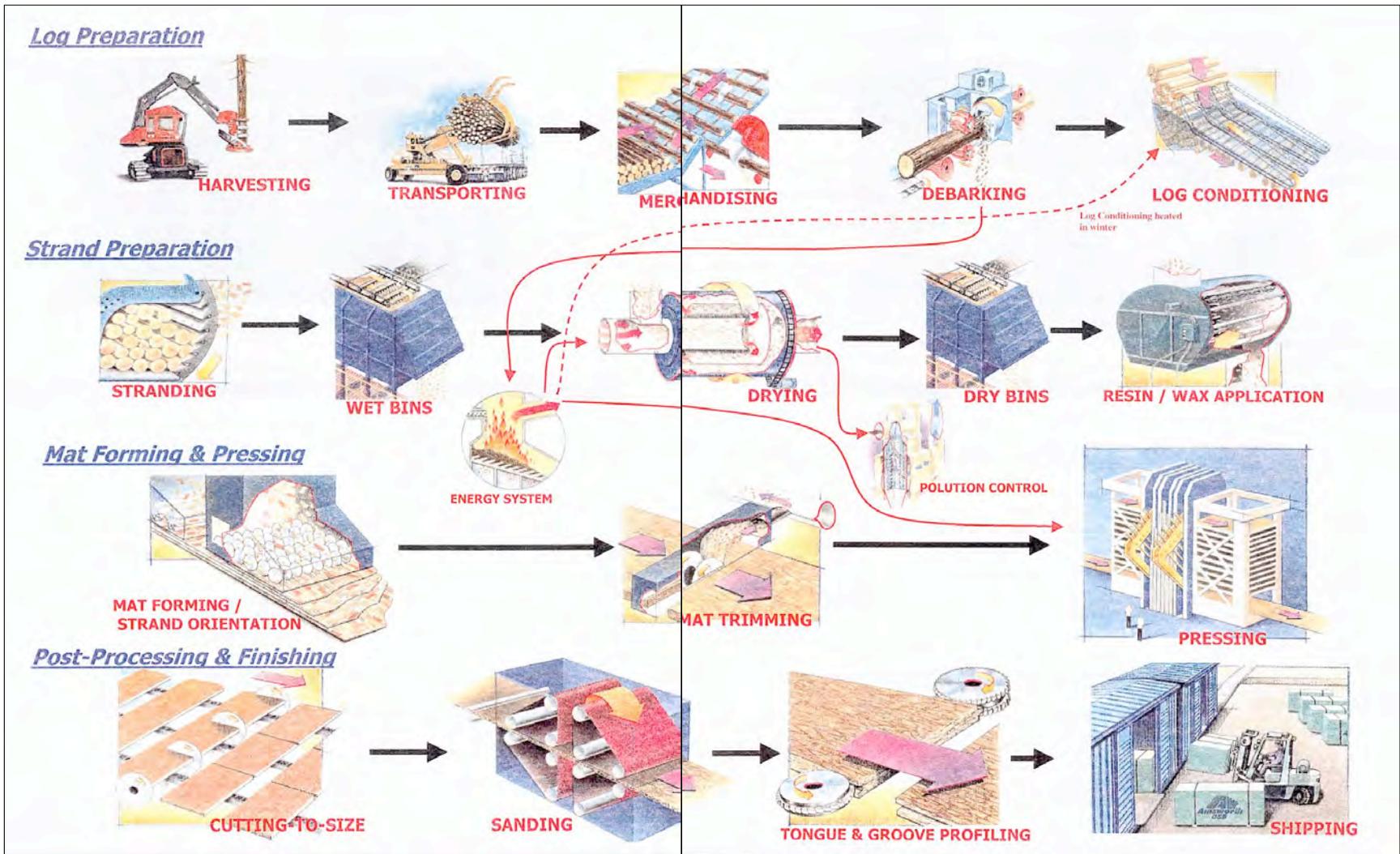
Log Preparation

HARVESTING → TRANSPORTING → MERCHANDISING → DEBARKING → LOG CONDITIONING

Log Conditioning heated in winter

Strand Preparation

STRANDING → WET BINS → DRYING → DRY BINS → RESIN / WAX APPLICATION

ENERGY SYSTEM

POLUTION CONTROL

Mat Forming & Pressing

MAT FORMING / STRAND ORIENTATION → MAT TRIMMING → PRESSING

Post-Processing & Finishing

CUTTING-TO-SIZE → SANDING → TONGUE & GROOVE PROFILING → SHIPPING

Figure 4.1: Flow of OSB Process at Ainsworth 100 Mile House Mill (Ainsworth Lumber Company, 2000).

Variables Affecting Board Quality:

The log yard variables which affect board quality are the wood species, age, length of storage time, log length, log diameter, wood moisture content, and wood quality (knots, pitch pockets, sloped grain, rot/decay, insect damage)

Immediate Impact:

The immediate impact of the log yard variables are the wood recovery (amount of useable product vs. waste), strand quality (width, thickness, size distribution, fines percentage, surface characteristics), strander knife sharpness, and all panel properties as impacted by the mix of species and individual species properties.

Log yards may vary from very poorly managed, where the variability in terms of species, age and moisture content fluctuates greatly from minute to minute, resulting in an out of control process to a very well managed log yard with excellent inventory control where the wood mix being supplied to the mill is consistent at all times.

4.3 Bucking

The logs travel on chains along the log deck to a bucking station, where they are trimmed, both for length and to remove defects. Trimming is done by means of a series of large circular saws, at fixed spacings, which can be raised or lowered by the operator, after the log has been positioned by a series of hour-glass shaped rollers. The operator cuts short lengths off the butts and tops, as well as any large visible defects such as areas of rot, or large crooks. The butts and tops are removed as they often become embedded with sand and gravel from the log yard, which can damage the strander knives further down in the process. The other role of the bucking station is to cut or "buck" the logs into 16 foot lengths, which can then fit through the rest of the process up to the stranders.

Quality-Affecting Variables:

The quality-affecting variables related to the bucking operation include the abundance of defects (rot/decay), sand, gravel embedded in the ends of logs and remaining on the other surfaces of the logs. Also, the relative straightness of the log as a result of being cut where bends/crooks are impacts the stranding operation further on in the process.

Immediate Impact:

Strander knives will dull if sand and gravel are present, which will in turn decrease strand quality. An abundance of rot, large knots, etc. in logs will result in high fines percentage (fines are small unusable wood particles). Bent/crooked logs will result in a difficult to strand batch of logs, and an increase in fines percentage and strands with grain not parallel to surfaces.

4.4 Debarking and Log Ponds

The logs then pass lengthwise through one of two cambial ring type debarkers, where the bark is removed by a set of three arms with knives on the tips, which rotate around the log and peel off the bark. The knife pressure is critical, and is set to remove as much bark as possible, while at the same time not removing too much of the wood underneath the bark. It can be difficult to optimize if several different species with different bark types are being processed at the same time. The logs then proceed to the ponds, where they soak for approximately 4 to 8 hours, depending on how fast the rest of the mill process upstream is running. The role of the log ponds is to thaw the frozen logs in the winter time, and to otherwise clean the logs to remove any sand or grit which could harm the strander knives. They can also be beneficial in raising the moisture content of logs which may have remained in the log yard for too long and have become overly dry, although this benefit may be marginal in that the rate of moisture absorption is likely very slow. It should be noted that other types of debarkers exist in the industry, but are far less common. Also, the order in the process of

the placement of the log ponds and debarkers is often varied, with many mills passing the logs through the ponds before debarking.

Quality- Affecting Variables:

The quality-affecting variables related to debarking and the log ponds include the amount of bark remaining on logs, log core temperature (it must be maintained above freezing), amount of sand or dirt remaining on log surface, and the moisture content of logs.

Immediate Impacts:

The immediate impacts of the variables in debarking and the log ponds include the fines percentage produced (bark, rot and knots turns into fines), strand quality (frozen wood does not tend to strand well, resulting in a high percentage of toothpick shaped strands and fines), strander knife sharpness (which will be compromised if sand or dirt on log surface), and overly dry logs will again result in large percentage of fines and poor quality strands (however, the amount of water that can be absorbed by the logs during the short time they are in the ponds is limited).

4.5 Stranding

Next, the logs are cut into small elements called strands, by a machine called a strander. Stranders come in three main types: the more common drum type strander; the short log or bolt disc strander; or the long log disc type strander. The drum strander, which is the type used in the mill for this study, consists of a rotating drum, approximately 2030mm (80") in diameter and 680mm (26.75") deep, with the axis of rotation in the horizontal plane. The walls of the drum are lined with 42 sharp knives which run the depth of the strander. Logs are first metered by the operator into a trough in front of the strander drum called a batching chamber, until enough logs have accumulated to form what is called a batch. A batch consists of the number of logs which will just fit into the rotating strander drum. If too few logs are in a batch, the logs will move around while

Figure 4.2: Knives in Rotating Strander Drum (With permission of IDAC Logic©)

being stranded, resulting in a poor quality cut, and an excess of fines and small strands. The batch of logs is then pushed end-first into the rotating strander drum until they touch the end wall, and are held down with a hydraulic arm just outside of the drum. The strander drum then travels perpendicular to the long axis of the logs through the batch of logs, as the rotating knives cut through the wood, reducing the logs to strands. The strander drum then returns to its start position, and the process is repeated until the length of the batch of logs has been reduced to strands.

The geometry of the strands, geometry distribution, and overall strand quality are all critical to the OSB process, and are monitored closely. Strand size distribution is measured in the OSB mill laboratory both according to thickness, and length and width. Mean thickness, standard deviation and range are determined by measurement of a random sample of approximately 100 strands with a calliper. Length and width distributions are measured by passing a random sample of strands through a set of sieves (wire screens each with a different opening size) in a mechanical shaker.

The distribution of thickness, and length and width, is determined by a number of factors, both in the strander itself, and the wood being stranded. In the stranders,

the main factors are: knife sharpness, knife angle, knife angle type, knife projection, drum carriage travel speed, drum rotation speed, scoring tip spacing, scoring tip sharpness, and counter knife set up. The critical wood factors in relation to stranding are: moisture content, species, bark content, log diameter, log length, log quality (rot etc.) and log batch tightness and arrangement.

The two Pallman stranders in the 100 Mile House OSB mill were of the drum type, and contained 42 knives each, rotating at approximately 500 RPM. The strands produced measured approximately 0.025" (0.64mm) thick by 4.5" (114mm) long, and the width varied from almost 4" (100mm) down to less than half an inch (13mm), depending on where the strands fractured during the stranding process.

Quality-Affecting Variables:
Strand quality is affected by: knife sharpness, knife angle, knife angle type, knife projection, drum carriage travel speed (controls feed rate of wood into knives), drum rotation speed, scoring tip spacing (determines strand length), scoring tip sharpness, and counter knife set up (fractures strands along grain into widths), log density in charge/load, and log packing/organization in load.

Immediate Impacts:
All aspects of strand quality and size distribution, including strand length, width thickness, percentage of fines, surface quality (roughness), etc. will impact all panel properties and the overall wood recovery down the manufacturing line.

4.6 Drying

Next the strands are dried from a green moisture content often as high as 150% (mass of water / mass dry wood), down to approximately 2% moisture content for the core layer, and 3% moisture content for the surface layers. Drying is by means of four rotary triple-pass dryers, which are very large, slowly rotating cylinders with internal baffles causing the strand to travel through the length of

the dryer three times before exiting. Many other dryer types exist in the industry, but the rotary single or triple pass are most common. The dryers are fired by heat and combustion gases from the furnaces or energy system, which burns wood residue from the OSB process. The heat and combustion gases are often at over $1600^{o}C$, and are blown through the driers by means of high power fans, carrying with them the strand to be dried, which is introduced into the air flow path through an airlock at the in-feed end of the dryer.

Quality-Affecting Variables:

The drying quality-affecting variables include the dryer inlet and outlet gas temperatures, flow-through rate (dwell time) of the strand, and the strand feed rate into dryer.

Immediate Impacts:

The primary immediate impact of the drying variables is the final strand moisture content, which in turn directly affects: bonding in the panel, pressing time needed to avoid press blows (steam pressure induced internal panel delamination), plastification of lignin component of wood structure during pressing (determining final panel density profile), heat transfer rate from mat surface to core (in turn affecting resin cure rates and final density profile), and the cure rate and degree of polymerization (moisture content is critical for MDI (methylenediphenyl diisocyanate) resins). The maximum temperature of the strand during drying can also have an impact, in that if it is too high, it can affect the surface chemistry and bonding characteristics of the strand.

4.7 Screening

After drying, the strands are screened (passed over a wire mesh with small holes) to remove fine wood particles known as "fines". The fines are removed from the remaining strands in an attempt to improve the efficiency of the blending process, as well as to maintain the desired panel mechanical properties. As the fines are very small, they have a very large surface area to volume ratio, and

thus deprive the remaining strands of resin. They are removed from the material flow, and in some mills, such as the 100 Mile House mill, resinated (coated with resin) separately in a specialized fines blender, and then re-introduced into the material flow after the strands are blended, and before the forming process. More commonly, all the fines are burned in the energy system of the mill to heat the dryers, press and other components.

Quality-Affecting Variables:

The screening quality-affecting variables include: the screening mechanism type (rotating drum, shaking or other), screen mesh size, and flow through rate.

4.8 Blending

The next step in the process is the addition of resin (glue) and wax to the strands, which is referred to in the industry as "blending". Blending is a critical process in OSB manufacture, and can have a large impact on both economy, as resins and waxes are the most expensive ingredients by mass in OSB, and on panel properties. The role of the blending process is to distribute the resin and wax over the strand surfaces. Contrary to common belief, the resin makes up a very small portion of the final panel, and when distributed on the strand surfaces, the amount is so small that it is barely detectable. Rather than visualizing the strands as being coated with resin, a better analogy is that of the strands being covered in a very light spray of tiny droplets, which then in turn "spot-weld" the strands to one another. Ideally, this will result in an even distribution over all of the strands, at the desired addition rate (% resin or wax fraction of the dry strand mass), and at the flow-through rate of strand necessary for the mill to run at the optimum production rate, all without coating the insides of the blender or the surfaces of the atomizers (resin distributing equipment) with excessive resin and fines build-up. The actual resin and wax addition rates vary widely from mill to mill, and product to product, but generally speaking on a solids basis (dry resin or wax with no water), would be somewhere between 0.5% and 5% of the oven dry wood mass.

Blenders come in a few different forms, of which by far the most common type in the OSB industry is the rotating drum blender. As the name suggests, this type of blender consists of a large, horizontal rotating drum, lined with fins called "flights" running along the length of the inside, and it operates much like a clothes dryer. As the blender rotates, the strands are lifted by the fins, and dropped through the air, allowing them to separate from one another and thus to be resinated. The blender is also designed on a slight incline, with the axis of rotation at a slight angle to the horizontal, such that when the strands are introduced though a chute in the elevated end, they will migrate during the blending process to the lower end, where they drop through another chute and exit the blender.

Within a blender there are several possible methods for resin or wax application, depending upon the resin type to be applied, as well as mill preferences. The ideal applicator creates the desired droplet or particle size at the desired rate, distributing them into the desired area of the blender, and operating reliably without becoming plugged or breaking down.

For powdered phenolic resins, which are not that common in the OSB industry, the powder is typically metered into the in-feed end of the blender, and as it tumbles with the strand, it becomes distributed, ideally resulting in a light, even dusting covering all of the strands. Both static electricity as well as mechanical adhesion are relied upon to keep the powdered resin on the strand surfaces.

Liquid resins currently come in two types: liquid phenol formaldehyde and liquid isocyanate or MDI (methylenediphenyl diisocyanate). Both resin types are most commonly distributed with a spinning disc atomizer, which consists of a cone or disc with holes drilled into the face, which spins at a very high rpm (10,000 to 15,000 RPM). As the liquid resin drips onto the spinning disc, it becomes "atomized", turning it into a mist of tiny droplets, which then exit through the small holes and become distributed on the strands.

OSB wax commonly comes in two forms: emulsified wax and slack wax. Emulsified wax, the more common of the two forms, consists of wax and an emulsifying agent, distributed in water. In appearance, the emulsion looks like milk, with approximately the same viscosity, and has a wax content by mass of approximately 50%. Slack wax on the other hand is in the pure form, and must be heated and melted before it can be blended. It is more problematic due to the necessity of heat, and is used less and less in the industry. The purpose of the wax is to impart some water absorption resistance to the OSB, and also for the lubrication of some OSB manufacturing equipment such as the strand conveyors.

At the Ainsworth 100 Mile House OSB mill, the strands are resinated in one of two blenders, one for the core layer and one for the surface layers. The blenders measure approximately 9m (30 feet) in length and 2.4m (8 feet) in diameter, each with six spinning disc atomizers for spraying the wax and resin.

Quality-Affecting Variables:

Resin and wax addition rates: mass of resin / wax per mass of wood strand.

Blender design: number, size and distribution of flights, diameter and length of blender.

Blender set-up: inclination angle and rotation speed, determine the dwell time of the strand in the blender.

Atomizers: cone type and # holes, rotation speed, angle of atomizer to axis of blender, # of atomizers in blender.

Maintenance of Blender: how often blender surfaces and atomizers are cleaned from build-up of resin / wax / fines.

Immediate Impacts

Resin addition % and distribution: affect all physical and mechanical panel properties (MOE, MOR, IB, thickness swell, etc.) as well as economy.

4.9 Forming

Forming is the process of laying the strands down onto a caul screen (a thick metal screen with small perforations in it used to transfer the mat of strands into the press) to form a mat, ready to be pressed into a final OSB panel. The forming process is critical in that it determines the degree of orientation of the strands, and the overall mass, density and the density distribution throughout the mat and thus through the finished panels. The differential (ratio) between face and core is also determined at this step, as well as the distribution of fines throughout the mat.

The strands are carried by conveyors to the top of the forming line and dumped into temporary storage bins called dosing bins, one for each former, which provide a small buffer for flow within the process. The Ainsworth 100 Mile House mill had four formers, and thus four dosing bins. The bins then drop strands at a controlled rate via moving live bottom belts into the formers below. The formers then distribute the strand evenly onto the moving caul screens below.

The dosing bins have many adjustments, some of which can control where the strands fall within the formers below. The formers also have many adjustments to determine how the strands fall onto the distributing discs or paddle wheels below, one of which is the type of pick, or plastic star shaped spinning wheel, which toss or distribute the strands within the formers.

The surface formers (the first and last formers along the process) orient the strands in the machine direction (long strand axis parallel to the direction of travel and the long axis in the finished panel) via a series of rotating discs. The discs are parallel to the machine direction, on shafts, and as the strands drop through the discs, they are oriented.

The core layer formers are the second and third formers along the forming line, in-between the surface formers. They orient the strand in the cross-machine

direction, perpendicular to the long axis of the finished OSB panels. They consist of a series of rotating "paddle wheels" on shafts, with the axis of rotation perpendicular to the line direction. The strands drop from the top of the former into the spaces between the paddles, and are then dropped onto the line oriented accordingly.

Quality-Affecting Variables:

The quality-affecting variables in the forming process include: the dosing bin live bottom belt speed (affecting the mat and panel density),
the disc design, spacing, and RPM (which affect strand orientation and distribution), the former height off the line (affecting strand distribution, where greater height results in more randomization), and the pick shape and RPM (which affects the Strand distribution).

Immediate Impacts:

Immediate impacts of the forming process are: mat and panel density, density distribution, surface to core differential (ratio of parallel to perpendicular mechanical properties), and strand orientation (parallel and perpendicular modulus of elasticity (MOE) and modulus of rupture (MOR).

4.10 Pressing

Pressing is quite likely the most technically complex and influential step in the OSB manufacturing process. It is the final step in which heat and pressure are used to consolidate the mat and then cure the resin to form the final product. It is part art, and part science. The control room operator, relying on experience and a continuous supply of process data, must constantly adjust the press cycle, minimizing pressing time for economy, while maintaining the required panel properties. The adjustments which the operator makes are based on experience, constant inputs and readings from processes all over the mill, and from the results of panel testing conducted around the clock by the process technicians.

From start of process to end, following is a list of the press cycle decision-making inputs:

- The product being made (thickness, density, performance requirements)
- Species mix and age/moisture content
- Season, as relates to wood temperature
- Resin and wax types and addition rates
- Strand moisture content on forming line, continuously measured by on-line sensors
- Mat weight, continuously measured by forming line
- The observation of any panel delaminations or "blows" as the press opens
- Continuous panel test results from process technicians (MOE, MOR, internal bond (IB))

OSB hot presses can be either pressure or distance/displacement controlled. The press at the Ainsworth 100 Mile House mill was used with distance control. The variables which can be controlled are the press temperature, and the press cycle. The press cycle involves the rate of close to mat contact, the rate of close and number of stages to reach final thickness, the time at final thickness, and then the opening of the press involving the release of the internal gas pressures before contact with the panel is relinquished and the press opens fully.

The press temperature essentially controls the rate of cure of the resin. Each resin requires a certain amount of energy to polymerize or cure it. Thus at a lower temperature, more time will be required for the resin to cure than at a higher temperature. Typically, the upper limit for press temperature is the temperature at which loose strands in contact with the press will ignite. The strands and resin at the top and bottom of the mat closest to the press platens receive the required energy and cure first, and the strands closer to the center of the mat cure last. In an efficient mill, the final cure, deep within the panel will occur after the panel has left the press.

Heat transfer from the hot press platens to the resin occurs through convection (both air and steam), conduction, radiation and latent heat. Each of these mechanisms is affected by the way in which the press is closed and reaches final thickness, and also the moisture content of the strands.

Besides the curing of the resin, pressing also controls plasticization and densification of the wood strands. As wood is heated, the lignin component becomes increasingly plastic in nature, and is able to flow and to be densified. As the heat energy from the press penetrates the matt first through the outer surfaces and then towards the center of the mat, these areas flow and densify first, relieving some of the pressure exerted by the press. Through the rate of close, stages of closing, and the rate at which heat energy is transferred to cure resin, the press cycle can be used to determine the vertical density profile of the final panel. Generally, a fast close with only one step to final thickness will result in the largest change in vertical density from surfaces to core, while a slow, step by step close will result in a "flat" or more uniform density profile (less density variation through the panel thickness).

With respect to the opening of the press, after the final thickness has been reached and held for the desired time, the primary issue is that of bleeding off internal gas pressure developed from the gasification of the components of resin, wood and water during the pressing cycle. If the press is opened too quickly, and contact is lost with the panel surfaces while the internal gas pressure exceeds the cohesive strength of the panel, the panel will explode or rupture in order to relieve the pressure. This is called a "blow". On the other hand, if the press is opened slowly enough to allow the release of the internal gas pressure to a point below the cohesive strength of the panel before contact is lost with the panel surfaces, then no rupturing of the panel will occur.

Quality-Affecting Variables:

The primary pressing related quality-affecting variables are the press temperature (which affects the rate and degree of resin cure, plasticization of the wood, and vertical density profile), and the press cycle (which affects the degree of resin cure, vertical density profile, and the likelihood of internal panel rupture upon opening of the press (blows)).

Immediate Impacts:

The immediate impacts of pressing include: the vertical density profile, average panel density, panel thickness, all mechanical panel properties (MOE, MOR, IB, Thickness swell etc.), and the occurrence of internal panel delaminations (blows).

4.11 OSB Manufacturing Summary

The manufacturing process for OSB is very complex, part art and part science, and a great number of steps and variables involved. Some variables such as strand moisture content, press temperature and pressing time are easily controllable, while others such as the strand length and width, resin distribution, density variation across panel width or length, and strand alignment / orientation are not. To complicate matters, each OSB mill is also different. Some use continuous presses, while others use multi-daylight opening presses. Some use single pass dryers, while others use triple pass or conveyor dryers. Then there are other variables such as wood species and quality, the specific process equipment type and make, the maintenance and operators involved, the proprietary product recipes used, and the resin and wax types. The end result is that no two sheets of OSB are exactly the same, so one has to be careful when making general characterizations. Measuring or determining the properties of a generic, off the shelf purchased product does little to help predict the properties of other unspecified OSB types. That said, the properties do fall within a certain statistical range, and that may be sufficient for certain applications.

Chapter 5

Experimental Design

5. Experimental Design Objectives

The rationale for the experimental design of this work follows from the overall objectives. The first objective was to investigate the effect of the variation in mill manufacturing parameters within the range of marketable panels on the critical moisture-related properties: water vapour permeance, and sorption. The OSB manufacturing process is complex, with numerous steps, each with several variables, some easily controllable and others not. A detailed analysis is provided of the process and variables involved at each step. The second objective was to evaluate the effects of post-manufacturing exposure to various moisture conditions on the moisture-related panel properties. The third objective

was to investigate the effect of the range of OSB moisture-related properties determined experimentally, on the performance of select wall designs subjected to Canadian climates. Since sorption testing takes a long time, easily over one month for certain specimen sizes for each step, a fourth objective was developed to investigate the use of OSB shavings as a faster test method to accurately duplicate the results of larger specimens.

The steps involved as part of the overall design of the experiment for this study were as follows:

1. Conduct one-day mill trial to manufacture the panels for this study, adjusting only one variable at a time. Mill quality assurance testing procedures were followed to ensure panels met commercial standards for quality.

2. Prepare specimens for laboratory testing of water vapour permeance and sorption properties, including RH-cycled and water-soaked specimens.

3. Conduct water vapour permeance and sorption testing over a three year period in a constant temperature and relative humidity controlled chamber over the full RH range with select specimen categories (not all could be tested over the full range due to time and space constraints).

4. Conduct water vapour permeance and sorption testing at mid-RH range for the remainder of specimen categories which were not feasible to test over the full RH range.

5. Analyze testing results and enter material data for four OSB types into WUFI (Wärme- und Feuchtetransport instationär) hygrothermal modeling software for investigation of the effect of the range of OSB properties on selected wall types subject to Canadian climate.

5.1 Test Panel Manufacture (Mill Trial)

The overall objective of this thesis is to apply the knowledge gained to real life building applications, and for that reason the test panels must accurately

represent those used in construction. The panels were therefore manufactured in a real OSB mill, under real manufacturing conditions at the Ainsworth 100 Mile House OSB mill, in 100 Mile House, British Columbia.

The panels were manufactured during a one-day mill trial in March of 2002, for the duration of which the production at the mill was placed under the direction of the author, essentially turning the mill into the laboratory. This was a very generous contribution, as lost production time is estimated at approximately $10,000 per hour.

All of the relevant mill conditions were carefully documented and controlled during the trial period, while the manufacturing parameters to be investigated were varied one by one. The panel thickness and grade chosen for the project are 7/16" (11 mm) performance rated sheathing (PRS). This is the most common OSB panel thickness and grade manufactured in industry, since it can be used for the largest range of applications, from wall sheathing to roof sheathing.

5.1.1 Manufacturing Variables

The OSB manufacturing variables selected for study were chosen for their impact on water vapour permeance and sorption, and based on whether or not they could be controlled in the manufacturing process. They are summarized in Table 5.1 along with the range of settings selected for each. The manufacturing variables chosen were:

1. Resin content
2. Panel density
3. Surface treatment (sanded or not)

Preliminary testing research conducted by the author indicated that these mill variables were likely to have the largest impact on permeance and sorption

properties. Also, these variables are adjusted at the mill for almost every product produced in accordance with each specific product recipe.

The units of measure used in the Canadian OSB industry to control manufacturing processes and for all process related measurements are imperial. Thus, all raw data collected for this work is in imperial units, and SI equivalents are provided. On some charts and Figures the various panel or specimen groups (34.5 lbs/ft^3 low, 39.0 lbs/ft^3 medium or control, and 42.9 lbs/ft^3 high unit weight) will simply be referred to by their target unit weight in imperial measure, as these serve as group names, just as the high resin group in which the resin addition rate was increased as the experimental variable, is referred to simply as "resin".

The density of a 7/16" PRS grade panel varies greatly in the industry, from as low as 546 kg/m^3 (34 lbs/ft^3 unit weight) to over 642 kg/m^3 (40 lbs/ft^3 unit weight), so the average of 626 kg/m^3 (39.0 lbs/ft^3 unit weight) was chosen as the midpoint or control density for this study. This is also a common target density for this product in industry. This density as measured in the industry is based on equilibrium moisture content (%) mass at the time of manufacture (not oven dried) and the virgin OSB thickness at time of manufacture. When bulk density is measured, it is based on the oven dry mass and the virgin OSB thickness as manufactured. The resin addition levels chosen as the base line or control were: 6.0% liquid phenol formaldehyde (PF) basis (3.0% solids basis)[3] in the surface layers, and 2.0% solids[4] methylenediphenyl diisocyanate (MDI) in the core layer. The wax addition level was 1.8% emulsified liquid basis (approximately 50% solids) in the surface layers, and 0.6% in the core layer. These are standard levels for this product at this mill, and are measured as a percent of total panel mass, at time of manufacture. Thus, the control group for the study, referred to

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[3] Liquid phenol formaldehyde resins and emulsified waxes are commercially manufactured and supplied to mills with water mixed with the actual resin or wax "solids", generally in amounts of approximately 50% by mass.

[4] Methylenediphenyl diisocyanate (MDI) resin is not mixed with water, and thus is by default on a solids basis.

as "control", was manufactured at the middle density of 626 kg/m^3 (39.0 lbs/ft^3 unit weight) and at the standard resin and wax settings of 6.0% liquid PF basis in the surface layers, 2.0% solids MDI in the core layer, and wax addition level was 1.8% emulsified liquid basis in both surface and core layers.

The target thickness for the 7/16" PRS product at this mill was 0.430" (10.9 mm) as opposed to the mathematical decimal equivalent of 7/16" which is 0.437" (11.1 mm). Each product has a permitted range of thickness for manufacture, and the manufacturer can choose to target any thickness within the range, provided the average thickness, based on a measurement of four points per panel and a pre-determined sampling frequency, falls within that range.

The "differential" is the industry terminology for the difference in % mass of material between the surface layers (top and bottom surfaces combined) and core. The differential at the time of trial and standard for this product was set at 8%, meaning that 54% of the mass of the product was surface material, and 46% of the mass was core material.

The first phase of the trial was to manufacture panels varying only in density. Other factors such as pressing time, press temperature and press cycle were kept constant. The standard resin and wax addition rates for 7/16" PRS grade OSB were used as three target densities were created: low density 554 kg/m^3 (34.5 lbs/ft^3 unit weight), middle density 626 kg/m^3 (39.0 lbs/ft^3 unit weight) and high density 689 kg/m^3 (42.9 lbs/ft^3 unit weight). These runs or products will be referred to hence forward by their target densities. The middle density run of 626 kg/m^3 (39.0 lbs/ft^3 unit weight) is the control density, serving as the benchmark where resin and wax settings were varied.

Next, at the "control density" of 626 kg/m^3 (39.0 lbs/ft^3 unit weight), resin addition levels in the surface and core layers were raised to the upper mill limit as dictated by the mill manufacturing equipment. The two resin addition levels

were: 6.0% liquid PF basis (3.0% solids basis) in the surface layers, and 2.0% MDI in the core layer for the control level, and 8.5% liquid (4.25% solids) surface and 4.0% core for the high resin level product which will be designated as "resin". The wax addition was always maintained at 1.8% emulsified liquid level (0.9% solids) throughout the trial for all runs.

The final variable to be adjusted was the surface treatment, whether or not the panels were sanded after being pressed. This was done again at the standard density and resin and wax settings. At least three press-loads of each trial step were made for this study.

5.1.2 Mill Conditions During Manufacture of Trial Panels

The trial panels were made on a 9 foot (2.74 m) by 24 foot (7.31 m), twelve opening multi-daylight press, with a 153 second pressing time and a press platen temperature of approximately 205°C. The surface resin was a liquid PF made by Borden Chemicals Inc., and the core resin was a MDI supplied by Huntsman Polyurethanes Inc. The wax was a Borden emulsified wax. The species mix at the time of the trial was 60% aspen (*Populus tremuloides*), 30% lodgepole pine (*Pinus contorta*), and 10% birch (*Betula papyrifera*). The core and surface strands were dried to approximately 2% and 3% moisture content respectively before the addition of resin and wax.

The manufacturing variables selected for this study are listed in Table 5.1, while the testing variables, which include both manufacturing variables as well as several post-manufacturing treatments are listed in Table 5.2. All of the OSB panels, with the exception of the 100% MDI panels, were manufactured at the mill by the author. The 100% MDI panels were manufactured at the mill by mill staff during a previous trial. The plywood and lumber specimens tested for comparison purposes were purchased locally by the author. Press data from the trial is presented in Appendix A in the form of print-outs of the PressMAN ^{TM} press monitoring software created by the Alberta Research Council.

Table 5.1: Summary of OSB Mill Manufacturing Variables

Variable	Range		
Density (kg/m^3)	Low 554	Medium[*] 626	High 689
Resin (%) Surface (PF) Core (MDI)	Standard[*] 3.0 2.0	High 4.25 4.0	100% MDI[**] 4.25 4.25
Surface Treatments	Standard[*] Unsanded	Sanded top surface only	

Mill Constants

Wax addition %:   surface 1.8%, core 0.6%

Target thickness: 0.430" (11 mm)

Pressing time: 153 seconds

[*] Control setting levels.

[**]Made with 0.630" (16 mm) target thickness and 220 seconds pressing time

5.2 Testing at the Mill

During the mill trial, the panels were subjected to mill quality assurance procedures, both internal (those of the OSB company) and those set by the Engineered Wood Association (APA). These procedures are standard practice whenever the plant is in operation, and are required to assure that the product meets all the requirements for grade stamping and designation as commercial PRS OSB panels. Panels were randomly selected several times during each phase of the trial runs, and were graded and tested in accordance with APA and CSA/ASTM D-1037, CSA 0437 and CSA 0325 standards. This provided assurance that the ranges within which the mill production variables were set during the trial, were within the limits for producing merchantable quality panels. If the trial panels had not passed the required grading and testing standards, then they would not have been representative of panels suitable for use in the construction industry, and the data obtained from this research would have been simply academic, and not directly applicable. Quality assurance testing results are provided in Appendix A. Note that these tests were conducted on hot panels, and do not reflect the final strength properties at the time of shipment. Final strength and stiffness values will be higher due to hot stack resin cure.

5.2.1 Mill Quality Assurance Testing Procedure
The quality assurance testing procedures at the OSB mill were as follows:
1. Randomly select one 4' x 8' panel immediately after it has been pressed, and has exited the sawline (right after manufacture).

2. Cut the panel into test specimen sizes, cutting extra specimens, and randomly select from these the specimens to be tested. Specimens are:

   a. 3 parallel (strand parallel to machine direction) bending specimens measuring 4.5" (114.3 mm) x 11.5" (292.1 mm) x 7/16" (11 mm)

b. 3 perpendicular (strand perpendicular to machine direction) bending specimens measuring 4.5" (114.3 mm) x 11.5" (292.1 mm) x 7/16" (11 mm)

c. 5 internal bond test specimens measuring 2" (50.8 mm) x 2" (50.8 mm) x 7/16" (11 mm)

d. 24 hr cold soak specimens measuring 6" (152.4 mm) x 6" (152.4 mm)

e. Other specimens (Linear expansion testing etc.) as required

3. In the mill laboratory, the specimens were tested as follows:

a. Bending Specimens: The three parallel to machine direction specimens and three perpendicular to machine direction specimens were tested in a three-point load arrangement under displacement control at a steady rate to failure. Modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated automatically by the Instron LabVantage software.

b. Internal Bond (IB) Specimens: Each specimen was fixed with a thermosetting "hot glue" on both 2" x 2" (50 mm x 50 mm) faces to machined aluminum blocks, such that the specimen was sandwiched between them. When cool, the specimens were tested in tension perpendicular to the glued surfaces or faces at a steady displacement controlled rate to failure. The ultimate tensile load was recorded and a failure stress was calculated in psi or N/m^2.

c. 24 Hour Cold Soak Specimens: Specimens were measured for thickness, once on each of the four sides, and weighed before testing. Specimens were then placed under 1" (25 mm) of cold water, with their top surface parallel to the surface of the water, for a period of 24 hours. Specimens were then removed, towel dried and measured again in the same spots (marked on the specimen with a permanent

marker) for thickness and weighed. The thickness swell was then calculated as a percent of initial dry thickness, and the water absorption calculated as a percentage of initial dry mass.

All specimens tested during the mill trial passed the required standards as outlined in Table 2.1: Minimum OSB Strength and Stiffness Values, Dry, at Time of Shipping, in Accordance to CSA 0437.0 for Grade 0-2 (Structural Use Panels).

After the required storage time for hot-stacking (minimum approximately 2 weeks) in the mill warehouse as shown in photograph 5.1, the bundles of panels were packaged and shipped to Toronto for this study.

Photograph 5.1: Bundles of OSB Panels, Stored in Mill Warehouse and Awaiting Shipping.

5.3 Rationale For Using Mill Manufactured Panels

OSB panels made in a laboratory, on a laboratory scale press, differ significantly in properties from OSB panels made in a full-scale industrial mill.   These differences can sometimes be ignored, for example when the goal is to simply conduct a sensitivity analysis, characterizing the general effect of changing one variable, but they cannot be ignored where the objective is to use the properties of the panels to directly infer the properties of industrially produced panels. These differences have been repeatedly demonstrated during numerous trials at various facilities with which the author was involved. Even when furnish (strand for making OSB), resin and wax are provided from an industrial mill, the laboratory cannot accurately reproduce the mill process. These differences in properties occur for a number of reasons:

- **Blending.** A laboratory scale blender is orders of magnitude smaller than an industrial blender, with far fewer (usually only one) atomizers or spray nozzle for distributing the resin, and operated in batches as opposed to as a continuous process. It is very difficult to reproduce the blending process which occurs in an industrial blender in this way.

- **Strand Temperature and Moisture.**   The laboratory panel manufacturing process happens with strands at room temperature, as opposed to at the temperatures experienced with the continuous mill process, which can be quite high in certain conditions and areas. The strand moisture content, moisture distribution within strands, and internal stresses resulting from the typical mill high-temperature drying in the mill will also be different in the laboratory environment.

- **Forming.** The continuous process of mat formation in the mill is likely the most difficult aspect of panel manufacturing to duplicate in the laboratory. In the lab, panels must usually be formed by hand, or at best, by some form of modified laboratory scale formers. For this

reason, lab-made panels are usually not oriented, but rather are laid up with a random strand alignment. When orientation is desired, primitive hand formers consisting of boxes without tops or bottoms but with partition walls are usually used, and the strand is dropped through them. In some cases, robot mat formers are used, which lay each and every strand one at a time, but the difficulty here lies in distribution of sizes and fines throughout the mat. Ultimately, none of these forming techniques can accurately replicate the properties of a mill formed mat, in terms of strand alignment, vertical fines distribution, horizontal density distribution, and edge density.

Strand alignment and mat structure influence the properties of an OSB panel in several ways. The most obvious influence is directly on the mechanical properties of a panel, due to the anisotropic properties of wood. Wood is much stiffer (MOE) and stronger (MOR) in the direction parallel to the grain than it is perpendicular to grain. More importantly with respect to this study, strand alignment is also critical to processes of heat and mass transfer within the mat, having a large influence on permeability during pressing (Garcia, 2002). The effect of strand alignment may quite possibly also impact the permeability of the final panel after pressing, but this has not yet been investigated to the knowledge of the author.

- **Pressing.** Typically, laboratory presses have only one opening, and usually measure up to 24" by 24" (0.6m x 0.6m), as compared to the much larger industrial mill presses which are commonly 12 opening or more, and measure up to 12' by 24' (3.7m x 7.4m). The differences in size are critical for several reasons.

  Internal Gas Pressure: Likely the most significant impact of press size is on the internal gas pressure generated during pressing. Internal

gases are created when the high temperature press platens come in contact with the mat of strands. The high temperature turns any moisture present in the strands into high temperature steam, and can cause many other constituents of the wood, resin or wax to change to the gas state. These expanding gases cause pressure to develop within the mat. The highest pressures are generated at the horizontal center (x-y plane) of each mat. The pressure drops with increasing proximity to the edge of the press, as the press edges are the only place for the gases to escape. Thus, the greater the distance from the edge of the press, the greater the internal gas pressure, and as such, smaller lab presses cannot create the same internal gas pressures. Figure 5.1 below shows internal gas pressure measurements made by the author and Garcia at the Ainsworth 100 Mile House OSB mill, using a PressMAN^{TM} pressure and temperature probe. The probe is inserted through the side of the press into the mat to different depths as desired. These measurements clearly show the edge effect with pressure and temperature decreasing from depths of 203 mm to 152 mm measured from the mat edge. Where small scale laboratory presses are used, which measure only 1000 mm by 1000 mm from edge to edge or less, the effect on internal gas pressure will be far more pronounced, resulting in significant pressure reductions.
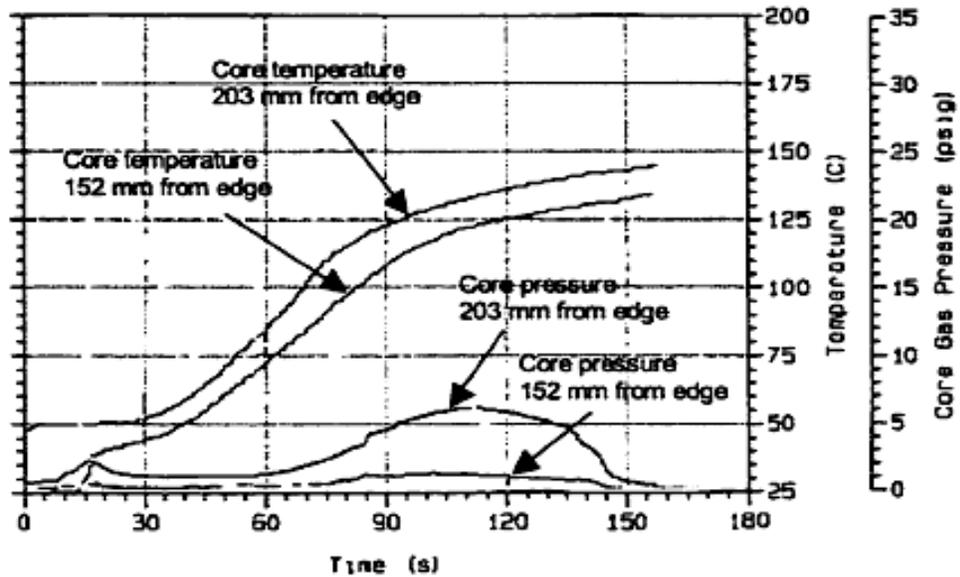
Figure 5.1: Measurements of the Effect of Distance From Mat Edge on Internal Gas Pressure and Temperature Within an OSB Mat During Hot Pressing, Made by the Author and Garcia at the Ainsworth 100 Mile House Mill (Garcia, 2002).

The internal gases are critical to the pressing process as they serve to transfer heat energy, from the platen surfaces to the core in the vertical direction, and from the center outwards in the horizontal plane. Also, pressure and temperature are directly related for example as illustrated by the ideal gas law:

$$pV = nRT$$

where p = pressure

V = volume

n = number of moles

R = constant

T = temperature

Higher pressures result in higher temperatures. The escape of internal gases through the edge of the press to the atmosphere also results in a direct loss of heat energy. Because temperature is critical for the

curing of resins, the transfer of heat energy through steam convection from the platen surface to the core, and the plasticization of the wood strands necessary for densification, the difference in internal gas pressure from the industrial press to the lab press result in panel property differences.

The thermal mass difference between the laboratory and industrial presses will also play a role, with the much smaller lab press cooling off much faster that the industrial press during the pressing cycle.

- ▪ *Hot-Stacking.* Hot-stacking is the process of newly produced panels being stacked one on top of another to form a bundle of hot panels, which insulate one another and share heat energy as the bundle cools very slowly. The result is that the resins have an extended time to continue curing, well beyond the short time they had in the press. Since the rate of cure of the resins (PF and MDI) used in the OSB process varies in a non-linear relationship with temperature, the resins will continue curing and polymerizing even at temperatures lower than the approximately 200°C of the press platens, although at a slower rate. This effect of hot-stacking is relied upon and taken into consideration by OSB manufacturers, and is included in the calculations of minimum pressing times needed to attain the desired final panel properties. In the laboratory process, although newly pressed panels are often placed in insulated boxes, the full effect of hot-stacking and the effects it produces cannot necessarily be replicated.

These are only some of the significant differences between the laboratory and industrial OSB manufacturing processes. Together, each adds cumulatively to the differences in physical properties between panels made in the two processes.

The variables at each step of the manufacturing process in the OSB mill, and their impact on panel properties were examined in Section 3.4. Ultimately, when one is trying to study the properties of OSB panels with implications to actual performance, the best panels to use are mill-fabricated panels from an industrial OSB mill, such as the panels used for this study. In effect, for more representative results, the actual plant must become part of the laboratory.

5.4 Specimen Preparation

The bundles of panels arrived by truck, covered with heavy tarps for protection from the elements. Each bundle was also wrapped in the mill around all four sides and the top with a polyethylene bag, over top of protective cardboard. The bundles were open at the bottom, and supported on three pieces of wood to keep them off the ground. Although the bundles were well protected during transport from rain and other weather, they were not sealed in a completely airtight manner and hence could have been exposed to varying relative humidities during transport. However, the bundles were painted on all sides with protective paint called "edgeseal", which contains wax and is designed to prevent the ingress of moisture, as shown in Photograph 5.2. Also, the total transport time was only a few days, so the time for possible exposure was relatively short.

The bundles were cut open (metal banding and protective cardboard removed), and the panels were sorted into the various panel groups, (according to how they were manufactured). The various groups were identified by markings made by the author at the time of manufacture at the mill, both on the sides and on the top surfaces of each test panel. Within each group, the panels were then sorted by full panel density, and panels which came closest to matching the target densities of the study were selected for testing [low density 554 kg/m^3 (34.5 lbs/ft^3 unit weight), middle control density 626 kg/m^3 (39.0 lbs/ft^3 unit weight), and high density 689 kg/m^3 (42.9 lbs/ft^3 unit weight)]. All panels were stored covered by polyethylene bags, inside a heated warehouse, and then in the Building Science Laboratory at UofT. Although the RH and temperature were not

measured, they would have been close to conditions expected inside normal habitable or laboratory space.

The selected panels from each group were then cut into one-foot wide (305 mm) strips, across the 4-foot (1220 mm) width of a full panel, and every other strip was selected for testing, in order to sample from a full panel.

Photograph 5.2: Panels in Lab Waiting to be Cut Into Test Specimens.

5.4.1 Permeance Disc Preparation

From the one-foot wide (305 mm) strips, permeance testing discs (Photographs 5.7 and 5.8) approximately the right size for the permeance cup test (92 mm diameter) were rough-cut on a band-saw, and only every other disc was selected again for more randomized sampling. The discs were then finished on a lathe to the size required to fit as a lid on the permeance cup test cups.

5.4.2 Individual Layer Permeance Disc Preparation

Individual component layers specimens of OSB were prepared from full thickness control (standard density and resin addition level) OSB. Each series was prepared by passing full thickness OSB strips through a planer. Repeated passes were made until only the desired layer remained, which was indicated by a change in strand alignment direction. Discs were then cut from the individual layers and finished on a lathe as described in Section 5.4.1. The three individual OSB component layer specimen groups were designated "top surface", "core" and "bottom surface".

5.4.3 Sanded Disc Preparation

Two sanded specimen series were prepared from control material, one by sanding off the top surface (approximately 3.5 mm), designated "Sanded Top Sfc.", and the other by sanding off the bottom surface material (approximately 3.5 mm), designated "Sanded Bottom Sfc." Sanding was done by means of a belt sander, very gradually, to prevent heat generation, which might have altered the OSB surface structure or chemistry. The depth of sanding was sufficient to remove the entire surface to the core layer beneath.

5.4.4 Sorption Slice Preparation

Two types of "slice" sorption test specimens were prepared, measuring approximately 137 mm long x 11 mm thick x 5 mm wide. The first type, called "full-thickness" slices, as shown in Photographs 5.3 and 5.4, were cut through the thickness of the panel, such that the 11 mm dimension was the panel thickness. These specimens were cut from the same panels selected for the full thickness permeance disc cutting. The second type of slice specimen, called "sorption slice layer" specimens as shown in Photograph 5.5, was cut from the individual component OSB layers prepared by the planing of strips as described in Section 5.4.2. These specimens were cut such that the specimen thickness was the thickness of the corresponding component layer, and the length dimension was oriented in the plane of the panel. All slice specimens were cut

from the strips on a table saw, and random slices (approximately every third slice cut) were selected in order to sample from a greater overall panel area.

Photograph 5.3: Full Thickness Sorption Slice Specimen, 42.9 lbs/ft^3 Unit Weight (689 kg/m^3 Density) Group.

Photograph 5.4: Full Thickness Sorption Slice Specimen, 42.9 lbs/ft^3 Unit Weight (689 kg/m^3 Density).
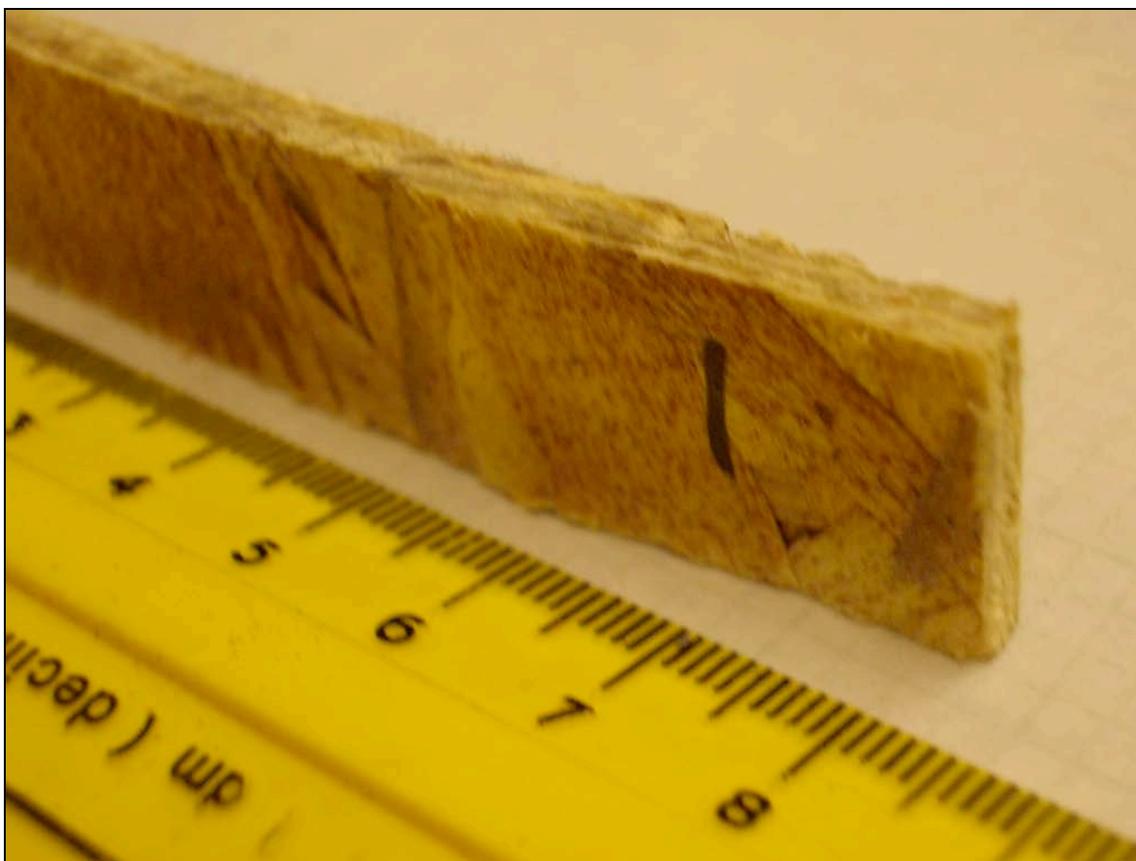
Photograph 5.5: **Sorption Slice Specimen of Top Surface Component Layer.**

5.4.5 Sorption Planer Shavings Preparation

The sorption planer shavings shown in Photograph 5.6, were made at the same time and in the same way as the individual layer specimens described in Section 5.4.2. As the OSB strips were passed through the planer, the shavings from the planer were deposited on a tarp laid on the ground around the machine. When the desired layer had been planed off the OSB strip, the shavings collected on the tarp were mixed to ensure a random sample, and a sample was collected for testing. The planer shavings were used to investigate whether smaller sections could be used to develop a rapid sorption test method. Large specimens often take over a month to come to equilibrium moisture content conditions.

Photograph 5.6: Sorption Planer Shavings Specimen.

5.4.6 Cyclic Soak Specimen Preparation

The three groups of cyclic soak permeance disc specimens were prepared from discs selected at random from the control group (standard density, resin and wax addition levels). The three cyclic soak panel groups consisted of: one cycle of soaking and drying; three cycles of soaking and drying; and eight cycles of soaking and drying. Each cycle consisted of soaking (submersion under 25mm of room temperature tap water) for 24 hours, followed by drying in a laboratory oven at $102^{o}C$ +/-$2^{o}C$ for 24 hours. The soaking and drying were repeated for the required number of cycles (1, 3 and 8). This moisture cycling method is intended to give an accelerated severe weathering exposure scenario, and to simulate real life exposure conditions panels would experience if left uncovered on the construction site, or wetted through rain leakage or condensation. The temperature setting of $102^{o}C$ +/-$2^{o}C$ for 24 hours was chosen, as this

temperature is used in many ASTM test methods for wood and composite panel testing including ASTM D-1037.

5.4.7 Cyclic Relative Humidity Specimen Preparation

One group of five specimens of full thickness permeance disc specimens called "RH Cycled Series" was prepared from specimen discs selected at random from the control group (standard density, resin and wax addition levels). These specimens were subjected to five RH cycles. Beginning at ambient room relative humidity and temperature conditions (42% RH at 22°C), the specimens were conditioned for 24 hours, and then exposed to controlled chamber conditions of 100% RH at 25°C for 24 hours. The 100% RH chamber consisted of a small plastic box with a sloped lid, coated with a light layer of petroleum grease (Vaseline) to prevent condensation from dripping onto the specimens. The specimens sat on a stainless steel rack, over top of distilled water in the bottom of the box.   The 100% RH box was in turn placed inside of the controlled temperature and relative humidity chamber.

Table 5.2: OSB Variables Selected for Study

Panel Types / Groups	Target Unit wt. (lbs/ft^3)	Target Density (kg/m^3)	Surface Resin (% solids)	Core Resin (%)	Surface Wax (% liquid)	Core Wax (% liquid)	Target Thick. (in.)	Press Time (sec.)	Perme-ance Tested	Sorption Tested
554 kg/m^3 (34.5 lbs/ft^3)	**34.5**	544	3.0	2.0	1.8	0.6	0.430	153.0	Yes	Yes
626 kg/m^3 (39.0 lbs/ft^3)	**39.0**	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	Yes
689 kg/m^3 (42.9 lbs/ft^3)	**42.9**	689	3.0	2.0	1.8	0.6	0.430	153.0	Yes	Yes
Resin	39.0	**626**	**4.25**	**4.0**	1.8	0.6	0.430	153.0	Yes	Yes
Top Surface	39.0	626	3.0	-	1.8	-	0.430	153.0	Yes	Yes
Core	39.0	626	-	2.0	-	0.6	0.430	153.0	Yes	Yes
Bottom Surface	39.0	626	3.0	-	1.8	-	0.430	153.0	Yes	Yes
Sanded Top Sfc	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
Sanded Bottm Sfc	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
1-cycle soak	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
3-cycle soak	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
8-cycle soak	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
RH Cycled	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
RH cycle control	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
Top sfc up	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
Top sfc down	39.0	626	3.0	2.0	1.8	0.6	0.430	153.0	Yes	No
100% MDI	**45.3**	**728**	**4.0**	**4.0**	1.8	0.6	0.630	220.0	Yes	Yes
Spruce plywood	26.8	**430**							Yes	Yes
Red Cedar (solid)									No	Yes
White Pine (solid)									No	Yes

5.5 Laboratory Testing

All small specimen water vapour permeance and sorption testing was conducted in the University of Toronto Building Science laboratory, between January of 2002 and September of 2005. Both the permeance and sorption experiments were carried out simultaneously within the same relative humidity and temperature controlled chamber.

5.5.1 Controlled Relative Humidity and Temperature Chamber

The controlled relative humidity and temperature chamber shown in Photograph 5.9 consisted of a box constructed of OSB, with the entire inside painted with three coats of low permeance aluminum paint, and lined with 6-mil polyethylene joined with 3-M vapour barrier tape and acoustical sealant. All box joints were also sealed with acoustical sealant. The front of the box was made of rigid clear plastic (Plexi-glass), and was sealed to the box with a latex gasket and acoustical sealant on both sides of the gasket.

The relative humidity inside the box was controlled with dishes of saturated salt solutions visible in the bottom of Photograph 5.9 for relative humidity control, and two small fans for air circulation. According to Time, "For relatively long-lasting sorption measurements on wood, saturated salt-solutions have shown to give more stable environmental conditions than conditioned air obtained from a mixture of heated water and air." (Time, 1998). Relative humidity and temperature were monitored with a Vaisala RH and temperature probe, and verified periodically by means of a sling psychrometer.

A target chamber temperature of 25°C was chosen in accordance with the range allowed by ASTM standard E-96 "Standard Test Methods for Water Vapour Transmission of Materials", which states that "The chamber temperature chosen shall be between 21°C and 32°C (70°F and 90°F) and shall be maintained constant within +/- 1°C (+/- 2°F)". The temperature inside the chamber was

controlled by means of three small, shielded, low wattage light bulbs, activated by a control program. The control program monitored the temperature within the box with three thermocouples, one located at the bottom of the box, one at mid-height and one at the top of the box. When the average chamber temperature deviated by +/- 0.5^{o}C from the set-point of 25° C, the light bulbs were switched either on or off. According to Burch (Burch, Thomas and Fanney, 1992) who conducted tests at 24°C and 7°C, the effect of temperature on permeability is negligible.

The chamber was placed within an insulated guard room, which was in turn inside of the climate simulator room, where the temperature was set at 21°C and controlled to within +/- 1° C by heating and cooling equipment. With the chamber temperature 4K above the guard room temperature, the need to provide separate cooling capacity for the chamber was eliminated. The chamber temperature could be precisely controlled simply by heating. Also, by placing the chamber inside of a guard room with insulated walls, the guard room environment around the chamber was buffered from any temperature fluctuations within the climate simulator caused by the heating and cooling equipment switching on and off.

The temperature and relative humidity data were continually recorded every minute and stored for the duration of the experiment. The chamber relative humidity values given by the Vaisala RH meter and temperature probe were periodically verified by means of a sling psychrometer held in front of the circulating fan inside the chamber. The relative humidity was then calculated from the dry-bulb temperature, the wet-bulb temperature, or the thermodynamic wet-bulb temperature, and the total barometric pressure (101,325 Pa) (Hutcheon and Handegord, 1995) (Results are in Table 5.3). The maximum difference found between the Vaisala measured and sling psychrometer measured results was 2.1%, with an average difference of 1.3%.

Table 5.3: Chamber Relative Humidity Verification Results.

Date	Dry-bulb temp. (^{o}C)	Wet-bulb temp. (^{o}C)	RH (%) from wet bulb (1)	RH (%) Vaisala Probe (2)	Absolute Difference (%) (1) – (2)
Oct. 16, 2003	25.5	21.4	70.1	69.6	0.5
Nov. 4, 2003	25.3	23.1	82.9	81.6	1.3
Nov. 6, 2003	25.1	23.3	84.2	84.5	0.5
Nov. 19, 2003	25.1	23.3	84.2	84.4	0.2
Nov. 21, 2003	25.6	23.9	86.9	85.0	1.9
Mar. 29, 2004	25.3	18.3	51.3	49.2	2.1
Apr. 27, 2004	26.1	18.7	49.7	48.7	1.0
May 7, 2004	24.6	17.6	50.5	49.9	0.6
May 12, 2004	25.3	18.3	51.2	49.7	1.5
June 18, 2004	25.4	18.3	51.3	49.7	1.6
June 23, 2004	25.5	18.7	52.6	50.5	2.1
July 26, 2004	25.4	18.3	50.7	49.0	1.7

5.5.2 Water Vapour Permeance Testing

A slightly modified form of the commonly used permeance cup test, ASTM E 96 (Standard Test Methods for Water Vapour Transmission of Materials) was used to measure the water vapour permeance of the OSB specimens as shown in Photographs 5.7 and 5.8. In the standard cup test used in this study, the material to be evaluated is sealed as a "lid" onto a dish or cup, containing either a desiccant (Dry Cup test) or liquid water (Wet Cup test). The lid is sealed to the cup with wax. Thus any water vapour entering or leaving the cup must pass through the lid of known surface area. The whole test assembly is then placed into a controlled atmosphere chamber at 50% RH and 25°C, illustrated in Photograph 5.9. In both cases, the relative humidity gradient across the specimen is 50%. Periodic weighing of the whole test assembly (cup, saturated

salt solution in cup, and test-specimen lid) determines the rate of mass gain or loss, and in turn the permeance of the material, but at only two RH gradients, and each spanning a 50% RH range.

The modification to the ASTM cup test method applied in this study, involved the use of five different saturated salt solutions, as well as a desiccant for the lowest relative humidity step for the control of relative humidity. The salts were laboratory grade and the water used was distilled water. This modification allowed for testing through six relative humidity gradient steps, ranging from 2% RH up to 100% RH, as shown in Tables 5.3 and 5.4. The first salt listed is the salt solution in the chamber, and the second listed is the salt solution in the cup, and the resultant relative humidity of each is listed below. Each time the chamber relative humidity was increased with the next saturated salt solution, the cup was filled with the previous salt solution from the chamber. The moisture gradient was always in the direction from the chamber into the cup, with the exception of the wet cup and inverted wet cup tests. This modification to the ASTM test method has been used by others (Burch, Thomas and Fanney, 1992). The use of saturated salt solutions for such work is outlined in ASTM test method E104-02, "Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions".

Table 5.4: Saturated Salt Solutions and the Resulting Relative Humidities.

Salt in Chamber: Salt in Cup:[*]	$CaCL_2$ - Desiccant	$MgNO_3$ - $CaCL_2$	$NaNO_2$ – $MgNO_3$	NaCl - $NaNO_2$	KNO_3 – NaCl	$MgNO_3$- H_20
Chamber RH:	28.0%	50.0%	60.0%	70.0%	85.0%	50.0%
Cup RH:	2.0%	29.0%	53.0%	64.4%	75.0%	100.0%
RH Gradient	26.0%	21.0%	7.0%	5.6%	10.0%	50.0%
Avg Specimen RH	15.0%	39.5%	56.5%	67.2%	80.0%	75.0%
Gradient (Pa @ 25°C)	823	665	222	177	317	1584

[*]Relative humidity values over saturated salt solutions taken from Wexler, 1991.

It is a property of most salts that, when in the form of a saturated solution, within a given temperature range, they create an environment of constant relative humidity above them, and the specific relative humidity created is unique to that specific salt. The rationale for this modified test method is that OSB, being made almost entirely of wood, is a hygroscopic material, and as such, its permeance varies greatly with relative humidity. Therefore, evaluating the permeance of hygroscopic materials across only two relative humidity gradients in accordance to the ASTM Cup Test method is of limited use for the accurate characterization of the material, and for the end goal of using the data for hygrothermal modeling and building design. Better resolution can be achieved with the six steps used in this study. Further, permeability increases non-linearly with relative humidity in hygroscopic materials, so the inherent error when a linear relationship is assumed between two points (dry-cup and wet-cup) for the standard cup method is reduced by using several relative humidity steps.

The "average specimen relative humidity" listed in Table 5.4 was calculated as the arithmetic mean of the cup and chamber relative humidities, and is close to that which would be measured at the midpoint of the thickness of the specimen. However, it is likely that the relative humidity at the mid point of a permeance specimen is not at the exact arithmetic mean of the relative humidities (Hutcheon and Handegord, 1995). Both are plotted in Figure 5.2 below for comparison. For hygroscopic materials the permeability increases with relative humidity and moisture content. Thus the permeability will be higher on the side of the specimen facing the high relative humidity side, essentially making it easier for water vapour to enter that side of the specimen. Thus, because of the relative humidity dependent variation in permeability, the vapour pressure or relative humidity gradient itself though the specimen is not linear. The result is that the relative humidity at the geometric mid point in thickness will be slightly higher than the arithmetic mean of the two sides. However, this difference will be relatively small, as explained by Hutcheon and Handegord (1995).
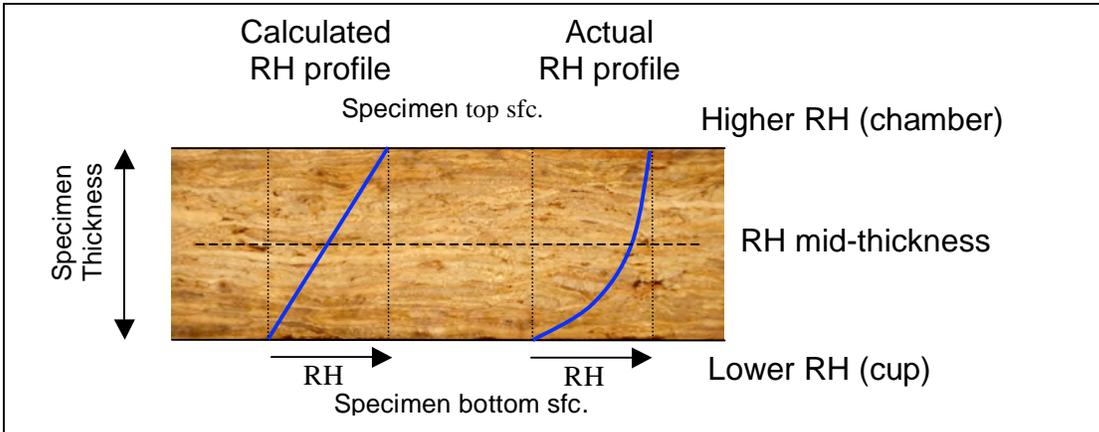
Figure 5.2: **Calculated Mean Specimen RH Profile and Theoretical RH Profile Through Specimen Thickness Subject to RH Gradient.**

A desiccant consisting of molecular sieves was used in the cup in the first step to attain a relative humidity as close to zero as possible. The same OSB test specimens were used throughout the experiment at every relative humidity step.

Photograph 5.7: **Permeance Test Assembly, Cup with Saturated Salt Solution and Full Thickness OSB Test Specimen Sealed to Cup with Parafin Wax.**

Photograph 5.8:   Permeance Cup Test Assemblies in Controlled Temperature and Relative Humidity Chamber.

Before being sealed to the top of each cup, the specimens were allowed to equilibrate to the ambient relative humidity of the Building Science laboratory over the period of one month (42% rh, at 22°C). The exception to this was the series of control density specimens, which were oven dried before testing for comparison. The cups were glass custard dishes, measuring 90 mm in inside diameter at the top, with a small lip at the top of the inside edge to which the permeance specimens were easily sealed. Each cup was filled to approximately 10 mm in depth with a saturated salt solution (with excess undisolved salt), prepared by mixing laboratory grade salt with distilled water. After conditioning to the ambient relative humidity of the lab, each specimen was weighed and measured for thickness with a micrometer at four locations around the edge, each 10 mm from the edge and radially at 90° increments. The specimens were then carefully sealed with warm microcrystalline paraffin wax around the entire

perimeter edge. The edge sealed specimens were then gently pressed into the top of each cup until they rested on the small inside cup lip. Heated wax was then painted or placed around the junction of the cup and lid with the aid of a soldering iron to help the wax flow, to fill any void left. Care was taken to ensure that the wax did not cover any of the top or bottom surfaces of the discs, and that the wax was not so warm as to penetrate into the edges along the grain of the specimens. The entire cup, lid and saturated salt solution assembly was then weighed again before being placed into the controlled environment chamber.

The cup assemblies were placed in the controlled environment chamber onto one of two carrousels as shown in Photograph 5.8. These carrousels were made of expanded metal mesh, each two levels high. The carrousels were on steel shafts held by pillow-block bearings at either end, and could be rotated for reaching the assemblies once in the chamber. The cup assemblies were periodically weighed on an electronic scale which was placed inside the chamber through a re-sealable opening in the bottom of the plexiglass front, seen in Photograph 5.9. The cup assemblies were reached by means of one of two circular openings with sealed doors, through which a sample was reached to carefully lifted and weighed. Each relative humidity gradient step was continued for a period of at least 30 days or longer, until a steady rate of mass gain was reached.

Photograph 5.9:   Test Chamber, Temperature and Relative Humidity Controlled, Within Guard Room, Inside Temperature-Controlled Climate Simulator, for Both Permeance and Sorption Testing.

A special cup test assembly was constructed. It consisted of a high density, ultra high molecular weight (UHMW) plastic lid sealed to a cup. This special cup assembly was used to verify whether or not the method used to seal the permeance discs to the cups with wax was in effect water vapour impermeable, and thus not a source of error. UHMW plastic is very dense, and almost vapour impermeable. The cup assembly was prepared with liquid water in the cup, and the UHMW plastic lid sealed in the same way as all the OSB specimens were sealed. The assembly was then tested at the second relative humidity step (50% RH – 29% RH) along with all of the other permeance specimen tests. Results indicated that no detectable water vapour penetrated the wax seal, UHMW lid or glass dish over a period of 350 hours, as the mass of the cup assembly did not change.

After permeance testing was complete, some permeance disc specimens were cut down in size to fit into the x-ray densitometer and their vertical density profile was measured. Results from one specimen were previously presented in Figure 2.1. The X-ray density profiler, (QMS model QDP-01X) is a computerized X-ray–based profiling device for determining density distribution in composite materials. It was used in this case to determine the density profile through the thickness of small OSB specimens, known as the vertical density profile (VDP).

5.5.3 Water Vapour Sorption Testing

The water vapour sorption specimens, consisting of discs, slices and planer shavings, were also conditioned to the ambient relative humidity of the Building Science Laboratory before testing. Before being placed into the controlled environment chamber, each specimen was weighed and measured. The small metal (tin foil) specimen dishes used to hold the planer shavings were also individually weighed. The specimens were then placed into the controlled environment chamber and onto one of the expanded metal carrousels as shown in Photograph 5.10. Throughout the duration of the experiment, each specimen was weighed periodically. Exposure was continued until the mass of each sample became constant (ie: no more water vapour was being absorbed or lost). Once the mass became constant, the sample was removed from the chamber and the relative humidity gradient step was deemed complete.

Photograph 5.10:   Various Sorption Test Specimens in Controlled Temperature and Relative Humidity Chamber During Testing.

5.6 Hygrothermal Modeling

The final stage was the analysis of the experimental results and their application / evaluation through computer modeling simulations. The hygrothermal computer modeling software used was WUFI, which stands for "Wärme- und Feuchtetransport instationär" ("Transient Heat and Moisture Transport"), developed by the IBP (Fraunhofer-Institut fur Bauphysik). After the laboratory testing was complete and the results were compiled, the material property data was used to create several types of OSB within the WUFI program, and various simulations were then run to evaluate the significance of the variation in properties between the various OSB types studied, and the ultimate impact on the performance of selected wall systems.

Chapter 6

Results of Water Vapour Permeance and Sorption Testing

6. RESULTS BACKGROUND

This chapter is divided into two sections: Section, 6.1 presents the results for water vapour permeance testing, and Section 6.2 presents the results for the water vapour sorption testing. Although water vapour permeance and sorption are two different properties with different test procedures, testing was carried out

concurrently within the same temperature and relative humidity controlled chamber. This chapter presents only results, whereas all the analysis including statistical analysis and discussion are presented in the next chapter, titled Analysis and Discussion of Results.

6.1 Water Vapour Permeance Test Results

As illustrated in Tables 5.1, 5.2 and 6.2, three density levels, one elevated resin content, and individual layers (top surface, core and bottom surface) were tested over the entire RH range. The control was the middle density 626 kg/m^3 (39.0 lbs/ft^3 unit weight) at the normal (non-elevated) resin and wax addition rates. The elevated resin content specimens were at control density, and the individual layer specimens were made from control material. Five individual specimens were tested in each category, and the same specimens were carried through the entire RH range. All specimens were virgin, as received from the mill, un-exposed to elevated moisture levels.

Specific investigations were then later carried out at the second relative humidity step (29% - 50% RH range) to study the effects of various surface treatments, moisture exposures, orientations (top surface up or down), and spruce plywood for reference.

A summary of all permeance test categories and relative humidity gradients applied is provided in Table 6.1

Table 6.1: Permeance Test Categories and Relative Humidity Gradients Applied.

Permeance Testing

| | Chamber Relative Humidity (%) | 28 | 50 | 60 | 70 | 85 | 50 |
	Cup Relative Humidity (%)	2	29	53	64	75	100
Non-Control	554 kg/m^3 (34.5 lbs/ft^3)	√	√	√	√	√	
	626 kg/m^3 (39.0 lbs/ft^3)	√	√	√	√	√	
	689 kg/m^3 (42.9 lbs/ft^3)	√	√	√	√	√	
	Resin	√	√	√	√	√	
Control Material	Top Surface	√	√	√	√	√	
	Core	√	√	√	√	√	
	Bottom Surface	√	√	√	√	√	
	Sanded Top Sfc		√				
	Sanded Bottm Sfc		√				
	Control 626 kg/m^3 (39.0 lbs/ft^3)		√				
	1-cycle soak		√				
	3-cycle soak		√				
	8-cycle soak		√				
	RH Cycled		√				
	RH cycle control		√				
	Top sfc up		√				
	Top sfc down		√				
Other	100% MDI (728 kg/m^3)		√				
	UHMW Plastic lid		√				
	Spruce plywood		√				
Control Material	Wet Cup						√*
	Inverted Wet Cup Top sfc wet						√*
	Inverted Wet Cup Top sfc Dry						√*

* Data presented in Appendix E and not discussed due to too few specimens.

Water vapour permeance testing, in accordance to ASTM E96-95, was conducted over the period of approximately three years, and over a total of five vapour pressure gradients (seven gradients including wet cup and inverted wet cup testing).

The raw water vapour permeance test results were in the form of mass gain over time measurements, for each individual cup test assembly, for a given relative humidity step. Results for the five individual cup assemblies for one group are presented in Figure 6.1.
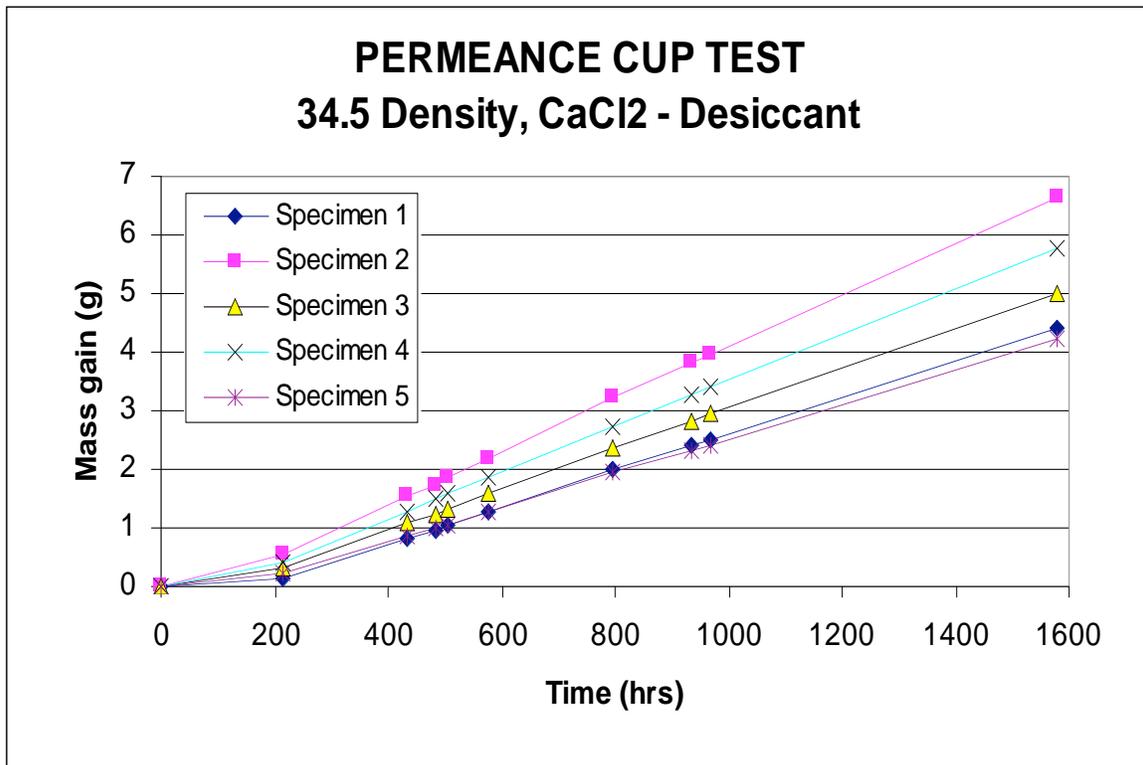
Figure 6.1: Water Vapour Permeance Mass Gain vs. Time; Test Results for Individual Cup Test Assemblies of the Low Density 554 kg/m^3 (34.5 lbs/ft^3 unit weight) Specimen Group at the First Relative Humidity Gradient Step (28% - 2% RH).

Each specimen group set of individual mass gain vs. time curves for a given relative humidity step will in turn yield one average mass gain vs. time curve, as illustrated in Figure 6.2.
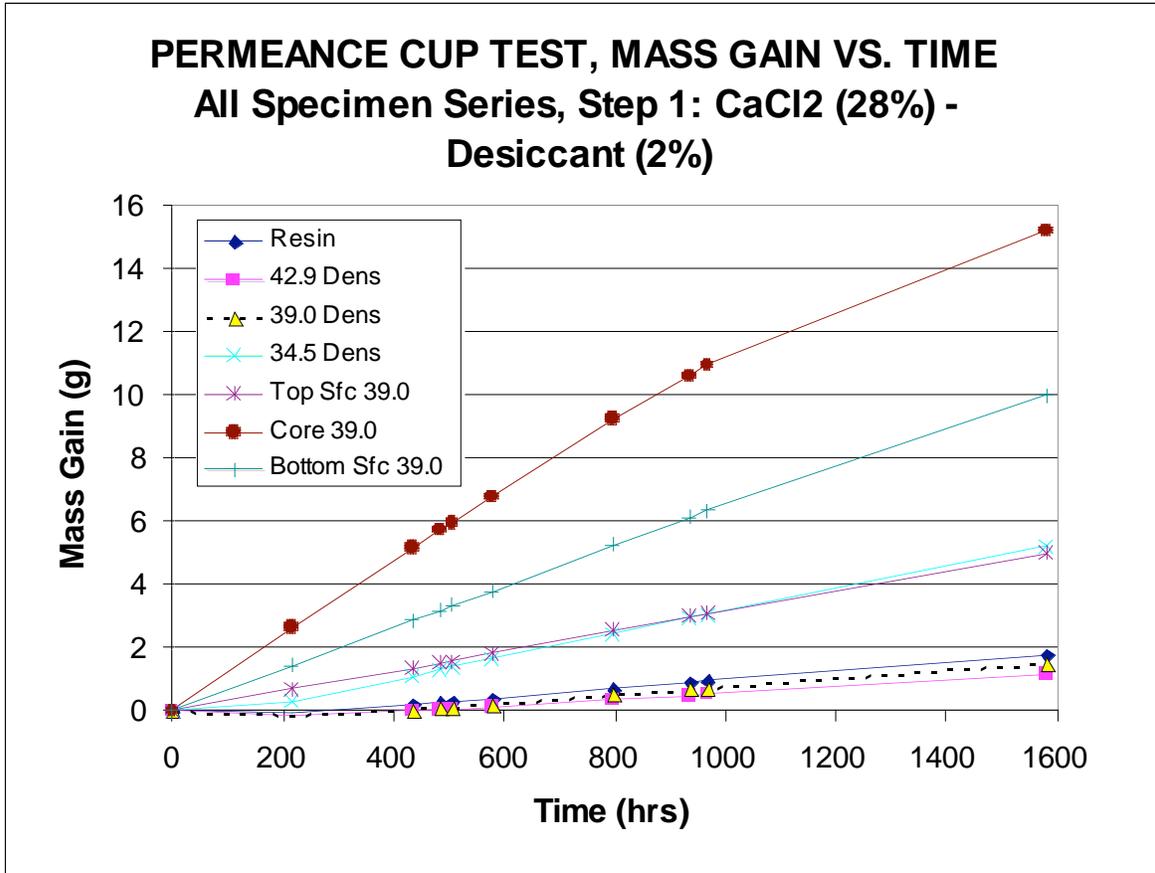
Figure 6.2: Mass Gain vs. Time, All Specimen Series; Each Curve Represents an Average of 5 Individual Specimens.

The specimens were not all of the exact same thickness, nor density due to inherent variability. The average of the permeabilities of each five specimens will in turn yield an average permeability value for that specimen series or treatment, at that one given relative humidity gradient. Such points are plotted to form a series on the "Permeability Summary over Full RH Range" summary chart, as shown in Figure 6.3. Standard deviation bars indicate the variability. For the purposes of comparison, all mass gain over time data were converted from permeance to permeability, and then plotted together over the entire relative humidity range.
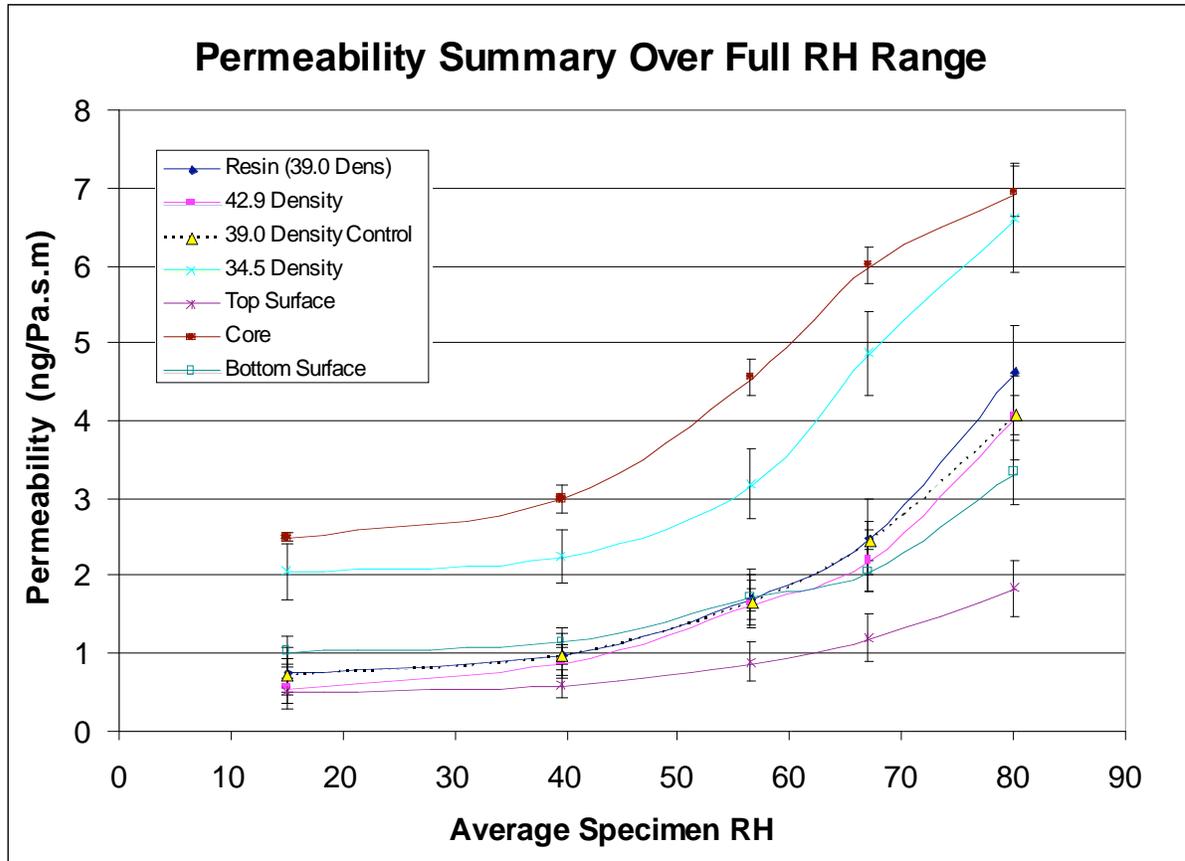
Figure 6.3: Permeabilities of Various 5-specimen Groups Over Full RH Range with +/- 1 Standard Deviation Bars.

Table 6.2: Permeability Mean and Standard Deviation Values for the Various Series Tested Over the Full RH Range.

Permeability Summary

Group	$CaCL_2$-Dessicant	$MgNO_3$-$CaCL_2$	$NaNO_2$-$MgNO_3$	$NaCl$-$NaNO_2$	KNO_3-$NaCl$
Chamber RH (%)	28	50	60	70	85
Cup RH (%)	2	29	53	64	75
Avg Specimen RH (%)	15.0	39.5	56.5	67.0	80.0

Mean Permeability (ng/Pa·S·m) with corresponding standard deviation

Resin (39.0 Dens)	0.76 (0.31)	0.99 (0.27)	1.71 (0.36)	2.49 (0.49)	4.65 (0.58)
42.9 Density	0.56 (0.30)	0.88 (0.20)	1.64 (0.30)	2.20 (0.40)	4.04 (0.54)
39.0 Density (Control)	0.71 (0.22)	0.98 (0.12)	1.68 (0.15)	2.46 (0.25)	4.07 (0.24)
34.5 Density	2.05 (0.36)	2.25 (0.36)	3.18 (0.44)	4.87 (0.54)	6.61 (0.71)
*Top Surface	0.51 (0.16)	0.60 (0.18)	0.89 (0.25)	1.19 (0.30)	1.84 (0.35)
*Core	2.48 (0.05)	2.99 (0.19)	4.57 (0.23)	6.01 (0.23)	6.96 (0.32)
*Bottom Surface	1.03 (0.19)	1.16 (0.18)	1.73 (0.29)	2.06 (0.28)	3.34 (0.41)

* Top surface, core and bottom surface all made from control material.

6.1.1 Permeability Variation with Relative Humidity

As would be expected with a hygroscopic material, the permeability in each group increases significantly with relative humidity, as illustrated in Figures 6.3, 6.4, 6.5 and Table 6.2. As the relative humidity increases, permeability increases by approximately three times in the core layer group, and up to seven times in the 42.9 lbs/ft^3 or 689 kg/m^3 "higher" density group.

6.1.2 Permeability Variation with Density

The relationship between specimen density and permeability was investigated. OSB discs cut from panels from three trials where only density was varied were tested for permeability with the ASTM cup test method over the full relative humidity range. Results indicate that the lowest target density group, (554 kg/m^3 or 34.5 lbs/ft^3 unit weight) showed the highest permeability, and the highest density group (689 kg/m^3 or 42.9 lbs/ft^3 unit weight) had the lowest permeability, as illustrated in Figure 6.4. The relationship between density and permeability

here is inverse where the higher the density of a given material, the lower the permeability. It must be noted that these are target and not measured densities.
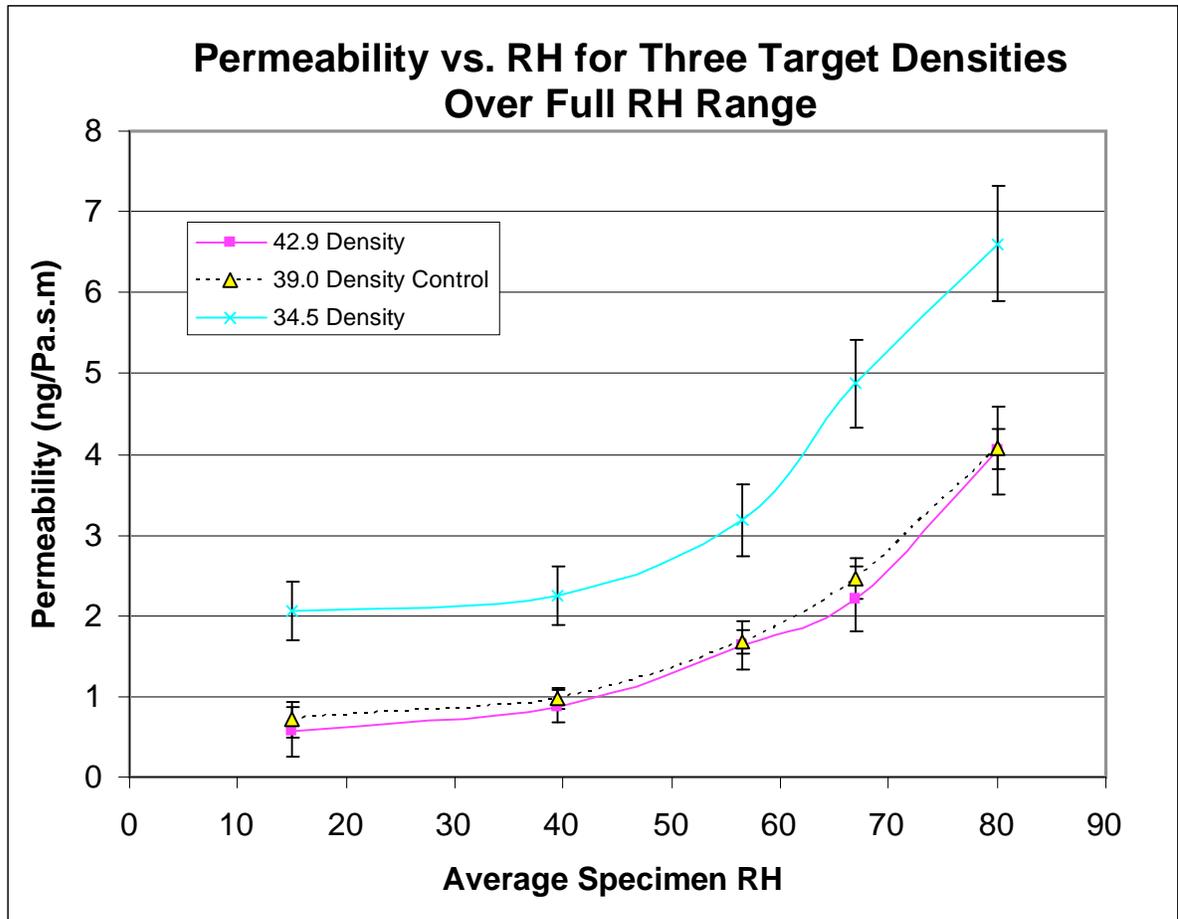
Figure 6.4: Permeability Variation Over Full RH Range for Different Target Density 5-specimen Series with Standard Deviation Bars.

6.1.3 Permeability Variation with Resin / Wax Content

The effect of varying resin and wax content levels was investigated in two ways, first by comparison of the OSB specimen series labelled "Resin" to the 626 kg/m^3 or 39.0 lbs/ft^3 control, and second by comparison of the individual component layers to one another. Results are plotted in Figure 6.5.
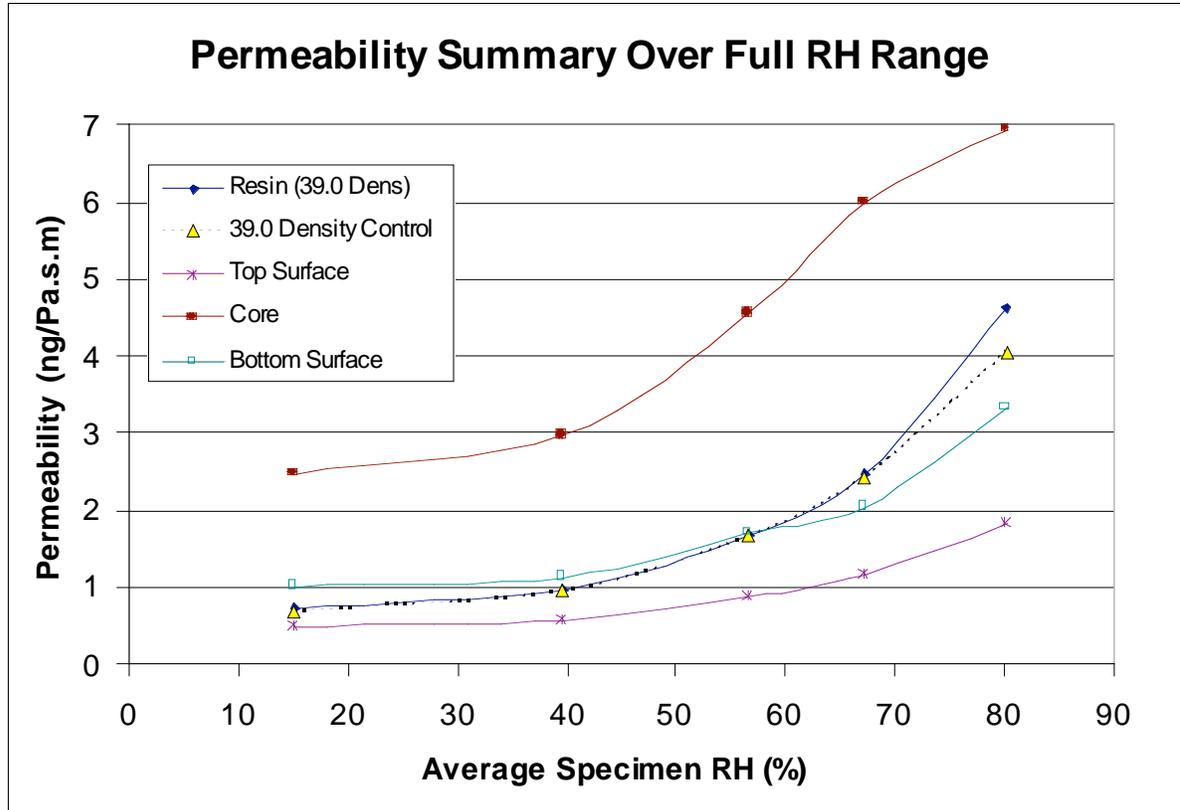
Figure 6.5: Permeability Summary Over Full RH Range, Comparing Layers and Resin Content, 5-specimens each.

The "resin" specimen series was produced with an elevated resin content of 4.25% PF in the surface layers and 4.0% MDI in the core layer, while the control was produced with 3.0% PF in the surface layers and 2.0% MDI in the core. All other variables were the same in both groups. The permeability of the high resin series is very similar to that of the control at every RH gradient except the highest, where the high resin series has a higher permeability than the control.

Differences among the permeabilities of the individual component layers appear to be much greater. The experimental results clearly show that the core layer has the highest permeability and the top surface layer has the lowest permeability of all the series, throughout the relative humidity range. Top and bottom surfaces were made with 3.0% resin / 1.8% wax, compared to 2.0% resin, 0.6% was in the core, solids basis. However, the large difference in densities may confound the comparison for difference in resin / wax.

6.1.4 Effect of Cyclic Soaking and Drying and RH Cycling on Permeability

The three groups of cyclic soak permeance disc specimens were prepared from control material (standard density (626 kg/m^3 or 39.0 lbs/ft^3 unit weight) and resin addition levels (3.0% surface, 2.0% core)) as described in Section 5.5.5, and can thus be compared directly against the non-cycled control specimens. The three cyclic soak panel groups consisted of: one cycle of soaking and drying; three cycles of soaking and drying; and eight cycles of soaking and drying. The permeance testing was carried out at the middle relative humidity range of 50% RH in the chamber to 29% RH in the cups, after the specimens were exposed to the final oven-dry or room RH step of their cyclic-conditioning.

Results indicate that cyclic wetting and drying clearly has a large effect on permeability, as illustrated in Figure 6.6. The increases in permeability compared to the un-soaked control specimens were 2.4 times after one cycle, 2.5 times after three cycles, and 3.1 times after eight cycles of wetting and drying.

Cyclic Soak and RH Cycled Specimen Mean Permeability and Standard Deviation
(29% cup - 50% chamber RH)

	Control	1-Cycle soak-dry	3-Cycle soak-dry	8-Cycle soak-dry	5 RH Cycles (100%-42%)
Series1	1.23	2.97	3.10	3.83	2.12
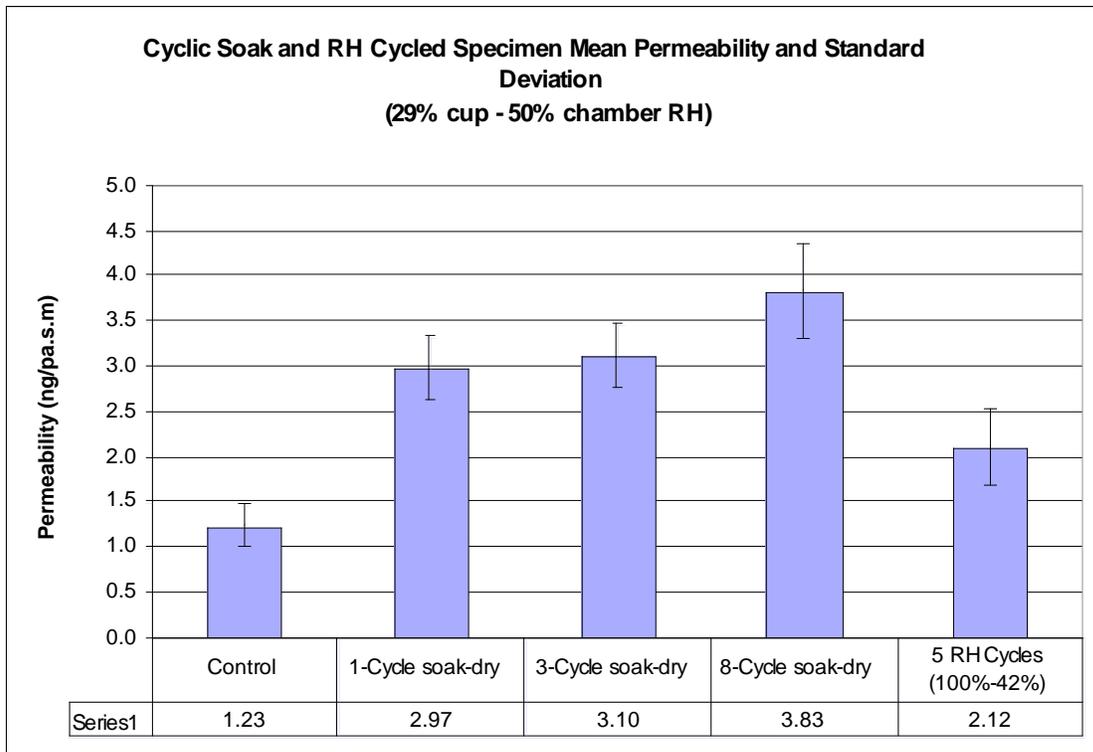
Figure 6.6: Mean Permeabilities and Standard Deviations for Cyclic Soaked and RH Cycled Specimens Made From Control Resin and Density Material.

The effect of relative humidity cycling on permeability was also investigated. A series of 5 full thickness permeance disc specimens were prepared from the standard control OSB, with standard density (626 kg/m^3 or 39.0 lbs/ft^3 unit weight) and resin addition levels (3.0% surface, 2.0% core) as described in Section 5.5.6, and can thus be compared directly to the un-cycled control series. The specimens were subject to 5 cycles from ambient room conditions (dry bulb temperature 22.3 ^{o}C, wet bulb temperature 14.6 ^{o}C, and 42% relative humidity) for 24 hours, to a 100% relative humidity environment for 24 hours. After completing five relative humidity cycles, the specimens were sealed to the water vapour permeance testing cups and placed into the chamber for permeance testing. The permeance testing was carried out at the middle relative humidity range of 50% RH in the chamber to 29% RH in the cups.

Test results indicate that the permeability almost doubled as compared to the unexposed control series. Permeability increased by 1.7 times, after only 5 relatively brief (24 hr.) exposures to high relative humidity, as shown in Figure 6.6.

6.1.5 The Effect of Cyclic Soaking and Drying and RH Cycling on Thickness Swell

Thickness swell caused by cyclic wetting and drying and by RH cycling was measured. Initial thickness measurements were at room equilibrium moisture content (EMC) conditions, and final thickness measurements were after cyclic testing and final oven drying. Results are presented with standard deviation error bars in Figure 6.7.
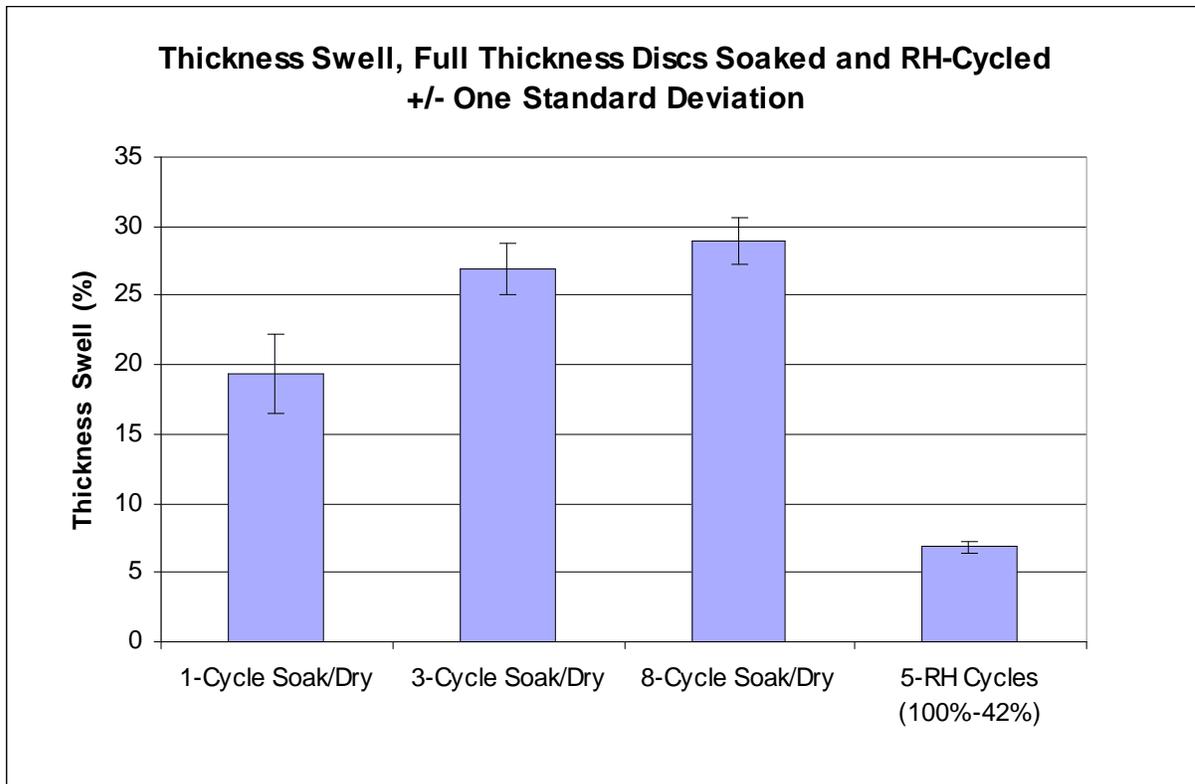
Figure 6.7: Thickness Swell of Full Thickness Discs Soaked and RH Cycled with +/- 1 Standard Deviation Error Bars.

Cyclic soaked specimens increased in thickness on average from approximately 19% after one cycle of soaking and drying, to approximately 28% after eight cycles of soaking and drying. As might be expected, the initial cycle caused the most swelling by the breaking of internal bonds and releasing compression caused by pressing and gluing. Subsequent cycles resulted in decreasing amounts of swelling, because decreasing numbers of bonds and amounts of compression remain unreleased.

The average thickness swell caused by five cycles of relative humidity cycling was found to be 6.8%. This is less swelling overall than caused by one cycle of soaking and drying as shown in Figure 6.7, as it is a less severe moisture exposure. The thickness swell values of the individual RH cycled specimens are illustrated in Figure 6.8.
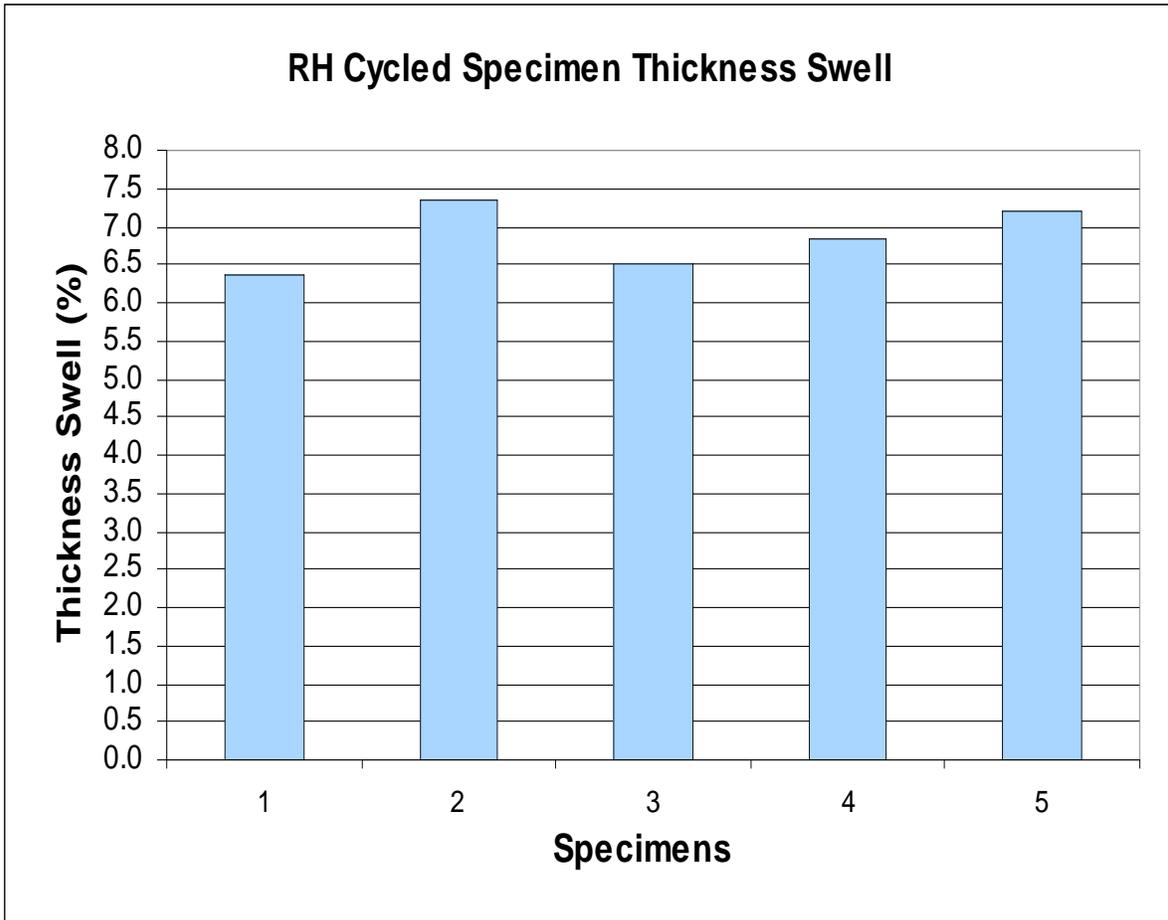
Figure 6.8: Thickness Swell of Individual RH Cycled Specimens Before Permeance Testing.

6.1.6 Permeability and Sanding of Surfaces

The effect of surface sanding on permeability was also investigated. Specimens were prepared from control material at standard density (626 kg/m^3 or 39.0 lbs/ft^3 unit weight) and resin addition levels (3.0% surface, 2.0% core) by removing 3.5mm of each of the less permeable top and bottom surfaces, leaving the core intact, as described in Section 5.5.3. The control specimens were intact, unmodified, full thickness specimens. Permeance testing was conducted at the middle relative humidity gradient step (29% RH cup, 50% RH chamber).

Results are presented in Figure 6.9, where each bar represents the average permeability of five specimens, and indicate that the effect of sanding was to increase in permeability, whether it was the top surface which was sanded or the bottom.

Permeability, Sanded vs. Control (29% cup, 50% chamber)

Series1	Control	Sanded Top Sfc	Sanded Bottom Sfc
	1.23	1.66	1.87

Specimen surface treatment

Y-axis: Permeability (ng/pa.s.m)
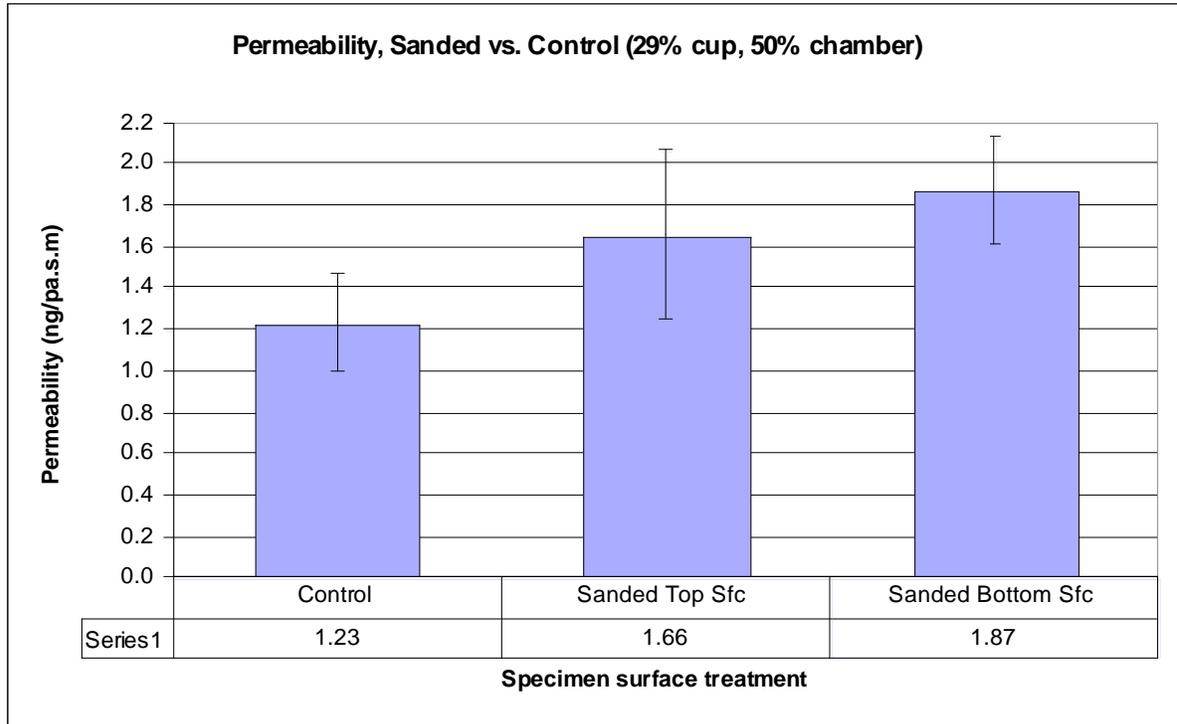
Figure 6.9: Mean Permeabilities and Standard Deviations for Sanded Specimens Compared to Control Specimens.

6.1.7 Permeability of 100% MDI OSB and Spruce Plywood

Samples were cut from OSB made with only methylenediphenyl diisocyanate (MDI) resin at the same mill as all of the other test panels for this study, but at a different time and density. Samples were also cut from purchased panels of construction grade three-ply spruce plywood, made with phenyl formaldehyde (pf) resin. Both groups were tested with samples of control (39.0 lbs/ft^3 626 kg/m^3) OSB for comparison, to put the permeability ranges found in this study, into perspective. MDI resin is generally believed to be of higher performance in terms of resistance to moisture and thickness swell than PF resin, and is often

used for premium OSB products where thickness swell is critical. It is primarily used in residential construction for floor and roof sheathing. Construction grade spruce plywood is also often used in construction instead of OSB, and many misconceptions exist about its comparative performance.

The results plotted in Figure 6.10 indicate that Spruce plywood was 17% more permeable on average than the control, and OSB made with 100% MDI was 54% less permeable than the control, although the 100% MDI product was higher density. A comparison of moisture-related performance results through hygrothermal modeling is conducted later in chapter six.
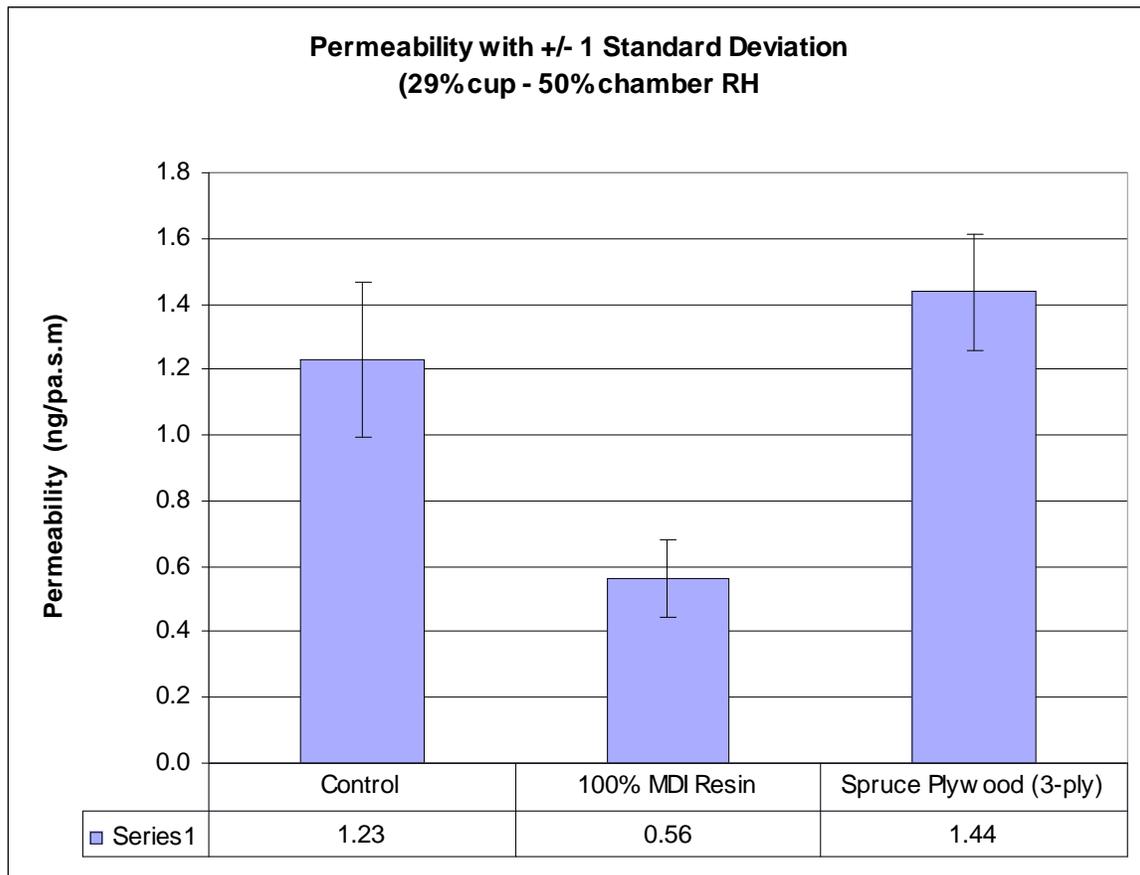
Figure 6.10: **Permeability with +/- 1 Standard Deviation Comparison of Control OSB to 100% MDI OSB and Spruce Plywood.**

6.2 Water Vapour Sorption Test Results

Sorption testing was carried out over the whole relative humidity range, from 28% RH up to 85% RH, as shown in Table 6.3. High RH (over 85%) testing was abandoned for most series because of mould formation on the specimens.

Table 6.3   Relative Humidity Steps and Corresponding Actual Relative Humidities in the Test Chamber.

Relative Humidity Step	1	2	3	4	5
Theoretical Salt Solution Relative Humidity	29%	53%	64%	75%	92%
Measured Relative Humidity in Chamber	28 %	50 %	60 %	70 %	85 %

The testing was conducted with 12 specimen types, some in several formats (full thickness, slices and discs), as shown below in Table 6.4. Three specimen sizes were investigated, which were full thickness, thin slices and planer shavings to investigate the effect of specimen size, and to investigate if smaller sizes can be used to quickly and accurately determine sorption values, which can otherwise often take more than a month. Parameters investigated included three density levels, and high resin addition for both full thickness and sliced specimens, as well as the individual OSB component layers, OSB made with methylenediphenyl diisocyanate (MDI) resin, and sliced specimens of spruce plywood, white pine and red cedar. The number of individual specimens tested in each group is also listed in Table 6.4.

Table 6.4: Sorption Test Specimen Types, Format and Number of Specimens in Each Group.

Group / Variable	Full Thickness Discs (# of Specimens)	Slices (# of Specimens)	Planer Shavings (# of Specimens)
Resin (high resin)	3 (A, B, C)	10	
42.9 (688.6 kg/m^3) Density	3 (A, B, C)	10	
39.0 (626.0 kg/m^3) Density	3 (A, B, C)	10	
34.5 (553.8 kg/m^3) Density	3 (A, B, C)	10	
39.0 (626.0 kg/m^3) Density Oven Dried Before Test		10	
39.0 (626.0 kg/m^3) Density Top Surface Layer		10	5
39.0 (626.0 kg/m^3) Density Core Layer		10	5
39.0 (626.0 kg/m^3) Density Bottom Surface Layer		10	5
100% MDI Resin (728 kg/m^3)		10	
Red Cedar		5	
Pine		5	
Spruce Plywood		5	

Some specific investigations were also later conducted on parameters such as relative humidity cycling and their effect on sorption, at specific relative humidity levels.

6.2.1 Mass Gain over Time

Specimens were introduced into the controlled relative humidity and temperature chamber for the first RH gradient step when they were at equilibrium moisture content (EMC) with the room relative humidity (approximately 42% at 22°C). That is, the specimens were not pre-conditioned, other than to ambient room conditions while being stored in the laboratory before beginning the sorption testing. After being introduced into the controlled relative humidity and temperature test chamber to begin step one, they were not removed until completion of all five relative humidity gradient steps. The exception to this was the group called "oven dried", which was oven dried at approximately 102°C in a convection lab oven for 24 hours before testing. This group was prepared from the control 39.0 lbs/ft^3 (626.0 kg/m^3) density material, and the objective was simply to study the effects of oven drying on sorption. The results of this comparison are presented below in Section 6.3.6.

For each of the five relative humidity steps, the sorption specimens were allowed to gain or lose moisture until they approached a state of equilibrium with the controlled conditions in the chamber. Approximate equilibrium was deemed to be reached when there was no detectable mass change, as determined through periodic weighing. The electronic scale used had a resolution of +/- 0.01g.

Figure 6.11 is a plot of specimen mass versus time for the first relative humidity step, for full thickness disc specimens. As the relative humidity within the chamber for the first step (28%) was lower than the relative humidity in the laboratory to which the specimens had become conditioned, the specimens initially lost moisture until equilibrium was reached after just over 200 hours. This is seen on the mass gain/loss over time curves as the downward sloping initial portion of each specimen plotted. The approach of equilibrium is indicated by the slope of the curves approaching zero.
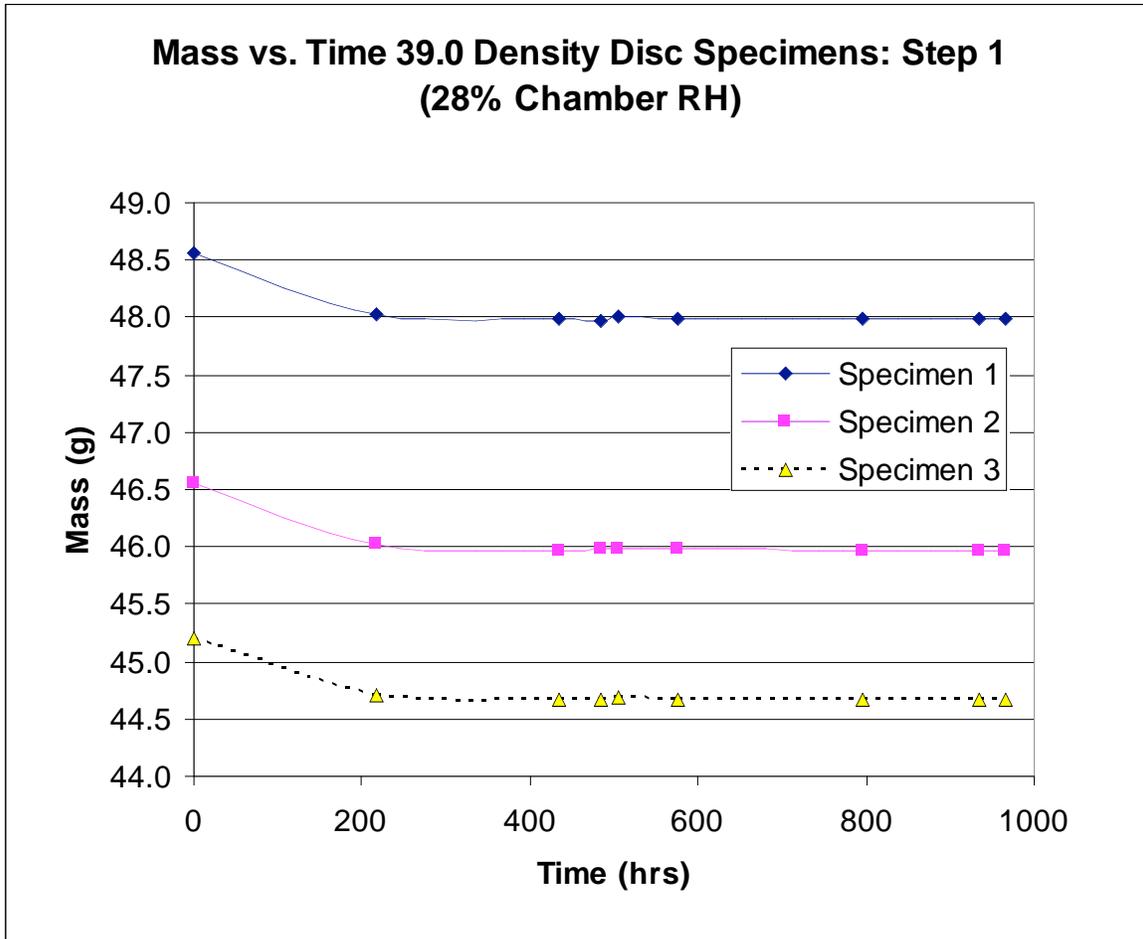
Figure 6.11: Sorption Test Mass vs. Time for 626.0 kg/m^3 Density (39.0 lbs/ft^3) Full Thickness OSB Disc Specimens, at Relative Humidity Step 1 (Chamber 28% RH)

6.2.2 Sorption Isotherms

When the various sorption specimens reached equilibrium with the environment within the chamber for a given relative humidity step, the chamber RH was changed to the next level for the next step by introducing a new saturated salt solution, and the process was repeated. After all five relative humidity steps were completed (or six steps where 100% relative humidity was reached), the specimens were removed from the controlled temperature and relative humidity

chamber and oven dried for 24 hours to determine their oven dry mass. Moisture content was calculated on an oven dry mass basis, where:

MC (%) = (wet mass – oven dry mass) / oven dry mass x 100

The results are most commonly displayed graphically as sorption isotherm curves as in Figure 6.12, where the x-axis represents the relative humidity as a percent (%), and the y-axis displays the corresponding moisture content on a percent dry mass basis (%). The results can also be represented on a volumetric basis, in kg water per m^3 of OSB material, in which case it will be stated that it is on a volumetric basis.   This form is useful in that the effect of density can be compared.
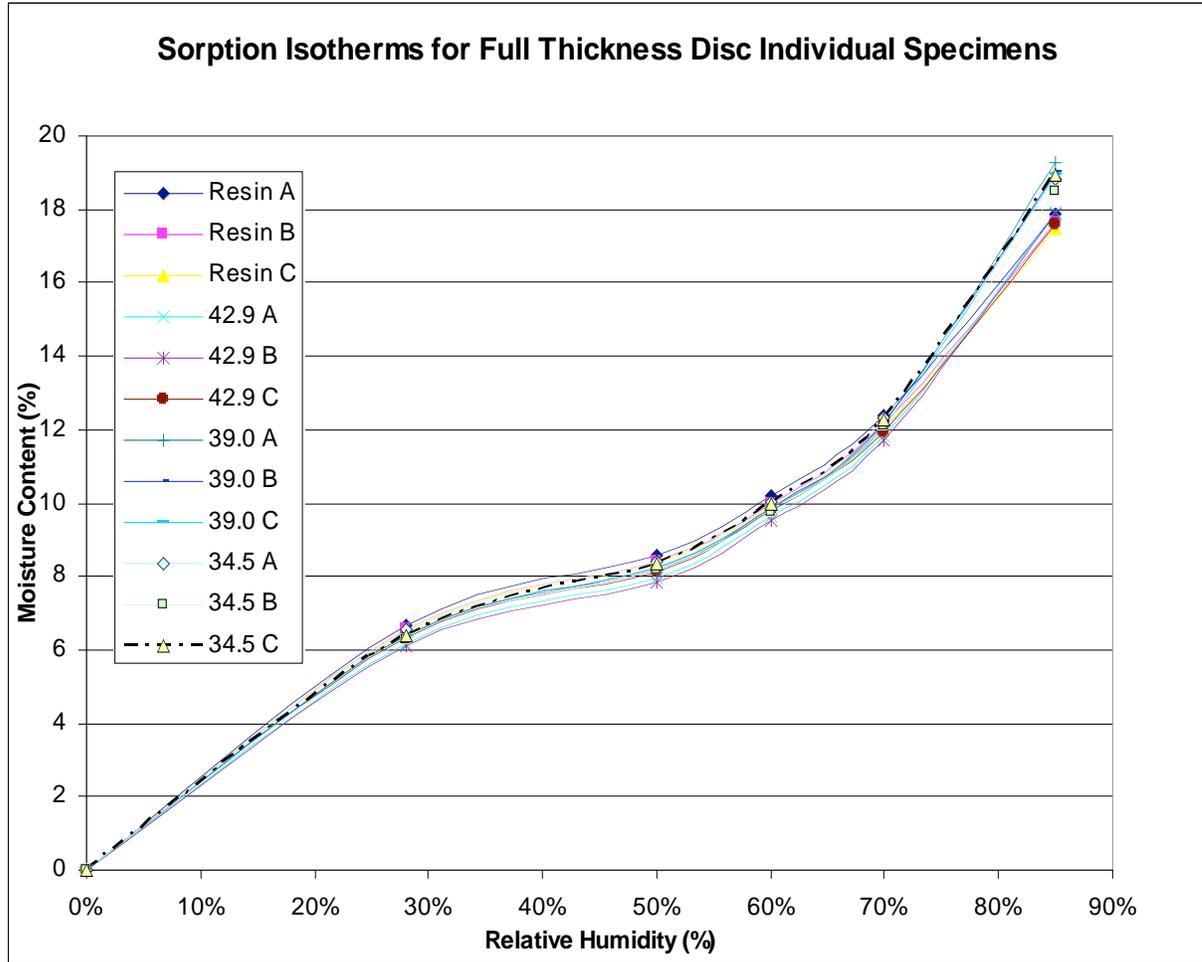
Figure 6.12: Sorption Isotherms for Individual Full Thickness Sorption Specimens Over Full RH Range.

6.2.3 Density vs. Sorption

To investigate the effect of OSB density on the moisture sorption, specimens were prepared from the 688.6 kg/m^3 (42.9 lbs/ft^3 unit weight), 626.0 kg/m^3 (39.0 lbs/ft^3 unit weight) and 553.8 kg/m^3 (34.5 lbs/ft^3 unit weight) target density panel groups, for which all variables except density were kept constant. Specimens of both the full thickness disc and slice types were prepared and tested throughout the whole relative humidity range.

The sorption test results from both the sliced specimen (Figure 6.13) and the full thickness disc specimen tests (Figure 6.14) did not indicate large differences

among the different densities of the series throughout most of the relative humidity range tested. The lower density specimen achieved a slightly higher resultant moisture content for a given relative humidity level. This relationship would indicate that equilibrium moisture content (kg water / kg dry wood mass) is inversely proportional to OSB density (kg dry wood mass / m^3).
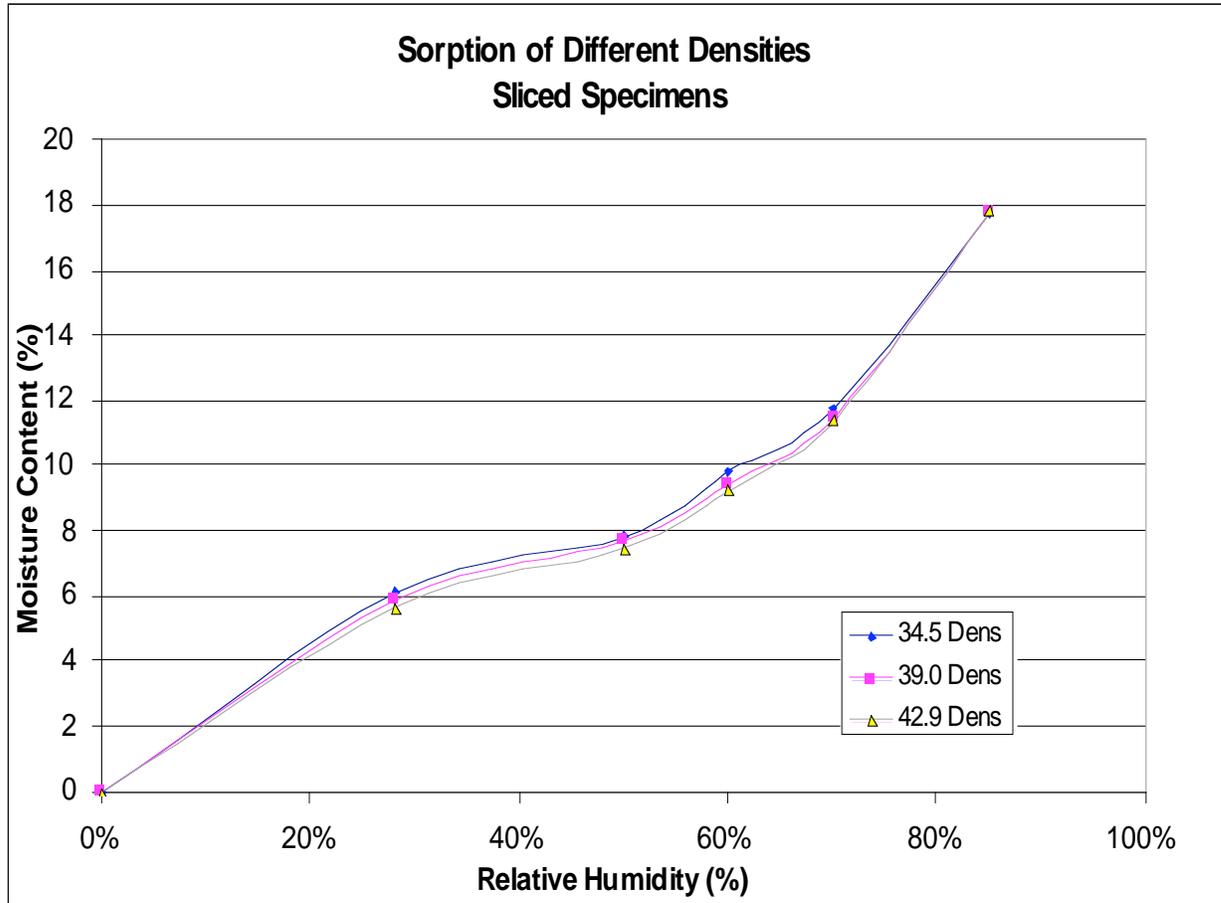
Figure 6.13: Sorption Test Results for Different Densities of Sliced OSB Specimens, 10-specimens each.
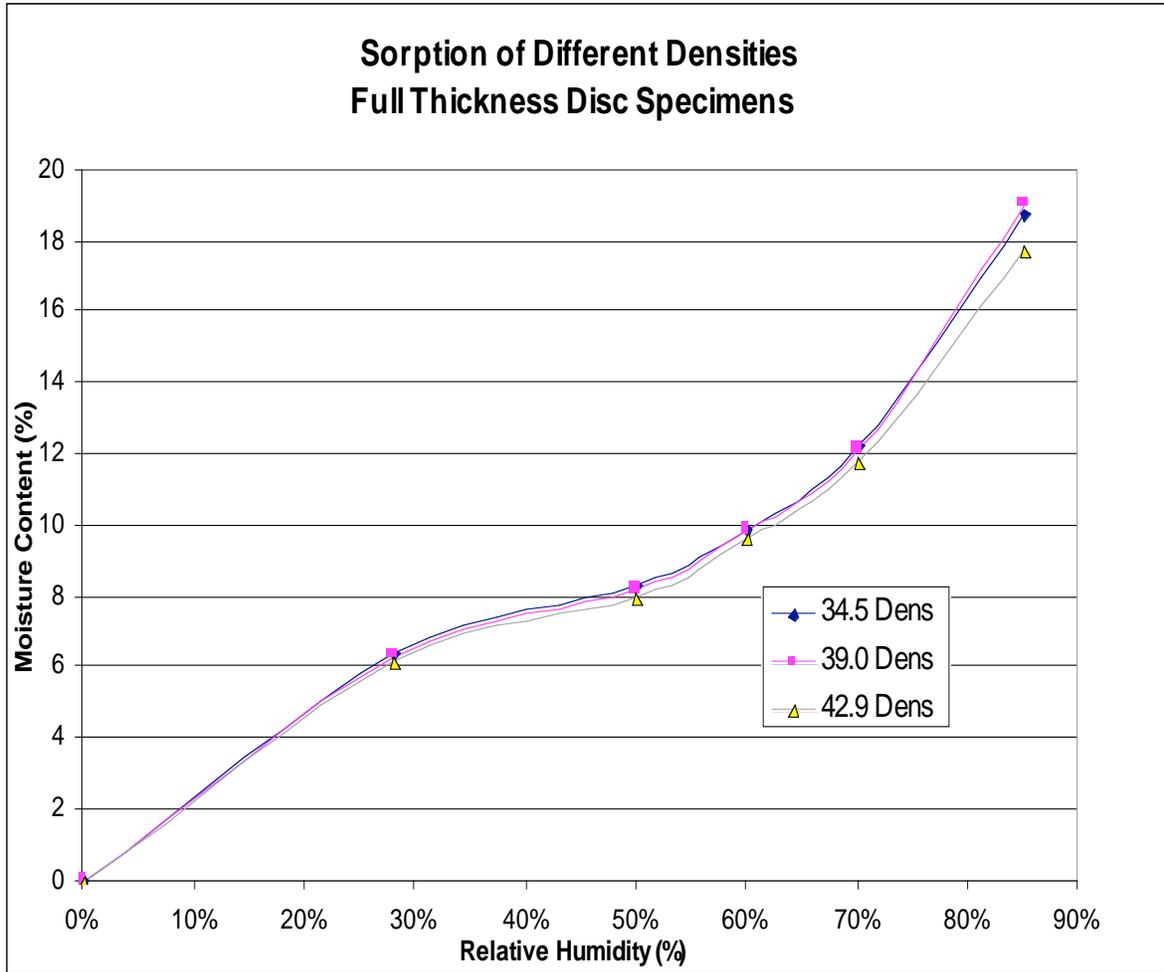
Figure 6.14: Sorption Test Results for Different Densities of Full Thickness OSB, 3-Specimens Each.

Another way of looking at the relationship between density and moisture content is to plot the densities of individual specimens and their corresponding moisture contents (%) at each of the five relative humidity steps. This is shown in Figure 6.15 for the individual slice specimens. Figure 6.16 shows the same specimens as Figure 6.15, but for a sixth step under saturated conditions, where the specimens were soaked in water for 24 hours to achieve the maximum water content with free water and bound water, without pressure applied. Figure 6.17 shows the individual full thickness disc specimens over the five RH steps. On all three plots, and at each of the five or six relative humidity gradient steps, the relationship seems to be one of a slight decrease in sorbed moisture content with

increasing density. That is, there is a slight inverse linear relationship between OSB density and sorbed moisture content at any given relative humidity, and general agreement between Figures 6.15, 6.16 and 6.17.
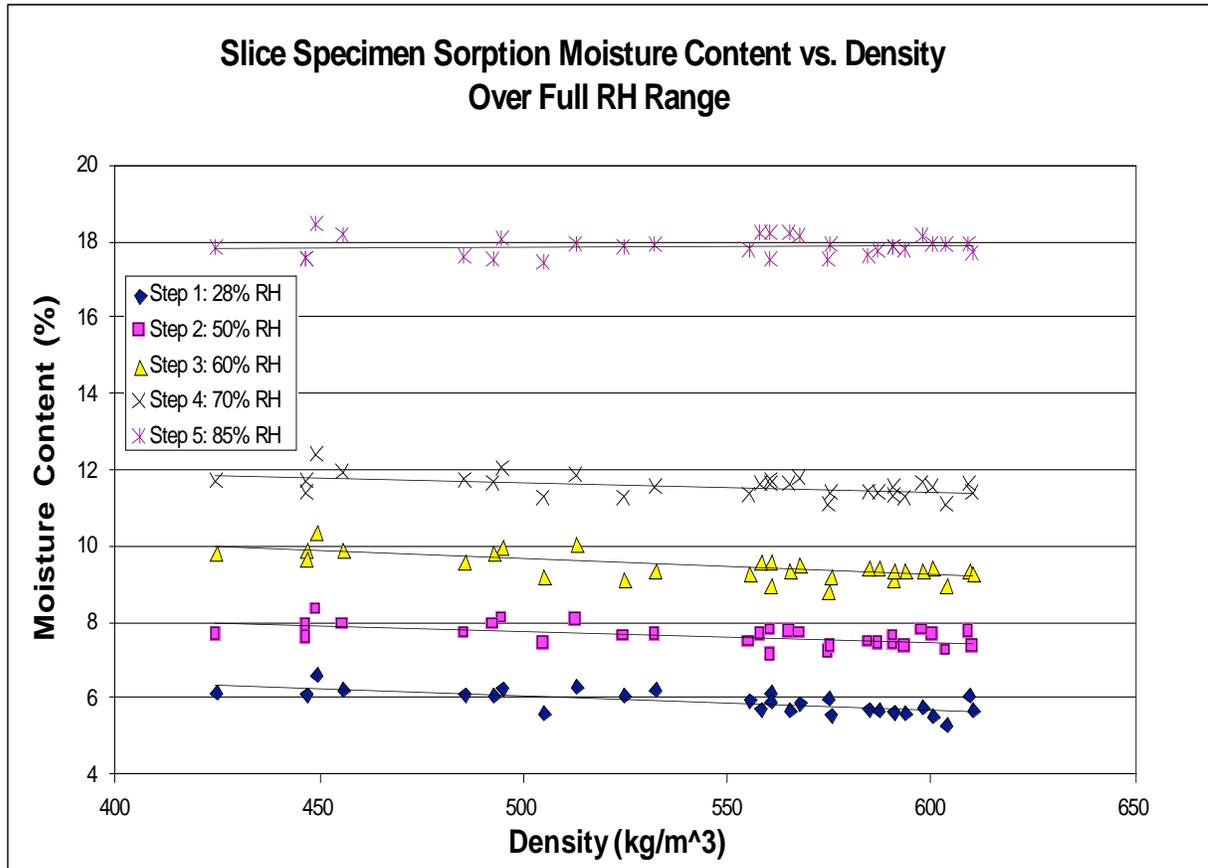
Figure 6.15: Sorption Test Results of Individual Sliced OSB Specimens of the Three Density Groups, Plotted as Equilibrium Moisture Content vs. Measured Specimen Density, at Each of the 5 Relative Humidity Steps.
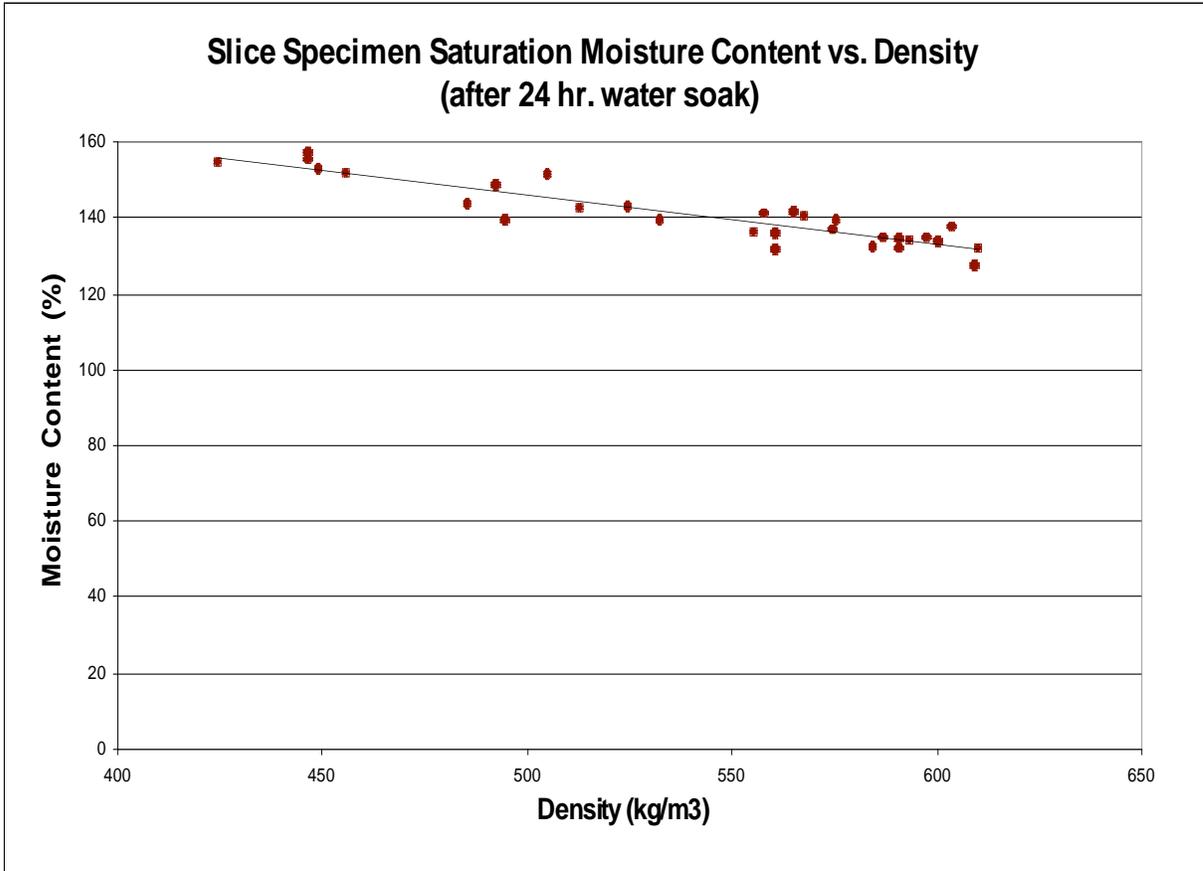
Figure 6.16: Sorption Test Results of Individual Sliced OSB Specimens of the Three Density Groups, Plotted as Equilibrium Moisture Content vs. Density, After Being Soaked in Water for 24 Hours.
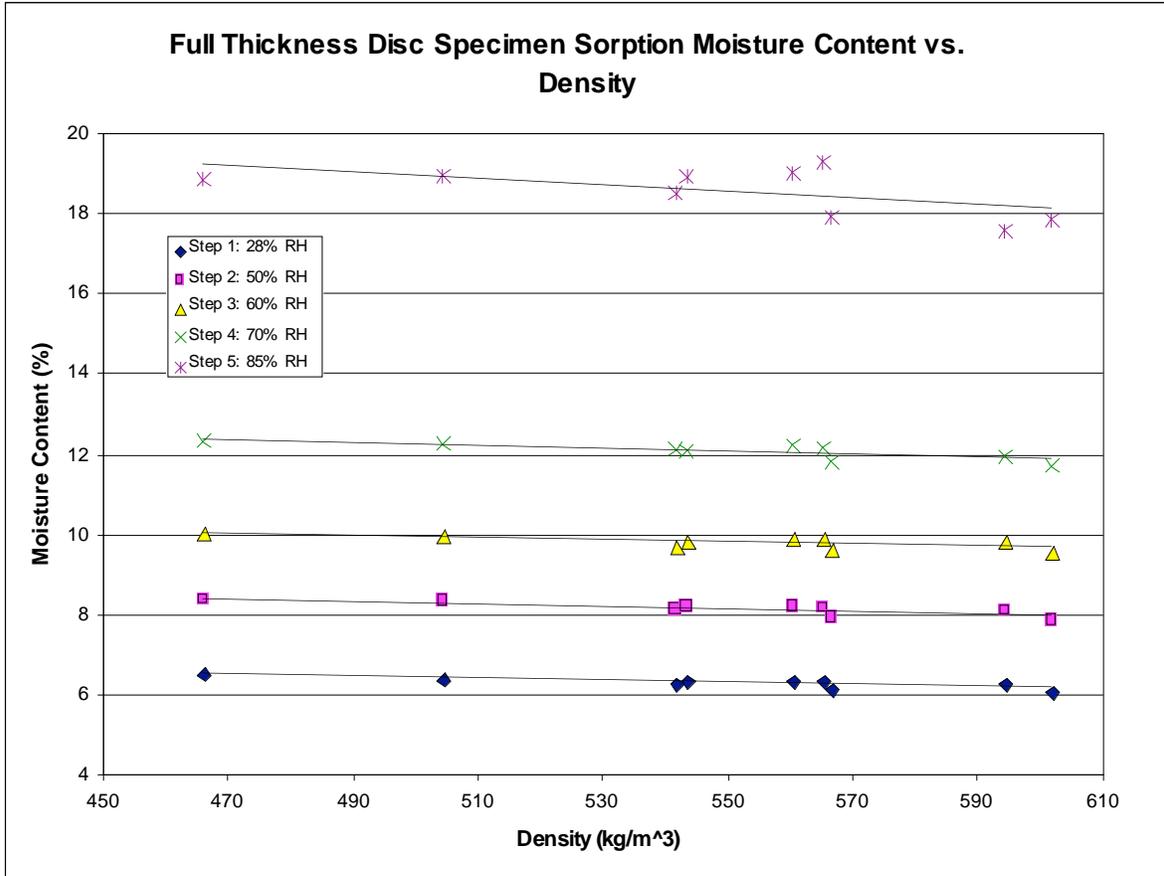
Figure 6.17: Sorption Test Results of Individual Full Thickness Disc OSB Specimens of the Three Density Groups, Plotted as Equilibrium Moisture Content vs. Density, at Each of the 5 Relative Humidity Steps.

6.2.4 Specimen Size Effect on Sorption

The effect of specimen size on sorption was studied by running concurrent sorption experiments in the same chamber on different sizes of specimens, through the entire relative humidity range. Full thickness OSB discs, measuring 90 mm in diameter and the unaltered thickness of the panels, were tested side by side with smaller sliced OSB specimens, measuring approximately 136 mm long, by 5 mm wide, and 11 mm thick (unaltered panel thickness), for each of the density levels of 554 kg/m^3 (34.5 lbs/ft^3 unit weight), 626 kg/m^3 (39.0 lbs/ft^3 unit weight) and 689 kg/m^3 (42.9 lbs/ft^3 unit weight). The resulting sorption isotherms are plotted in Figures 6.18, 6.19 and 6.20.
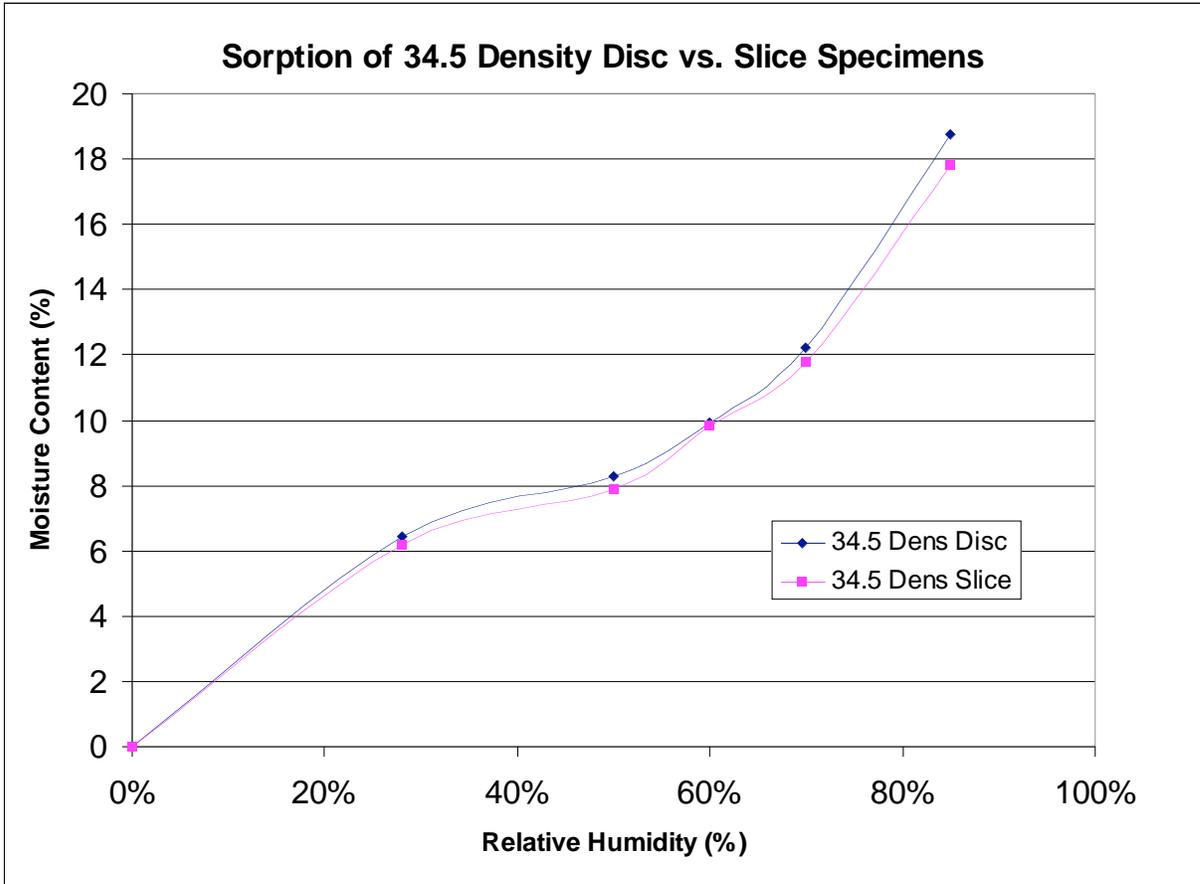
Figure 6.18: Sorption Isotherms for 554 kg/m³ Density (34.5 lbs/ft³) Disc (3-Specimens) vs. Slice (10-Specimens) for Size Effect.
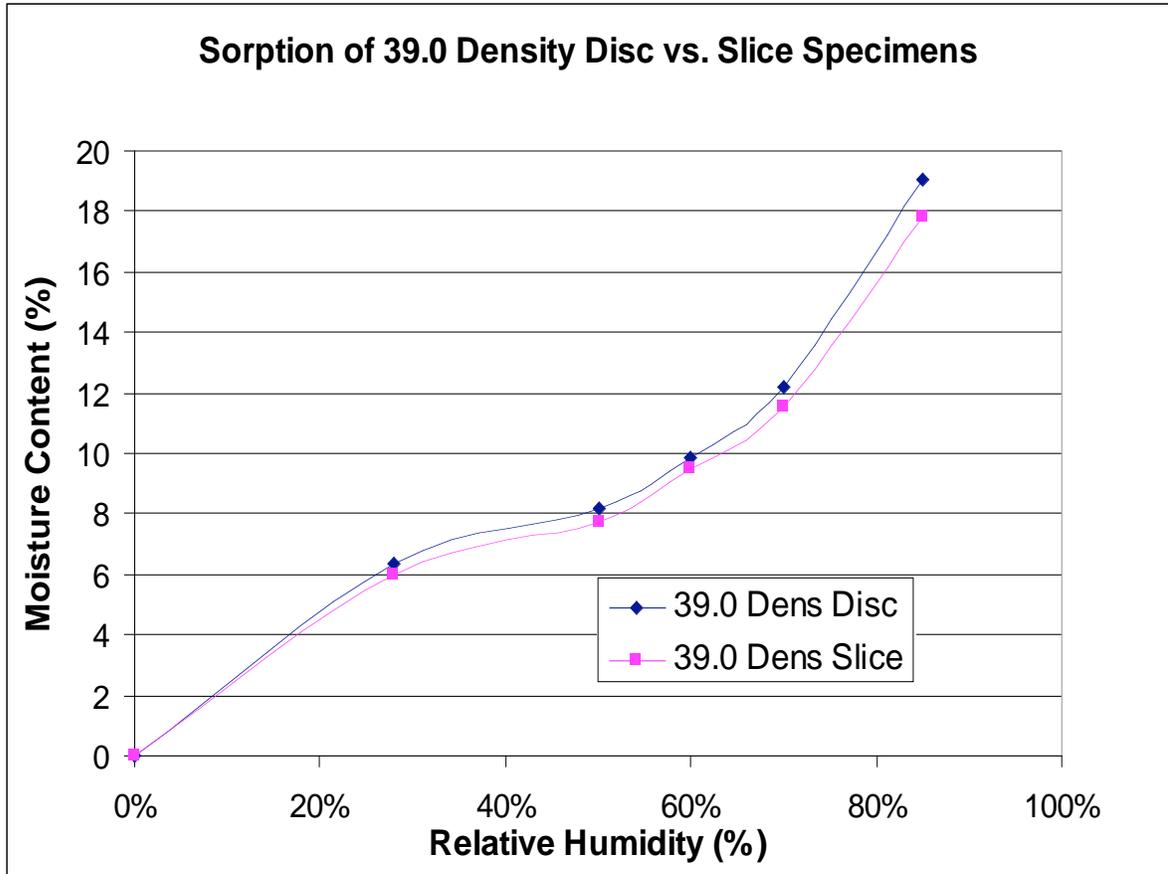
Figure 6.19: Sorption Isotherms for 626 kg/m^3 Density (39.0 lbs/ft^3) Disc (3 Specimens) vs. Slice (10-Specimens) for Examination of Size Effect.
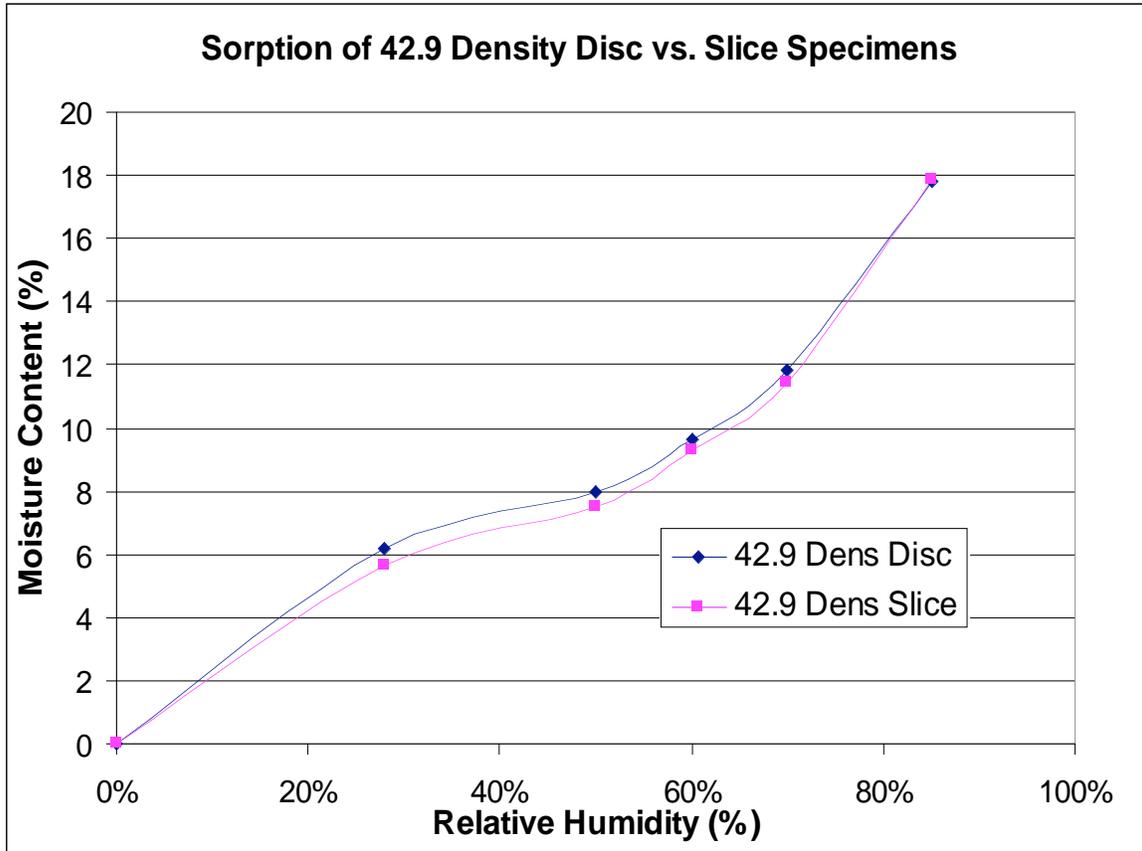
Figure 6.20: Sorption Isotherms for 689 kg/m^3 Density (42.9 lbs/ft^3) Disc (3-Specimens) vs. Slice (10-Specimens) for Examination of Size Effect.

In the comparison of the full thickness disc specimens to the smaller slice specimens, (Figures 6.18, 6.19 and 6.20) in each density case the larger disc specimens exhibited a higher resultant moisture content for any given relative humidity than did the corresponding sliced specimen.

Planer Shavings

Another specimen size effect experiment was conducted concurrently, again through the entire relative humidity range, comparing sliced specimens to planer shavings (Figures 6.21, 6.22 and 6.23). The sliced specimens of the individual OSB layers were made by planing down full thickness OSB until only the desired layer remained. The shavings were produced through the same process, by collecting the planer shavings of individual layers of specimens cut from adjacent locations within the OSB panels, which were chosen from the 626 kg/m^3 density

(39.0 lbs/ft^3) control group. The shavings were then placed in a weighed thin-walled aluminum dish for the testing.

Sorption of 39.0 Density Control Top Surface Layer Planer Shaving and Top Surface Slice Specimens
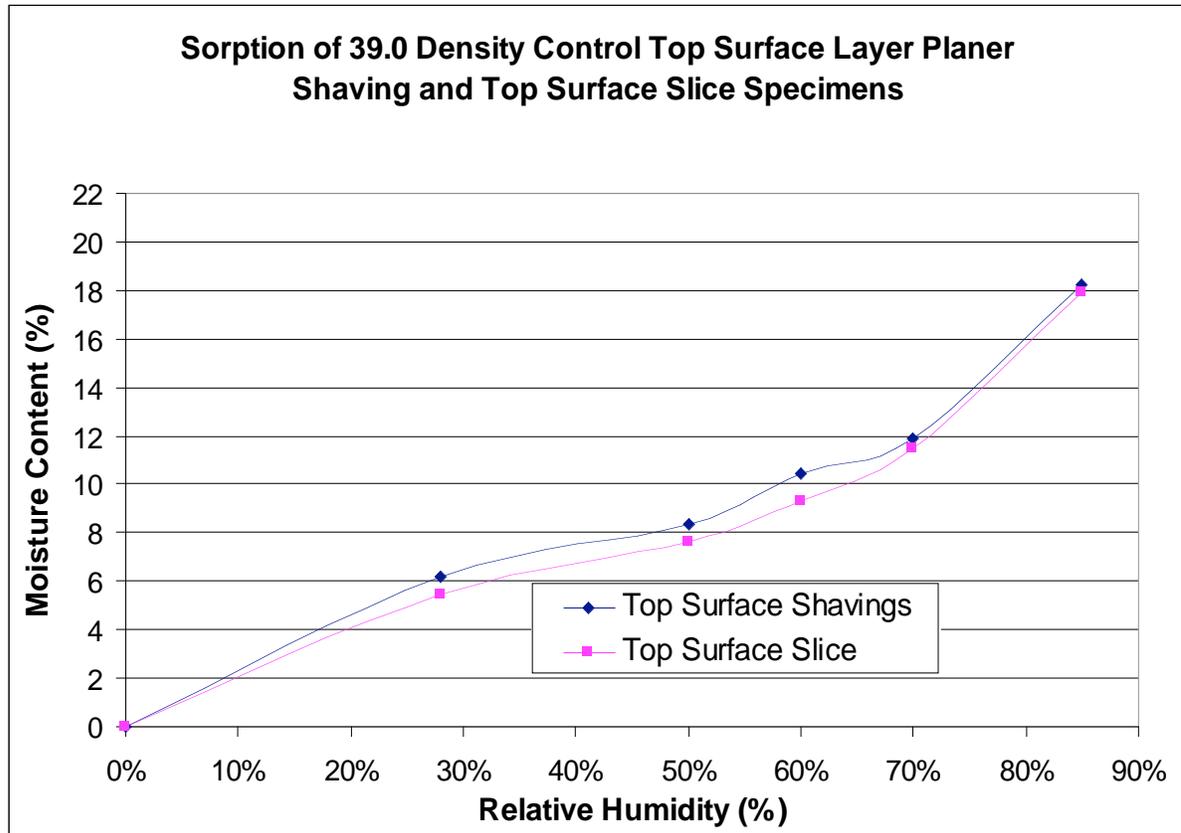
Figure 6.21: Sorption Isotherms for Top Surface Layer Planer Shavings (5-specimens) and Slice Specimens (10-Specimens).
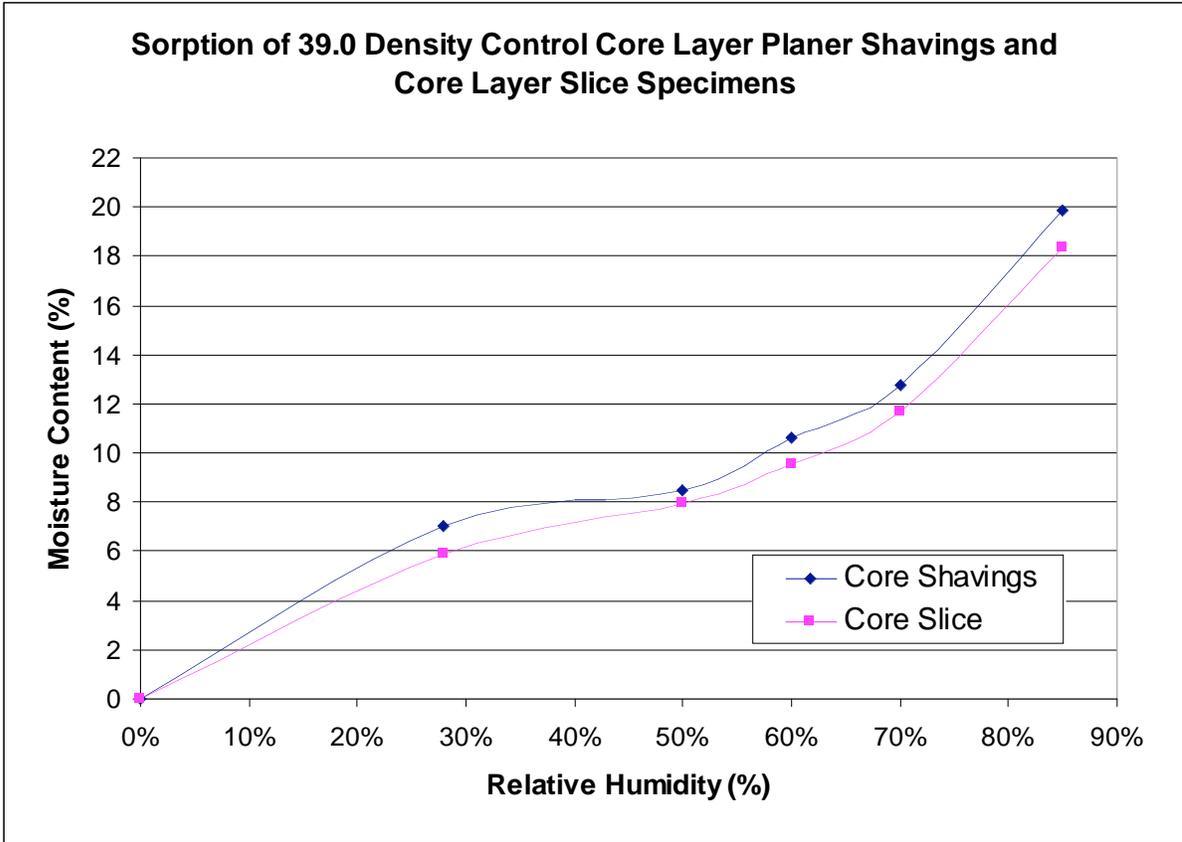
Figure 6.22: Sorption Isotherms for Core Layer Planer Shavings (5-Specimens) and Slice Specimens (10-Specimens).
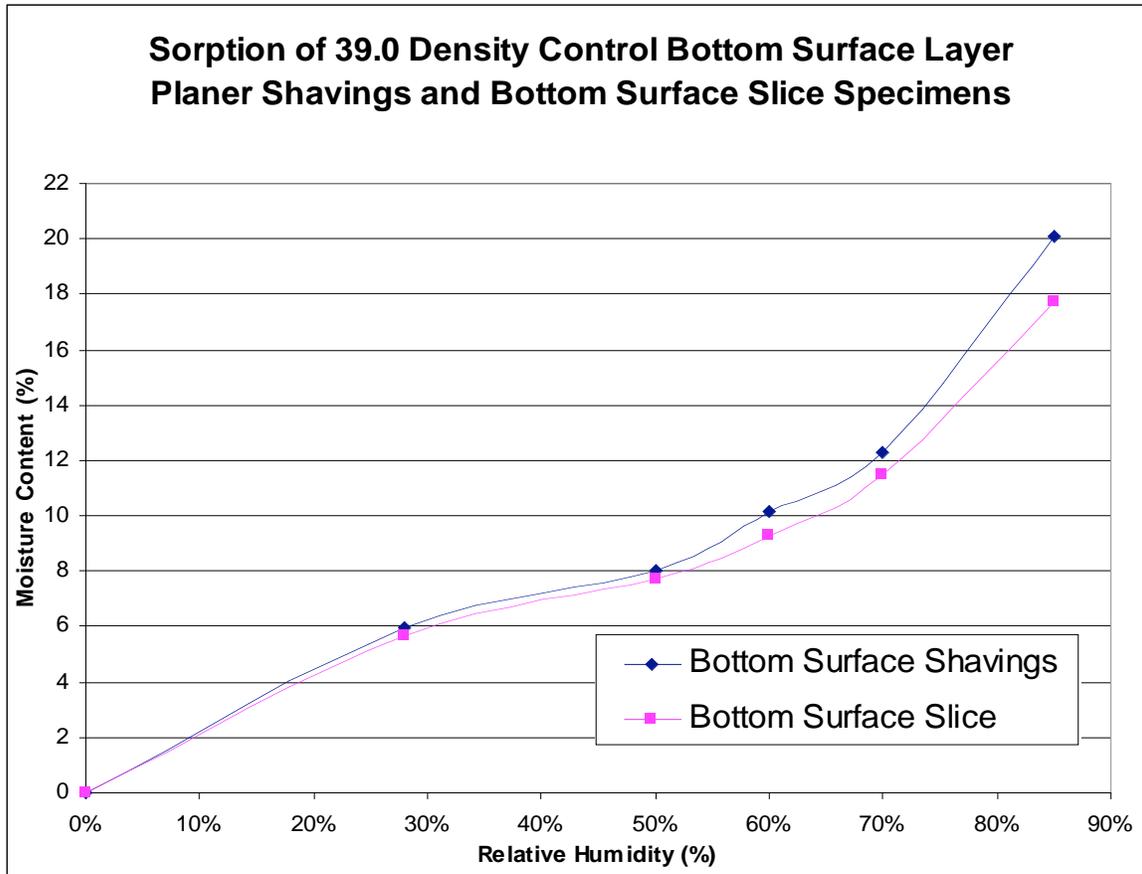
Figure 6.23: Sorption Isotherms for Bottom Surface Layer Planer Shavings (5-Specimens) and Slice Specimens (10-Specimens).

In the comparison of the individual layer OSB slice specimens to the corresponding layer planer shaving specimens (Figures 6.21, 6.22, and 6.23), the planer shavings exhibited a higher resultant moisture content for any given relative humidity than did the corresponding slice specimen.

6.2.5 RH Cycled Specimens

In order to investigate the effect of cyclic exposure to elevated relative humidity conditions on sorption moisture content, the series of five RH cycled full thickness discs specimens used for permeance testing were used. These specimens were prepared from control density and resin content material by being subjected to five cycles of high (100%) relative humidity exposure for 24 hours followed by 24 hours at room relative humidity as described in Section

5.4.6. After permeance testing at conditions of 29% RH in the cup to 50% in the chamber, the specimens were cut down in size to eliminate the wax covered edges used to seal them to the cups, and allowed to equilibrate to room conditions at 22°C and 48% RH. They were then weighed and measured (length, width, thickness), and then oven dried for 24 hours at 102°C, and measured again. In this way it was possible to obtain a sorption point. This is plotted in comparison to the non-RH cycled control series labelled 39.0 Dens on Figure 6.24.
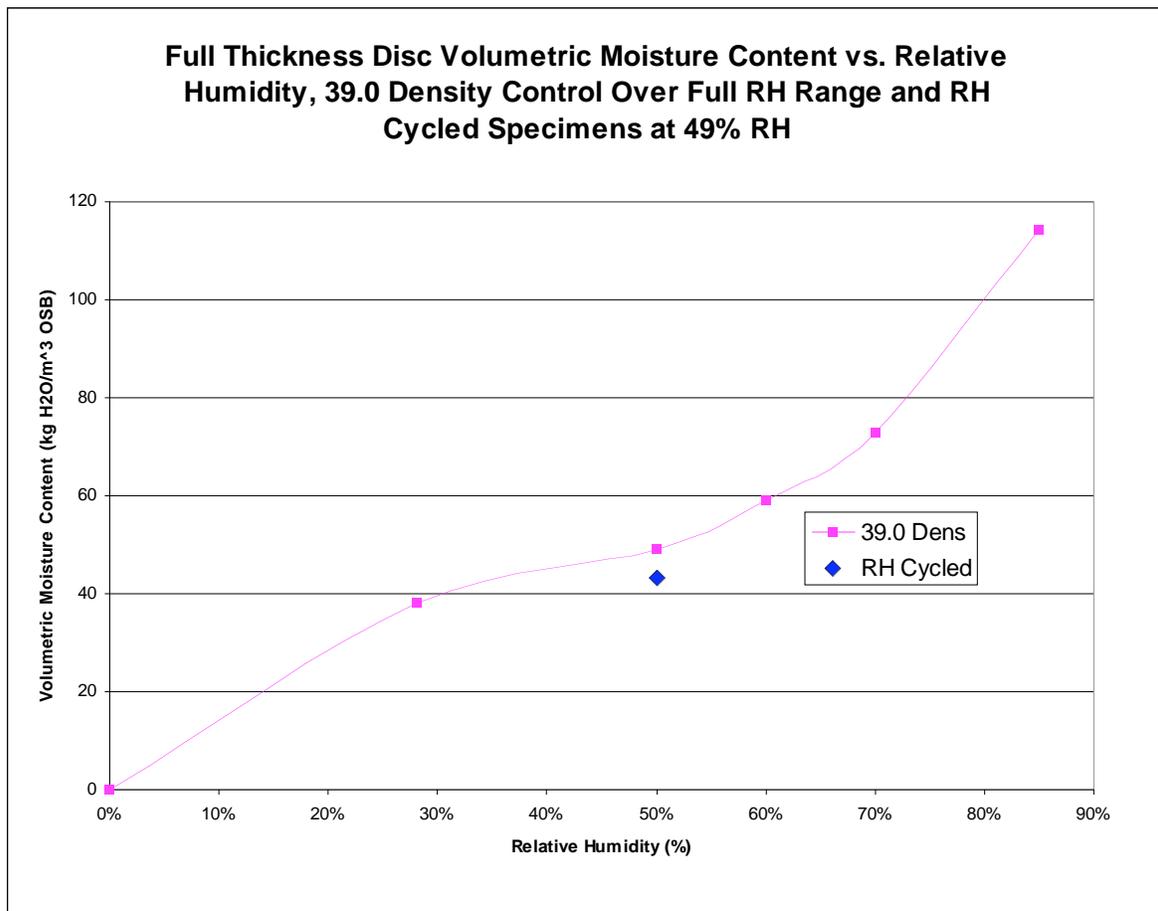
Figure 6.24: Full Thickness Disc Volumetric Moisture Content vs. Relative Humidity, with RH Cycled Specimens (5-Specimens Each).

The RH cycled specimen series moisture content point falls below the control 626 kg/m^3 density (39.0 lbs/ft^3) series.

On the more traditional gravimetric moisture content basis plotted in Figure 6.25 below, the RH cycled specimen series also falls below the control 626 kg/m^3 density (39.0 lbs/ft^3 unit weight) series.
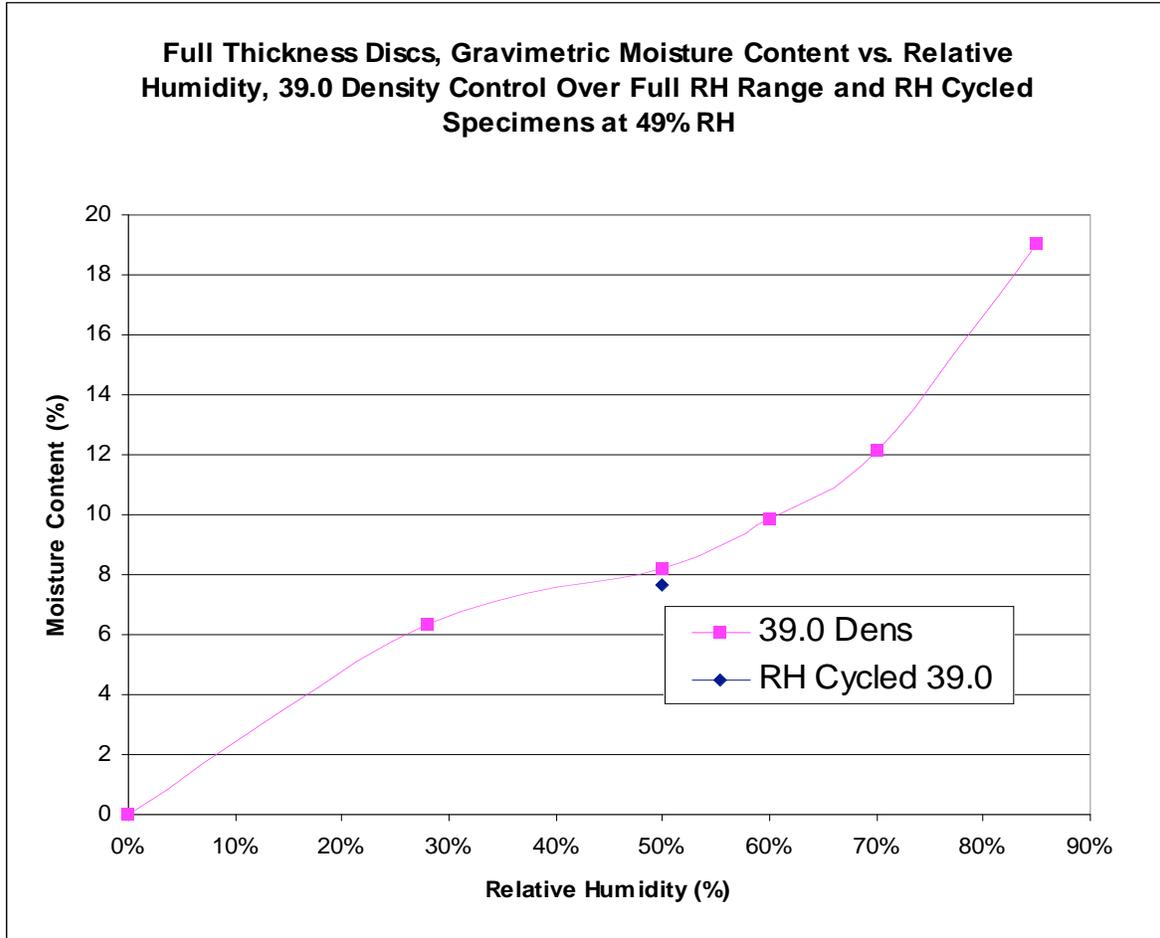
Figure 6.25: Full Thickness Disc Gravimetric Moisture Content vs. Relative Humidity, with RH Cycled Specimens (5-Specimens Each).

6.2.6 Effect of Oven Drying on Sorption

The effect of pre-drying the OSB specimens before beginning the sorption testing was examined. Two sets of 10 slices of specimens were cut from adjacent areas of a 39.0 lbs/ft^3 control panel, for which there was no statistically significant difference in density at the $\alpha = 0.05$ level (the probability of falsely rejecting the null hypothesis of there being no difference between means was always less

than 5%). One set was oven-dried at the standard $102^{o}C$ +/- $1^{o}C$ temperature for 24 hours, and the other set was not. Both sets of 10 specimens each were then tested for moisture sorption throughout the entire relative humidity range concurrently. The resultant sorption isotherm curves are displayed in Figure 6.26.
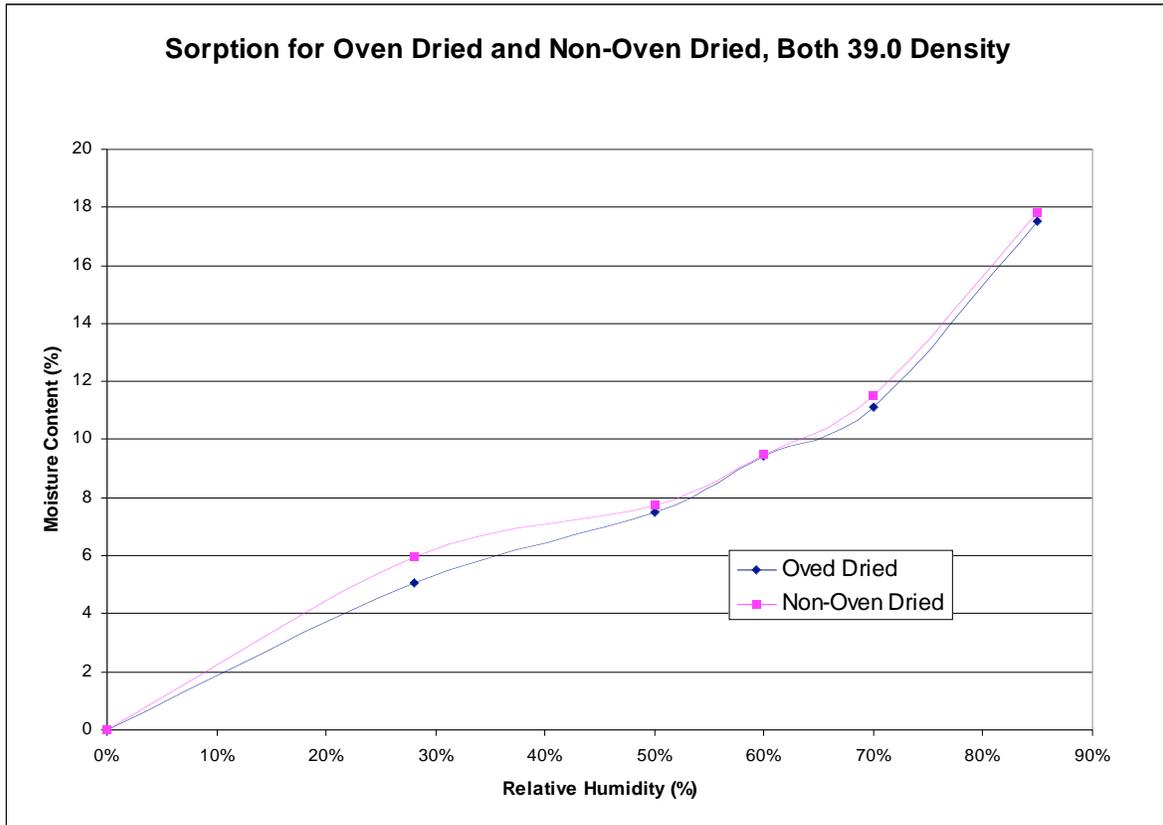
Figure 6.26: Sorption Isotherms for Oven Dried vs. Non-oven Dried Matched Slice Specimens Cut from Control Material, 10-Specimens Each.

It was found that the oven dried sorption isotherm lies below the non-oven dried. That is, for a given relative humidity, the oven dried specimens exhibited a slightly lower moisture content and thus were not able to hold quite as much moisture as were the non-oven dried specimens.

6.2.7 Sorption Isotherms for Different Component Layers of OSB

As described earlier, the individual component layers of OSB were prepared from full thickness OSB by running full thickness strips through the planer until only the

target component layer remained. They were prepared from a 39.0 lbs/ft^3 (626 kg/m^3) control material. Determining the location of the interface between two layers was based on visual observations, as the strand alignment direction changes 90° from parallel to machine direction in the top and bottom surface layers, to perpendicular to machine direction in the core layer. Based on the mill production settings at the time of manufacture, the differential between surface and core layers was set at 8%. That is, 54% of the panel material, by mass, should lie in the core layer, and 46% should lie in the top and bottom surface layers in approximately equal portions. These numbers are approximate, as the control of these weights is not exact, and the process does drift and fluctuate resulting in variation from panel to panel. An added complication is that the differential is by mass, whereas the thickness is not, and also the density profile through the thickness of the panel is non-linear, with the surface layers being denser than the core.

The individual layer strips were then cut into slices measuring approximately 137 mm in length, 20 mm in width, and the thickness was as per the thickness of that individual layer of OSB, which were as follows: top surface layer 3.15 mm; core layer 5.15 mm; bottom surface 3.15 mm. Sorption test results for the three component layers are displayed in Figure 6.27.
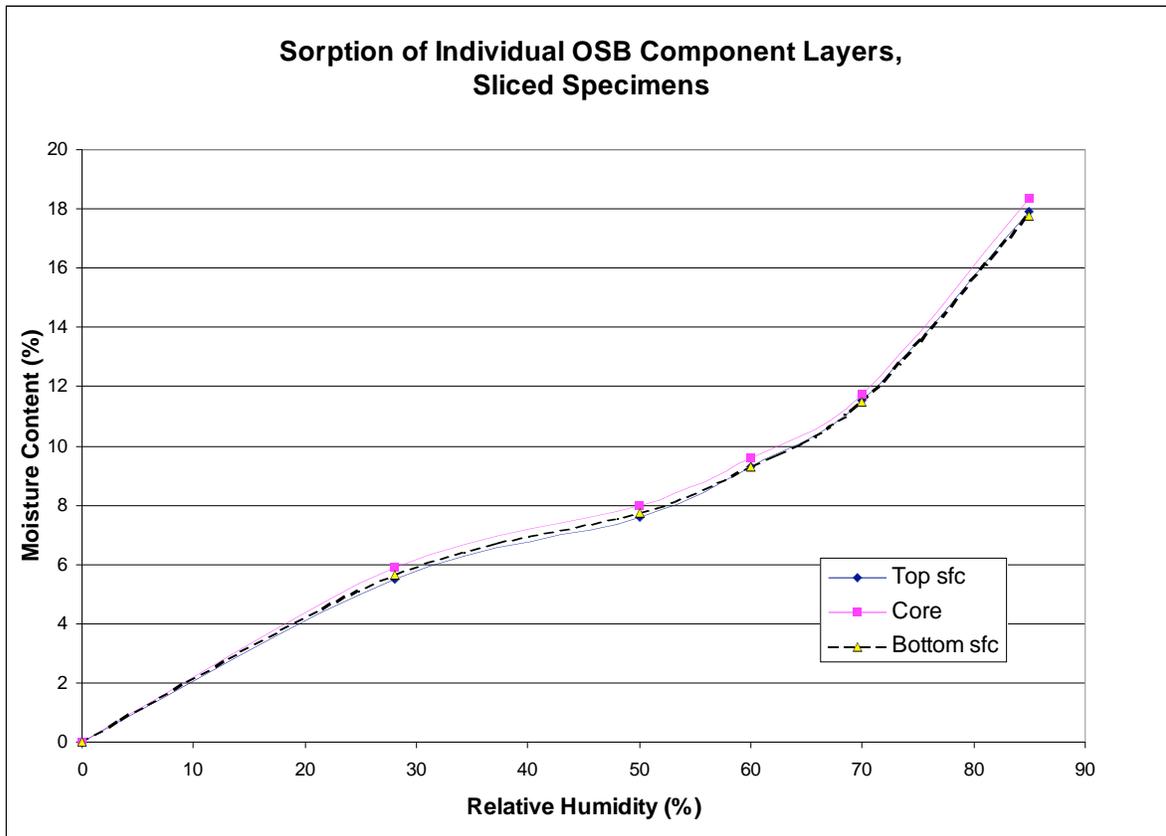
Figure 6.27: Sorption Isotherms for Individual OSB Component Layers as Slice Specimens Cut from Control Material, 10-Specimens Each.

The results show that the sorption isotherm for the core component layer lies slightly above both the bottom and top surface layers, throughout the relative humidity range. At the lower end of the range, below 60% relative humidity, the bottom surface component layer isotherm lies slightly above the top surface component layer isotherm, but above 60% the isotherms cross, and the top surface component layer isotherm lies slightly above the bottom surface layer. In other words, for any given relative humidity, the core layer exhibited the highest resultant moisture content, followed by the two component surface layers.

The sorption characteristics of the individual component OSB layers were also looked at on the planer shaving element size level. These shavings were collected from the planer as the individual component layers for the slice

specimens were being prepared, and were thus made from the same OSB panel strips.
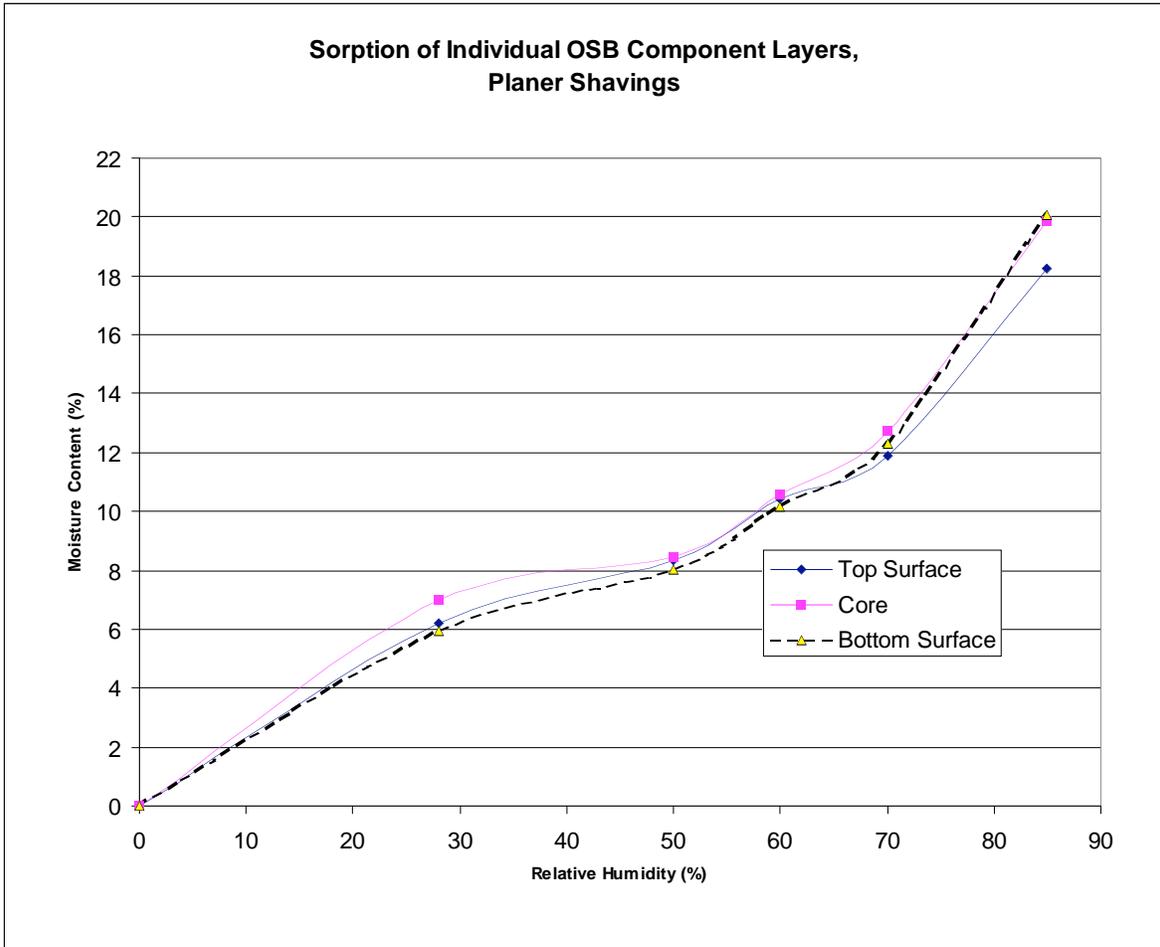
Figure 6.28: Sorption Isotherms for Individual OSB Component Layers as Planer Shaving Specimens, Cut from 626 kg/m^3 (39.0 lbs/ft^3) Control Material, 5-Specimens Each.

The resultant sorption isotherm curves are illustrated in Figure 6.28. The results again show as with the sliced specimens, that the sorption isotherm for the core component layer lies above those of both surface layers, throughout the relative humidity range, with the exception of at the high relative humidity range, where the bottom surface layer sorption isotherm just crosses the core isotherm at about 80% relative humidity. At the lower relative humidity range, both the top surface and bottom surface component OSB layer sorption isotherm curves lie very close together, but at the higher relative humidity range, above

approximately 60% relative humidity, the bottom surface isotherm climbs above the top surface isotherm.

6.2.8 Resin Content Effect on Sorption

The effect of the resin alone was studied by examination of the high resin content OSB specimens (called "Resin") in comparison to the control 626 kg/m^3 density (39.0 lbs/ft^3 unit weight) specimens. The high resin content series were manufactured by varying only the resin content, and thus at the same target density and wax content as the control. Two sets of high resin specimens were studied, both in full panel thickness. The first were as sliced specimens (Figure 6.29) cut through the thickness of the panel, and the second as full thickness OSB disc specimens (Figure 6.30). In both cases, the high resin content specimen sorption isotherm curves lie above the control group [626 kg/m^3 density (39.0 lbs/ft^3) at standard wax and resin addition rate] curves.
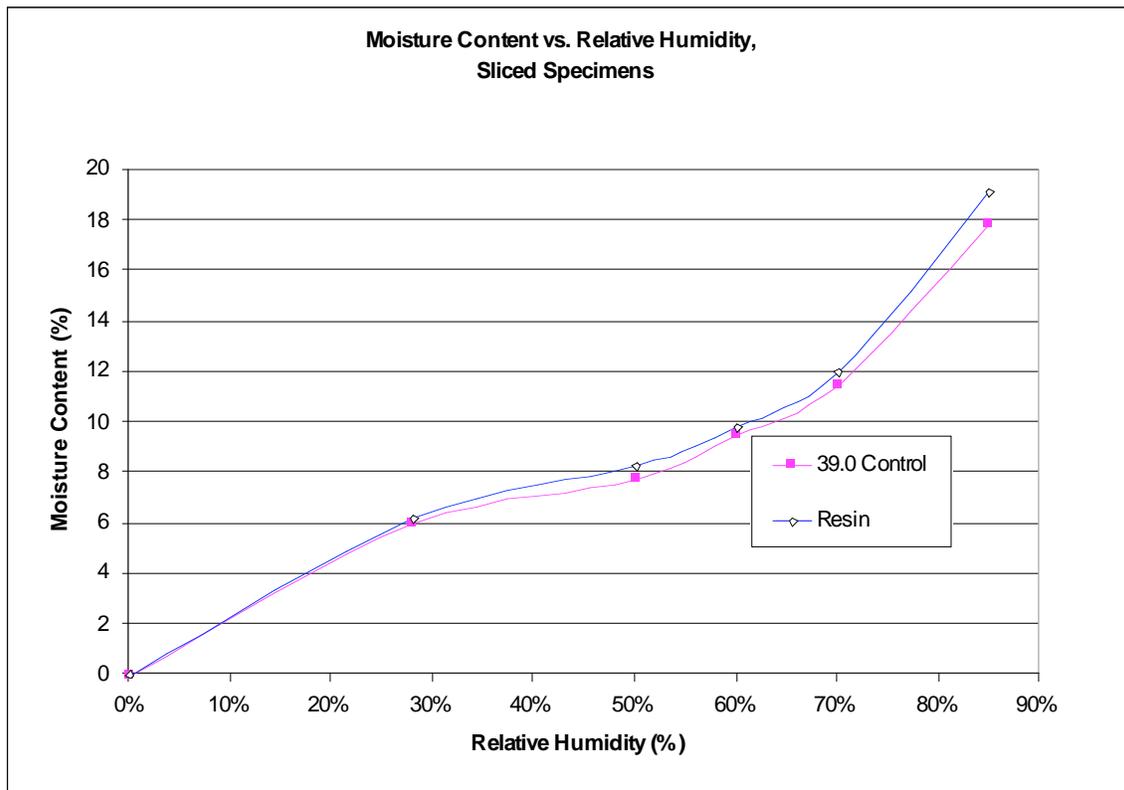
Figure 6.29: Sorption Isotherms for Sliced Specimen High Resin (at Control Density) vs. Control, 10-Specimens Each.
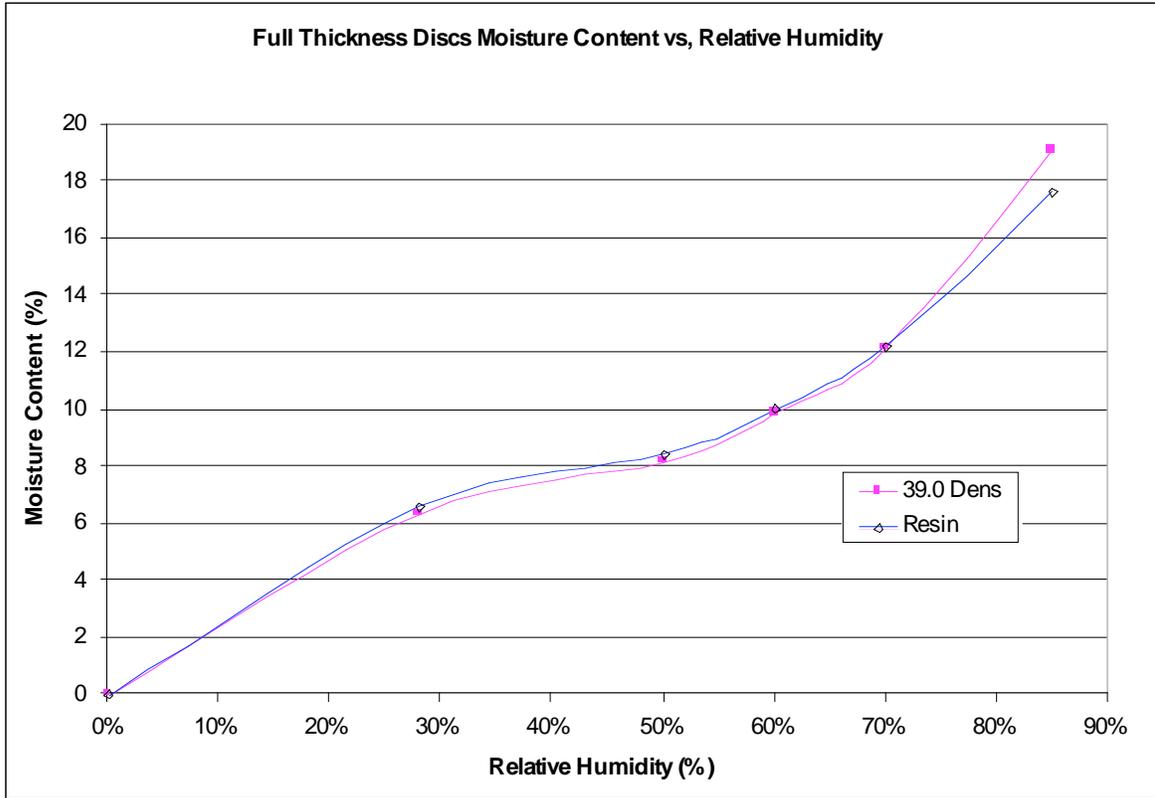
Figure 6.30: Sorption Isotherms for Full Thickness Disc Specimen High Resin (at Control Density) vs. Control, 3-Specimens Each.

The exception is with the highest relative humidity point on the disc specimen plot, where the curves cross and the high resin series shows a lower moisture content than the control.

6.2.9 Sorption Comparisons of Plywood, Pine, Western Red Cedar

Figure 6.31 compares the sorption isotherm of the control 626 kg/m^3 density (39.0 lbs/ft^3 unit weight) OSB to the high resin OSB, 100% MDI resin OSB, solid western red cedar, spruce plywood and solid pine slice specimens, all in sliced format. The 100% MDI curve lies at the bottom of the moisture content range, exhibiting the lowest resultant moisture content per given relative humidity throughout the range (with the exception of the very highest relative humidity step. The highest moisture content series vary from red cedar at the low relative humidity range, then pine at the middle range, and finally spruce plywood at the very high end of the relative humidity range. At any given relative humidity point,

there is a two to four percent moisture content difference between the lowest and highest sorption isotherm curves.
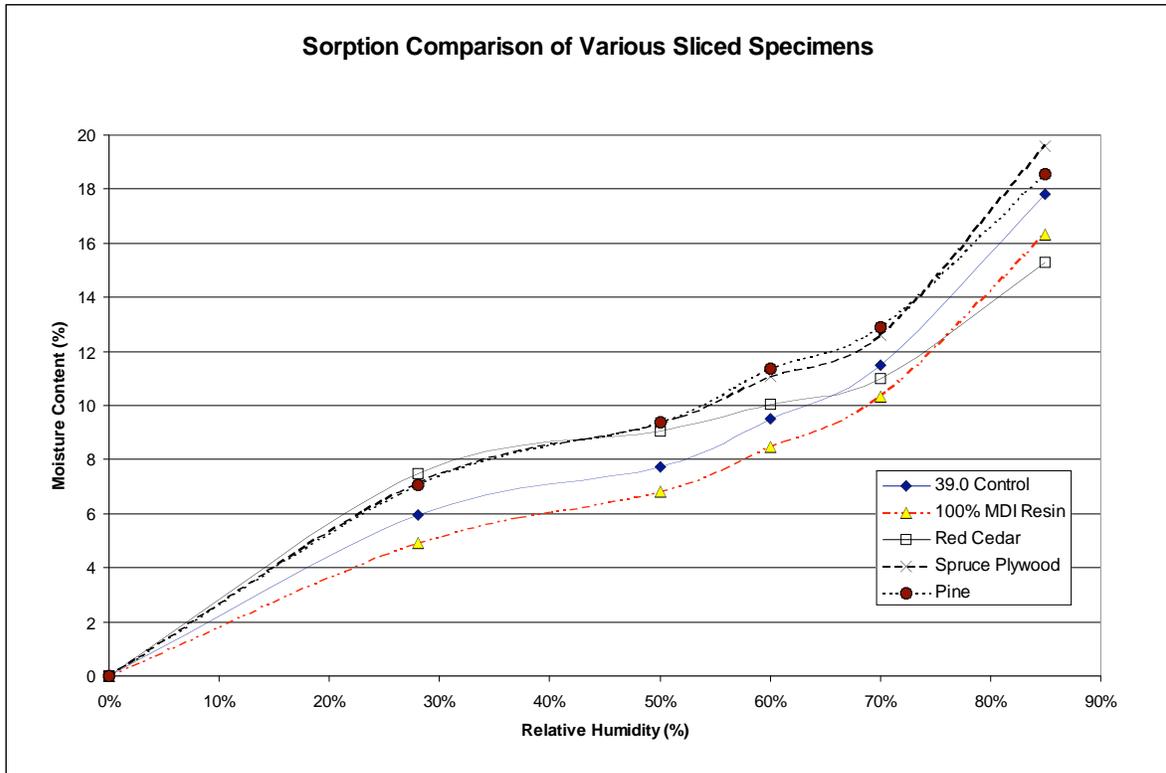
Figure 6.31: Sorption Isotherms for Various Sliced Specimens, Table 6.4 for Number of Specimens.

Chapter 7

Analysis and Discussion of Results

7. Statistical Approach and Organization

Statistical analyses were carried out using the statistical software SPSS 14.0 for Windows, and the results reported within each individual analysis section. Paired data were compared using an independent sample two-tailed t-test and multiple comparisons were conducted using a one-way ANOVA (analysis of variance). The minimum significance level of $\alpha = 0.05$ was always used, such that the probability of falsely rejecting the null hypothesis of there being no difference between means was always less than 5%. Both cases of equal and unequal variances were always examined before conclusions were made. For the one-

way ANOVA analyses, post-hoc comparisons were made using the Tukey HSD test for when equal variances were assumed, and a Tamhanen's T2 when unequal variances were assumed. This chapter is divided into two sections, 7.1 and 7.2, which present the analysis of results and discussion on the water vapour permeance tests and the water vapour sorption tests, respectively.

7.1 Water Vapour Permeability Testing Analysis and Discussion

Permeance tests showed that the material generally exhibited a steady rate of mass gain for each relative humidity step, once steady state conditions had been reached. Before steady state conditions were reached however, time to reach equilibration was required. The amount of time depended on how different the new relative humidity conditions were from the previous test. This equilibration time can be seen at the start of some mass gain vs. time charts where the plotted curves deviate from the relatively straight steady-state curves. Each series shown in Figure 6.2 represents the average of the results from five individual specimens in each series, such as shown in Figure 6.1 and Figure 7.1.
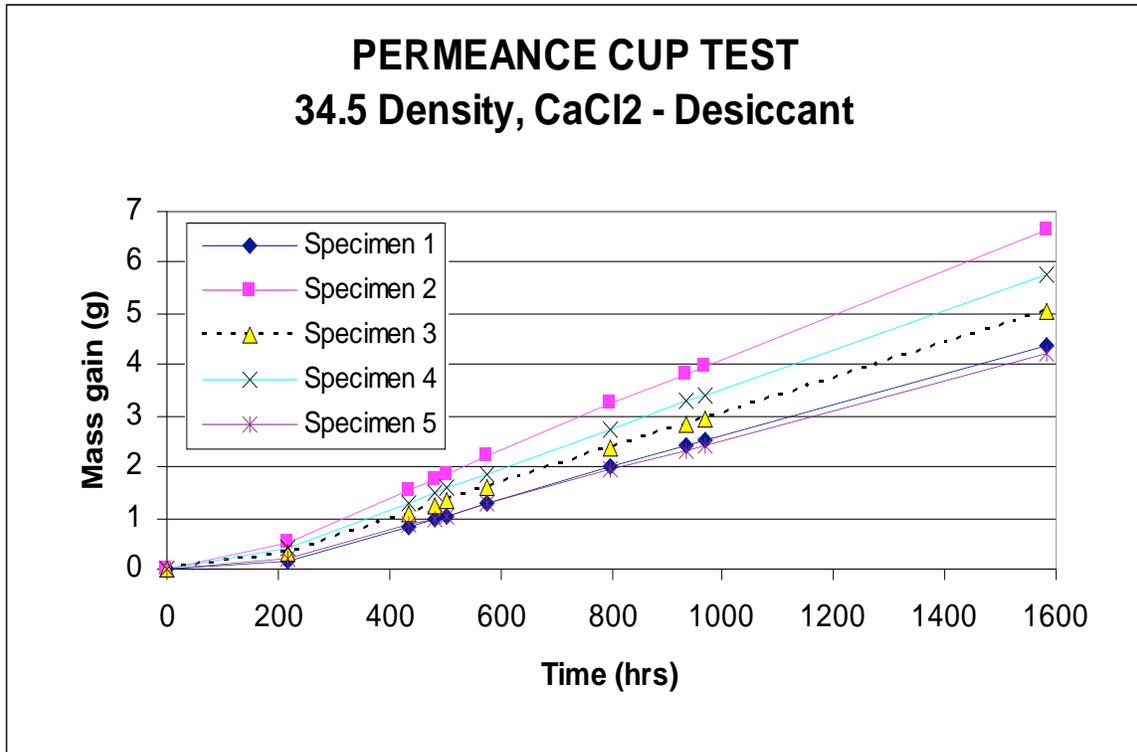
Figure 7.1: Mass Gain of Permeance Cup Assemblies Over 66 Days, at First RH Gradient (2% - 28%).

Given the difference in slopes of the five individual specimens for mass gain vs. time curves, there is considerable variation from specimen to specimen. The main cause is suspected to be due to variation in specimen density, which varies even amongst specimens cut from a single panel. The range of density variation is illustrated in Figure 7.2, for 5 full thickness permeance disc specimen series bulk density averages, each with plus or minus one standard deviation error bars. Other possible reasons could be due to slight variations in thickness, resin and wax distribution, strand alignment, species mix or other variations from specimen to specimen, most of which are inherent in the material and largely uncontrollable.
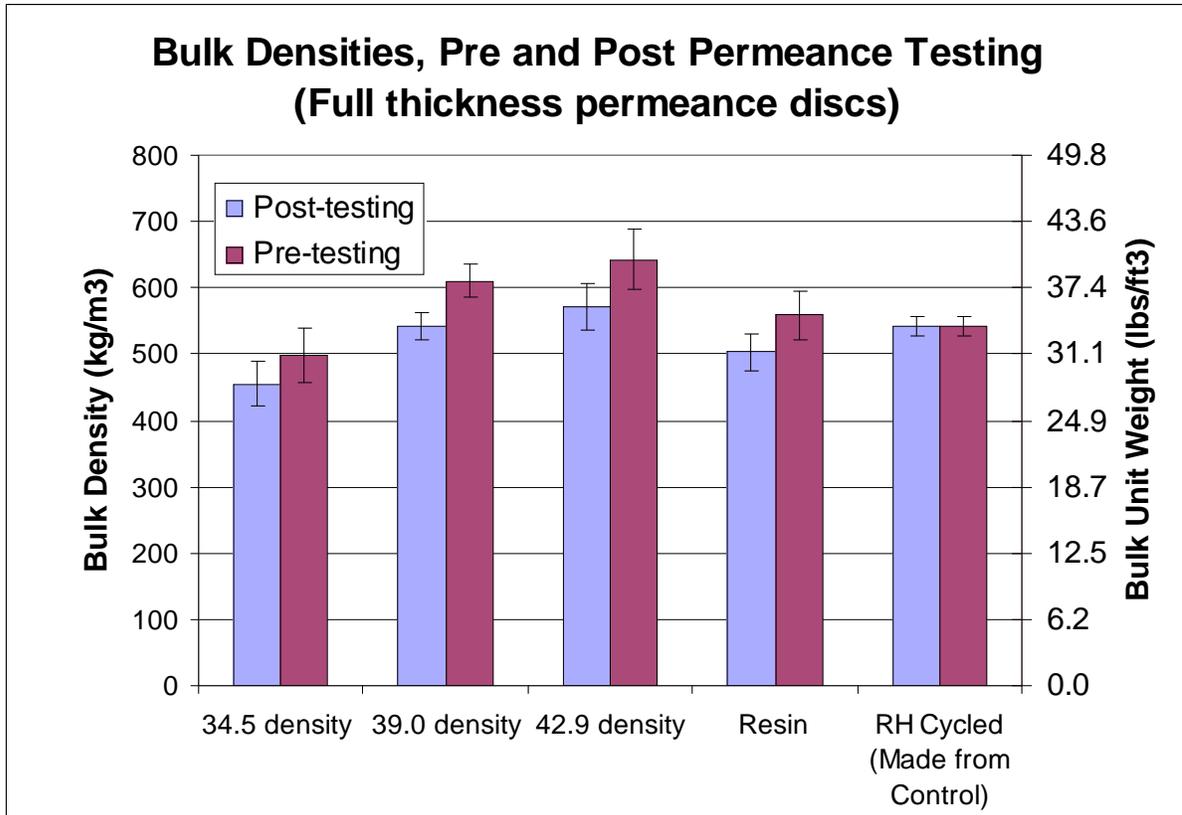
Figure 7.2: Mean Bulk Densities of Full Thickness Disc Permeance Test Specimens, Pre and Post Permeance Testing, with +/- 1 Standard Deviation Error Bars.

7.1.1 Permeability Variation with Relative Humidity

The finding that the permeability in each group increases significantly with relative humidity is a general behaviour of hygroscopic materials, and can be explained by the various moisture transport mechanisms involved at various stages in the RH range, as described in detail in Section 3.4. As the relative humidity increases, permeability increases by more than three times in the core layer group, and up to a seven times in the 689 kg/m^3 density (42.9 lbs/ft^3) "higher" density group. These results underscore the need to know the permeance of hygroscopic materials such as OSB over the entire relative humidity range, and not simply at two conditions as commonly measured with the ASTM wet-cup and dry-cup test methods.

A fundamental change which occurs between the third and fourth relative humidity steps is the increase in free or capillary water in the wood. In step three, the water is still mostly in the adsorbed and vapour forms, but by step four, condensed water begins to appear, first in the smallest capillaries, and then gradually in larger and larger capillaries. As the amount of capillary water increases, the overall rate of moisture transport through the material also increases, as indicated by the increasing permeability shown in Figures 6.4 and 6.5.

Another possible factor related to increased permeability with increasing relative humidity is swelling of the wood. As water molecules begin to occupy the spaces between the wood structure, from wood fibres to microfibrils, they cause the wood to swell. This is discussed in the latter half of the next Section, 7.1.2, *Permeability Variation with Density*. Thickness swell measurement results are presented in Figures 6.7 and 6.8 for various cyclic soak-dry and RH cycled specimens, but were not explicitly made for each specimen series at each relative humidity step.

7.1.2 Permeability Variation with Density

Permeability was found to vary with specimen density, but before further discussion, it must first be explained that OSB can have a great deal of inherent density variation.

Density variation in OSB occurs from press-load to press-load, panel to panel, and specimen to specimen taken from the same panel. Thus, the smaller the sample or specimen, the greater the variation is between samples or specimens. It is relatively easy to achieve the target density on a full press-load of panels, where the variation from sample to sample will average out with high density areas or samples compensating for low density areas or samples, but as the size of the specimen gets smaller, the variation in density increases. This relationship is illustrated by Dai, Knudson and Wellwood (2001) in the Figure 7.3 below from

their paper *Research and Development in Oriented Strandboard (OSB) Processing:*
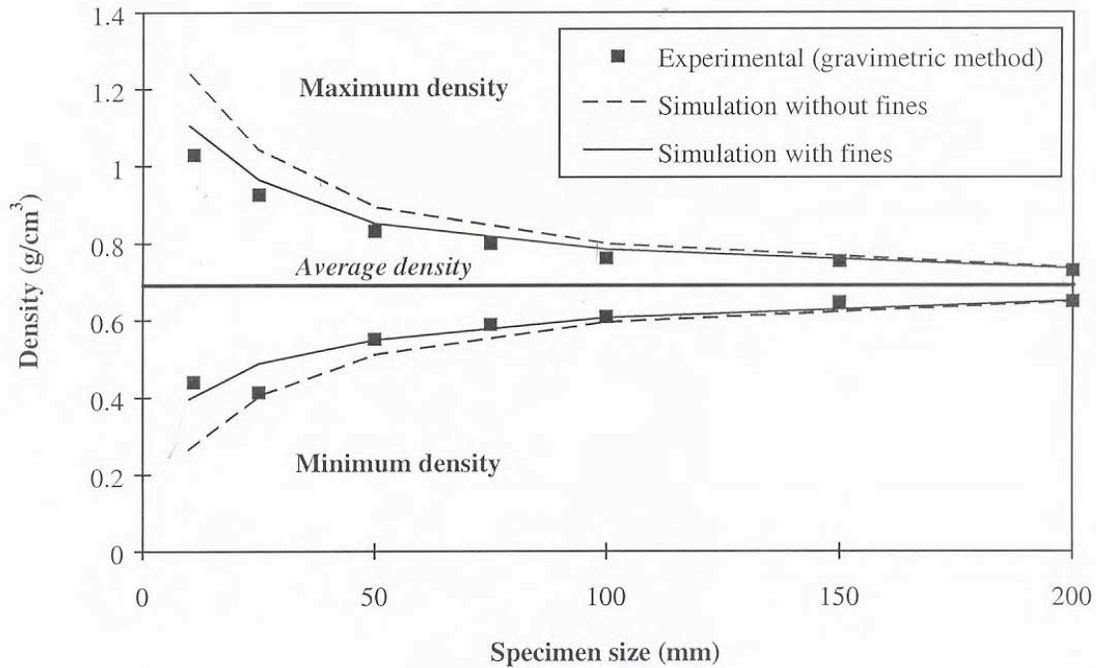
Figure 7.3: Density Variation vs. Specimen Size in OSB (Dai, Knudson and Wellwood, 2001). (Figure used with permission).

The variation in specimen density as measured from permeance disc specimens in this study is illustrated below. Figure 7.4 is a plot of the individual full thickness (approximately 11.1 mm thick) 92 mm diameter discs, while Figure 7.5 is of the individual component layer thickness discs, also 92 mm in diameter.
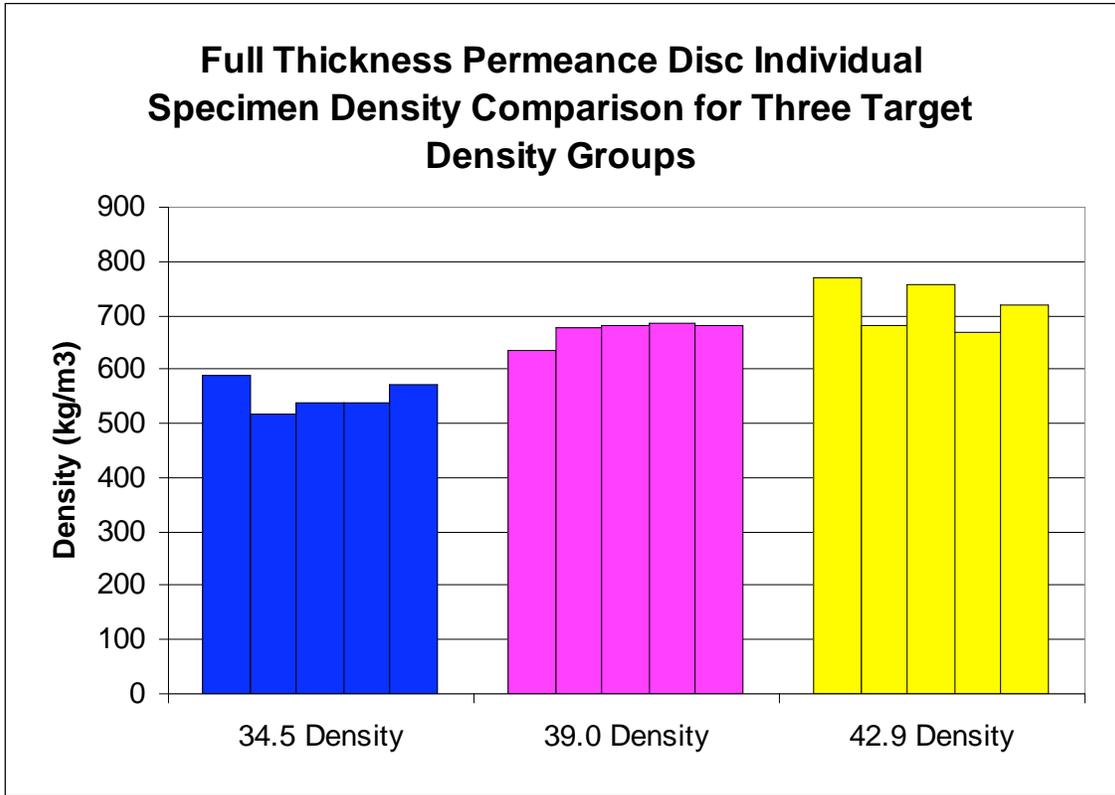
Figure 7.4: Full Thickness OSB Disc Specimen Density Comparison for Three Target Density Groups.
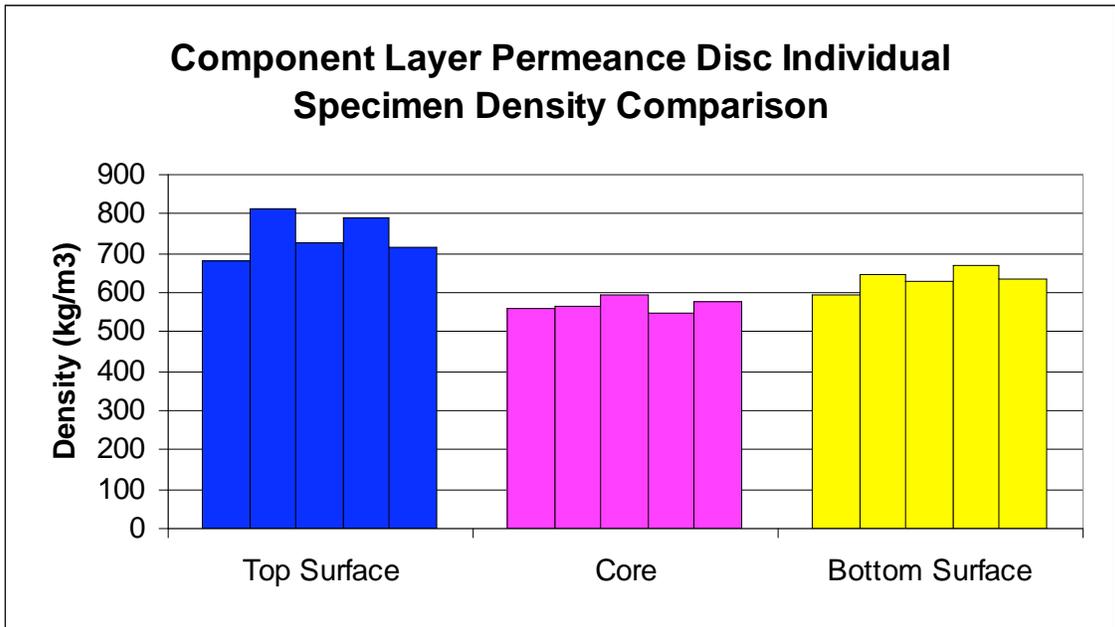
Figure 7.5: Component Layer OSB Disc Specimen Density Comparison for Three Different OSB Component Layer Groups.

The relationship between specimen density and permeability was investigated. Where only density was varied (Figure 6.4), it was found that the lowest density / unit weight group, (554 kg/m^3 / 34.5 lbs/ft^3), shows the highest permeability, and the highest density / unit weight group (689 kg/m^3 / 42.9 lbs/ft^3) had the lowest permeability. Statistical analysis using a one-way ANOVA and Tukey HSD as well as a contrast test at the $\alpha = 0.05$ significance level indicated that the low density / unit weight (554 kg/m^3 / 34.5 lbs/ft^3) specimen group is significantly different from the control (626 kg/m^3 / 39.0 lbs/ft^3), but the high density / unit weight group (689 kg/m^3 / 42.9 lbs/ft^3) is not, for this collection of data. It must be noted here that the three density groups were based on target densities, and not on actual measured densities, and thus some of the lack of difference between the high density and control groups is likely due to the actual density difference between them not being that large.

As one would intuitively expect, the relationship between density and permeability is inverse. The higher the density of a given material, the lower the permeability. This is primarily due to a reduction in the number of voids or free paths. With increased density, the paths through which water can move become blocked by low permeability wood cell wall material (Van Houts et al. 2004). At the low relative humidity range, the void space allows for increased water vapour diffusion, and then at higher relative humidities when capillary water begins to appear, the void space allows for increased capillary flow. Surface diffusion however would be expected to increase to a certain point with decreasing void space, as it is dependant upon internal surface area and the number of adsorption sites. Unfortunately, the transport processes all overlap, and cannot be separated to study their individual effects. Rather, one can only measure the overall rate of transport.

In an attempt to overcome the lack of significant difference between group mean densities for the high density group and control, and thus better examine the density to permeability relationship, the data can be examined as individual

specimens, as opposed to group averages based on target density groups. This is because the individual specimen densities span a broader range than the group averages. That is to say that within each target density group, there is a range of individual density specimens. In retrospect, the grouping of specimens into "density groups" based on press-load target densities is somewhat difficult, due to the inherent variability of OSB density from panel to panel, and variations from specimen to specimen cut from the same panel as illustrated in Figure 7.3 (Dai, Knudson and Wellwood, 2001). This can be done by plotting the densities of individual specimens against permeability at each relative humidity range (Figure 7.6). Here each individual specimen from the "density" specimen groups of 42.9 lbs/ft^3 (689 kg/m^3), 39.0 lbs/ft^3 (626 kg/m^3) and 34.5 lbs/ft^3 (554 kg/m^3), were plotted, such that the only variable changed was density. The relationship between permeability and density can be described by a linear function for each RH step, as shown in Table 7.1.
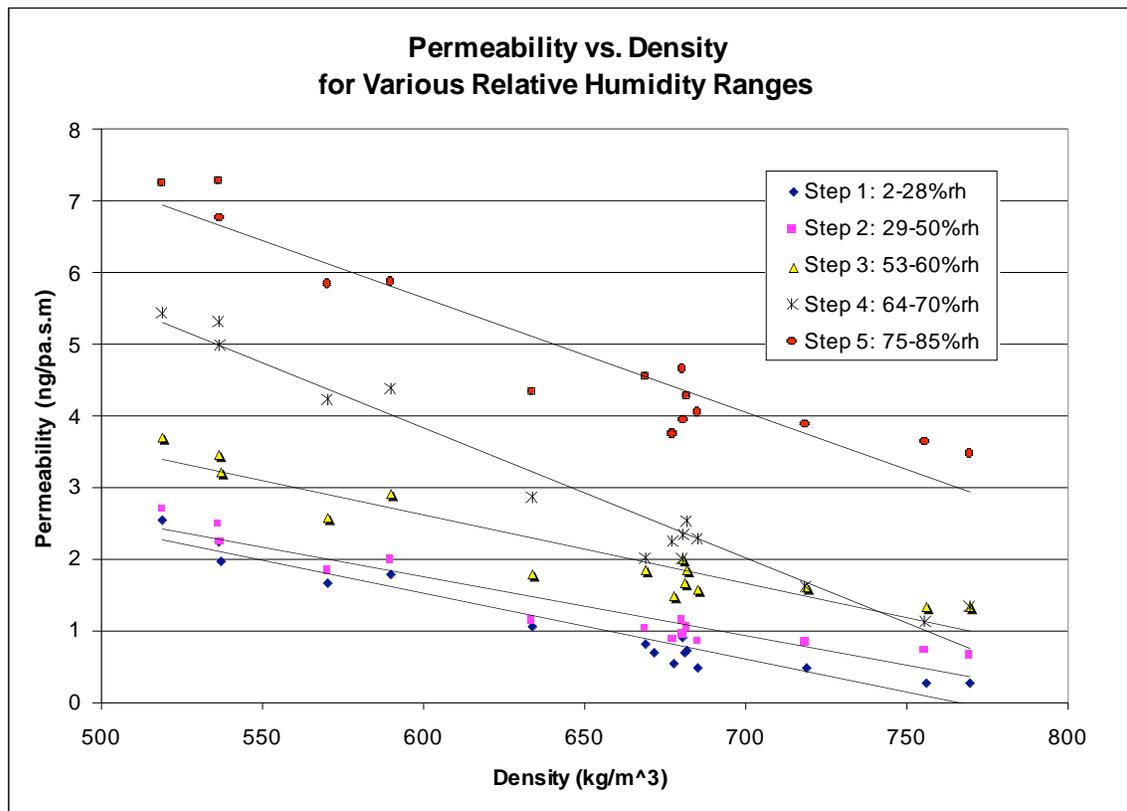
Figure 7.6: Permeability vs. Density for Various Relative Humidity Ranges, where Each Point Represents One Specimen, with linear regression trend lines.

Table 7.1: Permeability vs. Density Regression Analysis Linear Trend Lines with Calculated R^2 (Coefficient of Determination) Values.

RH Step	Equation	R^2 value
1. 2% - 28%	y = -0.009x + 7.007	0.94
2. 29% - 50%	y = -0.008x + 6.718	0.91
3. 53% - 60%	y = -0.009x + 8.326	0.89
4. 64% - 70%	y = -0.018x + 14.785	0.96
5. 75% - 85%	y = -0.016x + 15.275	0.90

Where: y = permeability (ng/pa·s·m)
           x = density (kg/m^3)

A less expected finding is that the slope of the permeability vs. density relationship becomes steeper beyond the third relative humidity step (above the 60% to 53% relative humidity gradient). That is, above a critical relative humidity level, the effect of density on permeability suddenly increases.   A closer examination reveals that the best fit curves of step three and four actually cross at about 740 kg/m^3, and that the highest density specimens appear to have a slightly lower permeability in the fourth relative humidity step (70% to 64% RH) than they do at the lower relative humidity in step three (60% to 53% RH). As this finding is based on only a few data points, it may be an anomaly resulting from experimental error and not of great significance.   If the finding were confirmed based on an adequate sample size, it would require further investigation as to the cause.

The fundamental change which occurs between the third and fourth relative humidity step, and theoretically as early as the third step, is an increase in the proportion of free or capillary water in the wood. In step three, the water is still mostly in the adsorbed and vapour forms, but by step four, increasing amounts of condensed water appear, first in the smallest capillaries, and then gradually in larger and larger capillaries. With the increase in capillary water, comes an increase in the overall rate of moisture transport through the material, from one surface to the other, as indicated by the increasing permeability (Figures 6.3, 6.4, 6.5, 7.6 and 7.7). The difference now between the lower and higher density specimens, is that the lower density specimens have less wood substance per

given volume, and thus bigger capillaries which do not begin to fill with free water until higher relative humidities are reached, at which point diffusion rates increase.

Statistical analysis of the group permeabilities using a one-way ANOVA and Tukey's HSD (honestly significant difference) at the $\alpha = 0.05$ significance level indicated that for relative humidity steps one, two and three, only the low density / unit weight (554 kg/m^3 / 34.5 lbs/ft^3) group was significantly different from the control (626 kg/m^3 / 39.0 lbs/ft^3) group and the high density / unit weight (689 kg/m^3 / 42.9 lbs/ft^3) group. However, at the fourth relative humidity steps, both the low and high density groups were significantly different from the control group, and each other. At the fifth relative humidity step, only the low density group again was significantly different from the control group.

Using the linear equations shown in Figure 7.6 and tabulated in Table 7.1, Figure 7.7 was generated. This figure shows the model points of permeability vs. relative humidity over the full RH range. Figure 7.7 also shows the results of curve fitting this model data using a quadratic equation. Three density levels (500, 600 and 700 kg/m^3) were chosen for this analysis since mill-manufactured OSB panels usually fall within this range of densities These quadratic equations are in the form: $Y = Ax^2 + Bx + C$. Examining the A, B, and C parameters, it is apparent that there is an inverse relationship between these model parameters and density. In Appendix D, quadratic relationships between the inverse of density and the A, B, and C parameters are shown. The parameters and the curves used to develop these parameters are also presented in Appendix D. For densities in the range from 500 to 700 kg/m^3, these relationships can be used to model or estimate the permeability of OSB sheathing across the full range of relative humidities.
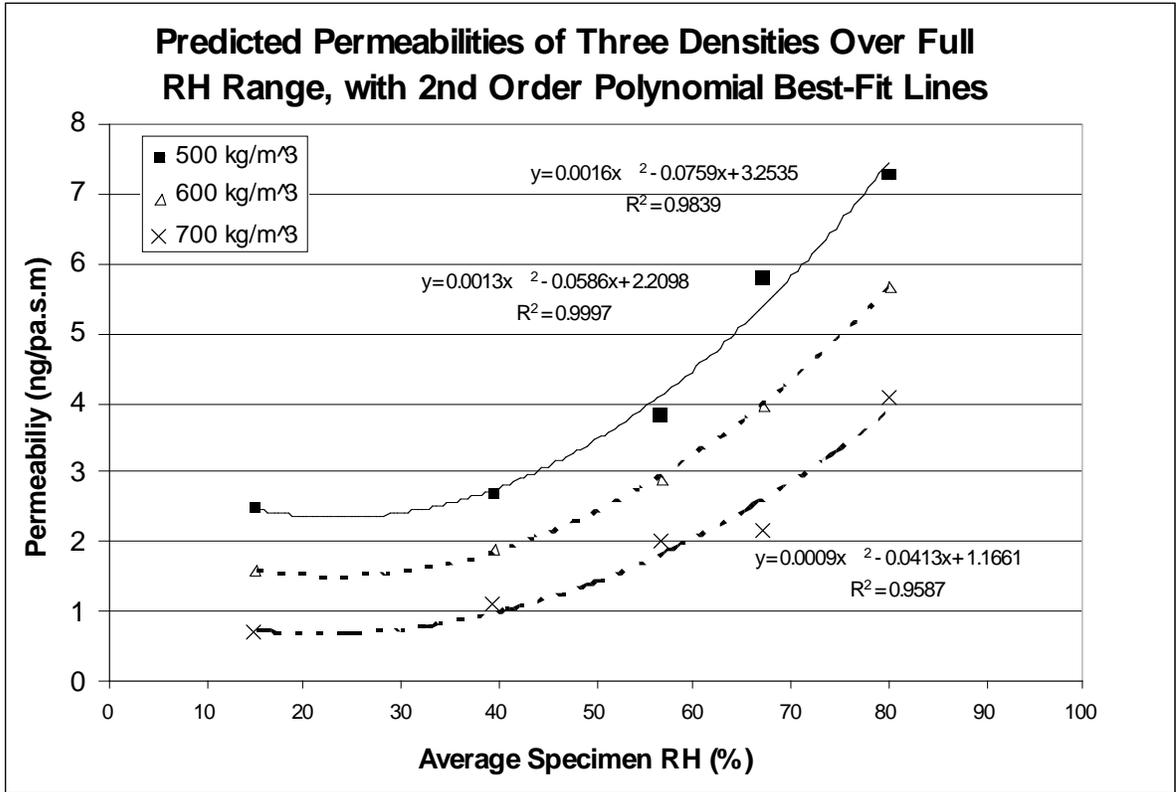
Figure 7.7: Predicted Permeabilities of Three Densities Over Full RH Range, with 2nd Order Polynomial Best-Fit Lines.

To illustrate this model relationship, Figure 7.8 has been provided. This figure shows model plots of permeability versus relative humidity for two different densities: 537 kg/m^3 and 675 kg/m^3. As well, shown on this graph are the measured permeabilities of samples of OSB corresponding to these same modeled densities. Comparing the measured data to the model generated data, it is clear that the model appears to be a reasonable estimator of permeability.
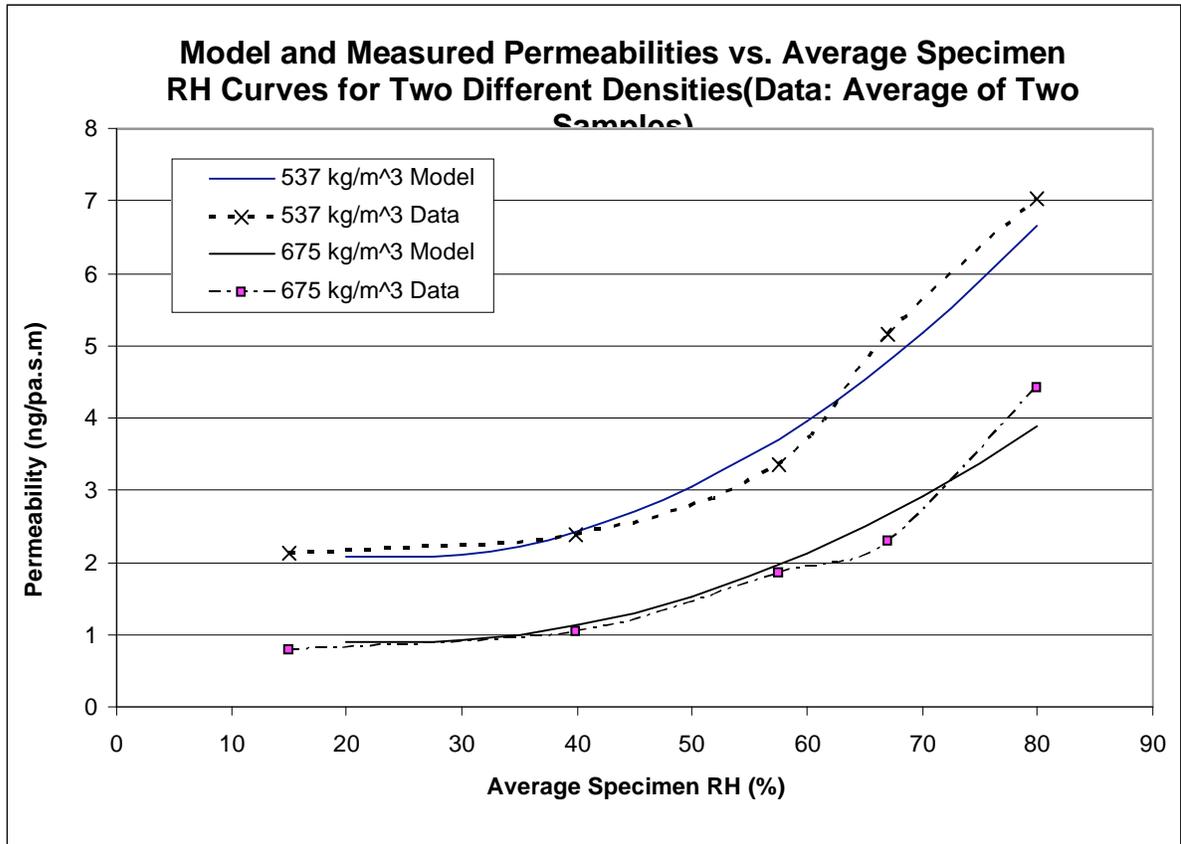
Figure 7.8: **Model Predicted and Actual Data Permeability vs. Average Specimen RH of Two Densities, with 2nd Order Polynomial Best-Fit Lines.**

The same model relationship was used again to produce Figure 7.9, over a slightly broader density range, including 450, 550, 650 and 750 kg/m^3. This range should cover most of what is produced in the OSB industry. Along with the four model curves, plotted is a curve based on averaged test data at 550 kg/m^3. Again, the model estimates the actual test data fairly well.
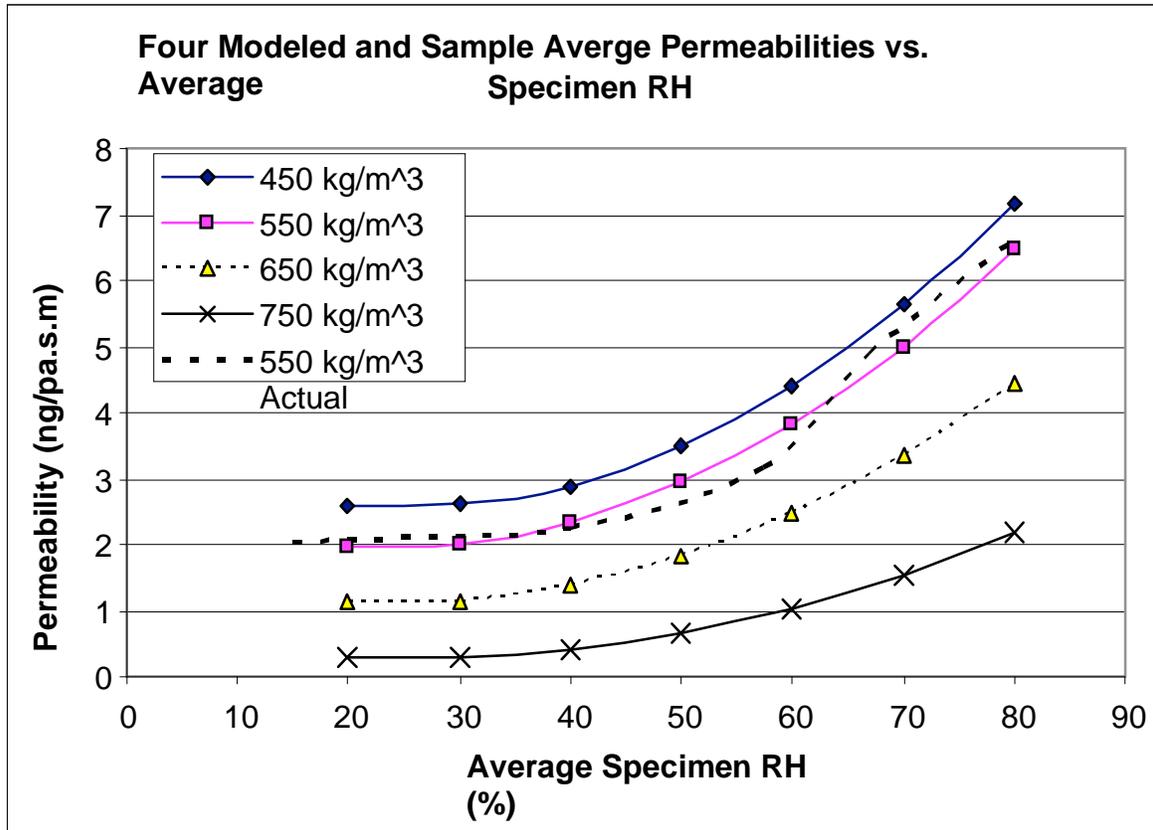
Figure 7.9: Four Model Predicted and One Actual Averaged Data Permeability vs. Average Specimen RH, with 2nd Order Polynomial Best-Fit Lines.

Thus, given an OSB density, hygrothermal simulation programs may be able to use this model relationship to modify the permeability of the OSB sheathing as a simulation progresses and relative humidities within the modeled element change.

Another fundamental change which occurs with increased relative humidity, that could possibly have an effect on permeability, is thickness swelling of the specimens. Figure 7.10 illustrates the thickness swell of the permeance disc specimens from before testing to after all relative humidity steps were complete. One might expect that swelling should lead to increased permeability. The results indicate that the higher density specimens swelled more than the low density specimens, which is to be expected and supported by extensive testing in

the OSB industry. However, since the permeability results indicate an inverse relationship between density and permeability, greater swelling did not seem to result in increased permeability. But although the low density specimens were consistently higher in permeability throughout the relative humidity range, the relative increase in permeability was greater for the high density specimens from low to high RH. These finding require further work in order to develop an adequate explanation.
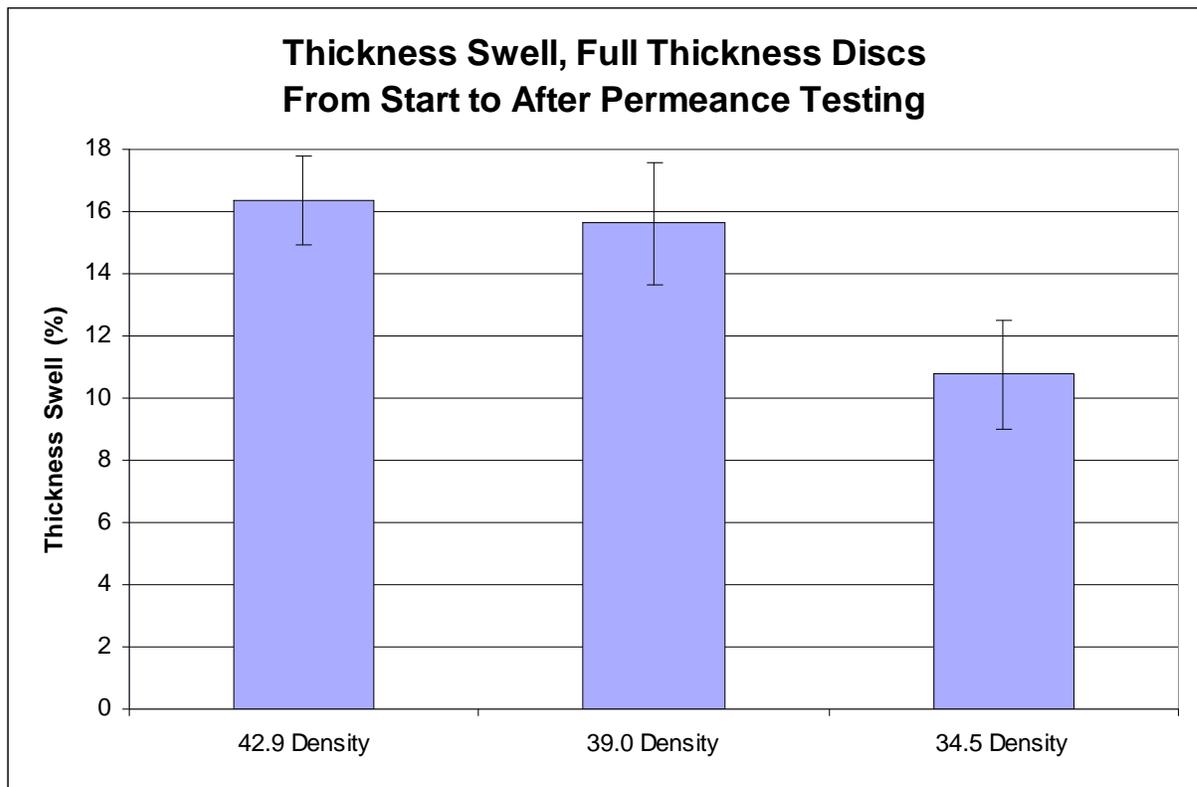
Figure 7.10: Thickness Swell of Full Thickness Permeance Disc Specimens From Initial Condition to After Permeance Testing.

The NRC MEWS consortium study (Kumaran et al., 2002) measured the permeabilities of purchased or manufacturer supplied OSB panels with bulk densities ranging from 575 to 725 kg/m^3, and thicknesses from 10 to 11.5 mm. The range of OSB bulk densities (oven dry mass/equilibrium volume) tested by the author were from 497 to 643 kg/m^3, all in the thickness group of 10.9 mm (7/16" or 0.430" target thickness).

A comparison of the range of water vapour permeabilities found for the range of densities of OSB tested by the MEWS consortium to those measured by the author is presented in Table 7.2.

Table 7.2: Comparison of Permeability Ranges of MEWS Consortium Study to Author's Study.

MEWS STUDY			THIS STUDY	
Lower	Upper	Average	Lower	Upper
Limit	Limit	RH	Limit	Limit
(ng/pa.s.m)	(ng/pa.s.m)	(%)	(ng/pa.s.m)	(ng/pa.s.m)
0.176	0.205	15	0.29	2.56
0.396	0.463			
0.704	0.823	39.5	0.66	2.71
1.11	1.29			
1.6	1.87	56.5	1.34	3.71
2.19	2.56	67	1.12	5.43
2.88	3.37	80	3.47	7.28

Density range: 575 – 725 kg/m^3 Density range: 497 – 643 kg/m^3

The results are all within an order of magnitude of one another, but the upper range of the MEWS permeability findings is consistently lower than those found by the author, and the overall range of permeabilities for any RH step is consistently much larger in the author's results. This finding is contrary to what one might expect.

Since the range of densities tested by both studies is almost identical (MEWS density range was 150 kg/m^3 vs. author's density range of 146 kg/m^3), density variation can be eliminated as a cause of permeability variation between the two studies. This leaves all of the other manufacturing variables as possible causes for the difference in variation, such as the mill where they were manufactured, resin and wax types and addition levels, species mix, strand moisture content, product formulations, press cycles, operators and so on. Since the author's study used panels all from the same mill, made on the same day with the various manufacturing variables except resin addition and density (which was not different in range between the two studies) kept constant, while the MEWS study

stated it's panels to be from several different manufacturers and manufacturing dates, inherently encompassing a much wider range of other possible manufacturing variables, it would have been expected that the permeability range would be much larger in the MEWS study.

7.1.3 Permeability Variation with Resin / Wax Content

The effect of resin and wax addition rate on the permeability of OSB was investigated in two ways; directly by comparing the permeabilities of the high resin content series called "resin" to the lower resin content control series; and indirectly by comparing the permeability variation among the three component layers, but where density is not constant, discussed in the next Section, 7.1.4.

The permeability of the high resin content series called "resin" is illustrated in Figures 6.3 and 6.5 and Table 6.2. Only the resin addition rate was changed, which for both the surface and core layers was raised to the upper end of the commercially feasible limit at 4.25% PF in the surface layers and 4.0% MDI in the core layer on a solids percent mass basis as described in Table 5.2. It was made at the control density or unit weight of 626 kg/m^3 or 39.0 lbs/ft^3, and at the control wax content of 1.8% in the surface layers and 0.6% in the core.

These high-resin specimens showed little difference in permeability when compared to the control group. The results from this study indicate that within the range tested, the resin addition level has little influence on the permeability of OSB, with no statistical difference measured when compared to the control at the $\alpha = 0.05$ level.

7.1.4 Permeability Variation Among Component Layers

Examination of Figures 6.3, 6.5 and Table 6.2 shows that each component layer has a very different permeability, statistically significant at the $\alpha = 0.05$ level, where the core layer has the highest permeability and the top surface layer has the lowest permeability of all the series, throughout the relative humidity range. This suggests that OSB is not a uniform homogeneous material, and should be seen as being composed of three distinct individual component layers. Some of the measured permeability differences may be due to differences in resin and wax content, even though the findings from the high resin series did not indicate an impact of resin content on permeability. Surface layers typically have 50% more resin and 200% more wax than the core layer. In this study, with the exception of the high resin content specimens, the surface resin content was 3.0%, while the core was 2.0%, on a resin solids percent mass basis. The wax content was 1.8% in the surface layers, and 0.6% in the core, on a liquid percent mass basis (approximately 50% solids content). However, other significant differences exist between the component layers, such that the permeability differences cannot be attributed to differences in resin and wax content alone.

The way in which OSB is pressed results in significant differences between the component layers. One such difference is the large variation in density throughout the thickness of OSB, called a vertical density profile (VDP). Both surface layers are significantly more dense than the core layer, as illustrated in the x-ray densitometer vertical density profile plot shown in Figure 2.1. This is because of the heat transfer process during pressing, resulting in the outer surfaces plasticising and densifying to a higher degree than the core. The top surface of the strand mat contacts the hot press platen and receives heat first as the press closes. The bottom surface of the mat which sits on the metal caul screen is the second part to receive heat. Although it sits directly on the caul screen, which in turn rests on the hot press platen even before the press closes, the caul screen provides a degree of insulation between the bottom of the mat and the platens. This is due to the caul screen being somewhat rigid and not

perfectly flat, such that without pressure exerted through the press, most of the screen and mat are not in direct contact with the hot press platen. The result is poor contact between the bottom press platen and the wood fibres until the press is closed. The direct impact on permeability has been described in Section 7.1.2, *Permeability Variation with Density*, where the top and bottom surface layers are higher density, and thus lower permeability than the less dense core layer.

Other physical and chemical differences between the very outer surfaces and the core result from how the panel is pressed. The very top surface has a glassy smooth finish to it, distinctly different from the bottom surface, or from any material within the core. This is due to the direct contact it makes with the hot, smooth metal platens of the press. A fine mist of water is often also sprayed on the top surface of the mat before pressing, to aid in heat transfer to the core primarily by convection. This moisture may also impact the top surface layer by increasing the plastification and densification. The bottom surface in contrast, with the exception of panels made on a continuous press, have a rough, textured surface from the caul screens used with a multi-daylight opening type press. As the caul screen is in fact a thick (approx. 2mm) woven metal screen, it leaves a deep imprint on the bottom of the panel during pressing.

The other possible variations in moisture performance properties may be due to the migration of resin, wax, gases and moisture during pressing. Just as steam moves from areas of high pressure to low pressure, the resins and waxes, as well as the lignin component of the wood likely migrate both in the gaseous state due to a vapour pressure gradient and flow in the liquid state during the pressing cycle. The impact on permeability is likely to be a larger reduction for the smooth top surface layer, and a somewhat lesser reduction for the rough bottom surface layer which was not heated to the same degree.

It is likely a combination of the differences in resin and wax content, density, surface chemistry and structure and other factors combined which together

explain the differences in permeability between the individual component layers of OSB. The implication is that OSB cannot be treated as a uniform material, with equal properties through the panel thickness. Thus a doubling in the thickness does not result in half of the permeability. Modifications such as sanding or planing will also significantly alter the properties, and are discussed in Section 7.1.7. These differences may also be of importance to water vapour transport calculations for predicting building performance, whether manually or through hygrothermal computer modeling, where a range of thicknesses of materials are needed. OSB cannot be treated as glass batt insulation or other uniform materials where one permeability value can be used to calculate the individual permeance values for each thickness needed.

7.1.5 Effect of Cyclic Soaking and Drying on Permeability

Cyclic soaking and drying of control OSB resulted in increases in permeability of 2.4 times after one cycle, 2.5 times after three cycles, and 3.1 times after eight cycles of wetting and drying, as compared to the un-soaked control specimens (Figure 6.6). All are statistically different from the control at a significance level of $\alpha = 0.05$, but no statistical difference was shown between the one-cycle and the three-cycle series at the $\alpha = 0.05$ level. After the first cycle, subsequent cycles had a diminished effect. Five specimens were tested in each group of cycles, and each bar in the plot of Figure 6.6 represents the average permeability for each group.

Even with the best intentions in mind, most building materials inevitably spend some time on the job site or in a poorly managed building supply yard fully exposed to the environment before they become part of the final structure. After they are attached to the wood frame of the structure as roof, floor or wall sheathing, their exposure does not end. This is often when they are most exposed for the longest period of time before they are covered with roofing shingles, a roof, or some form of siding. Then, for the remainder of their service life as part of the structure, conditions can and often do arise when they come in

contact with liquid water. This may be the result of air leakage causing condensation on the back of sheathing during the heating season, a roof, window or plumbing leak, condensation from the outside during the cooling season as the result of sun driven moisture, melting snow in the attic space, ice damming, or countless other unplanned occurrences.

Although the cyclic soaking and drying test method is more severe than simple exposure to cycles of high and low relative humidities, it is not unrealistic for OSB to occasionally experience such conditions, either before being installed, or after going into service. Even if such conditions arise but once and briefly in the service life of an OSB panel, the effect on permeability will be significant and non-reversible. The underlying cause for the increase in permeability is most likely due to the opening of internal OSB structure by the breaking of resin bonds and the relaxation of built-in compression that develops during pressing under heat and pressure, as indicated by the increase in measured thickness swell illustrated in Figures 6.7 and 6.8. This results in increases for all three transport mechanisms: water vapour diffusion, liquid capillary flow and adsorbed surface diffusion. Because it is not possible to separate the various mechanisms experimentally, only the overall combined effect can be measured.

7.1.6 Effect of Relative Humidity Cycling on Permeability

The findings from the relative humidity cycled specimen are perhaps the most significant of all the tests conducted. The permeability almost doubled as compared to the unexposed control series, increasing by 1.7 times after only 5 relatively brief (24 hr.) exposures to high relative humidity and was statistically different from the control at the $\alpha = 0.05$ level (Figure 6.6). The most obvious implication is that the moisture-related properties of OSB panels begin to change as soon as they leave the environment of the mill. Even after the panels have been transported across the country on a truck, and then stored inside a controlled temperature and relative humidity building for months as they had in this study, the moisture-related properties will again change as soon as they are

put into service. Although it was not possible to maintain the test panels used in this study at the exact RH conditions as manufactured before testing, they were protected from the elements during transport by means of water proof wrapping, and then stored indoors until testing.

The exposure conditions simulated by cycling between room relative humidity (approximately 42%) and 100% relative humidity (saturated condition) are not unrealistic to expect within wall assemblies or roof structures. OSB sheathing behind stucco or a poorly vented brick veneer can easily reach 100% relative humidity due to sun driven moisture, or by warm, moist indoor air leaking into and condensing on the surface of the OSB.

It has already been established that there exists a very large range in the moisture-related properties of commercially available OSB from panel to panel, product to product, and mill to mill. It has also been demonstrated that the history of exposure to moisture in the air can further complicate matters. Realistically, the only way to know the permeance or sorption of a given panel, or small section of a panel, is by testing it, but this is not practical in most cases. Off-the-warehouse-shelf panel values are not representative of the properties representing the panel during most of its service life, and therefore predicting the performance of a wall should be based on in-service properties, not those as manufactured. Another approach would be to have a range of properties available, and it would be up to the individual to select the exposure history which best matches the material in question. It should be noted that the small test specimens used in this study have a higher edge to surface area ratio than full-sized panels, and this may have an effect as compared to full size panels in the rate of moisture adsorption and desorption.

7.1.7 Permeability and Sanding of Surfaces

The effect of sanding on the permeability of OSB was investigated, as sanding is a common surface treatment. Sub-floor panels are usually sanded on both top

and bottom surfaces to ensure minimal thickness variation as required for overlayment with various floor cover types such as tiles or hardwood. Wall sheathing and roof sheathing panels are also sometimes sanded, depending on the specific customer or market.

Recalling the variation in permeability between the various component layers illustrated in Figures 6.3 and 6.5, one would expect that the removal of top or bottom surface material should change the overall permeability. Removing any portions of the less permeable top and bottom surfaces, leaving the core intact should increase the overall permeability of the panels, and this is what the results indicate. The permeabilities of both top and bottom sanded series (Figure 6.9) are statistically higher than that of the control group at the $\alpha = 0.05$ level, but not statistically different from each other.

These results indicating a statistical difference between the permeabilities of sanded and un-sanded OSB support a need for distinction where the permeability may make a difference in wall or overall building performance or durability, and again emphasizes that OSB is not a uniform material. Experimentation with the degree of sanding or the amount of surface material removed may warrant further investigation.

7.1.8 Permeability of 100% MDI OSB and Spruce Plywood

Control OSB (626 kg/m^3 density / 39.0 lbs/ft^3 unit weight) was compared to OSB made with only methylenediphenyl diisocyanate (MDI) resin (at 728 kg/m^3 density / 45.3 lbs/ft^3 unit weight), as well as construction grade three-ply spruce plywood made with phenyl formaldehyde (pf) resin for comparison, to put the permeability ranges of this study into perspective.

The results plotted in Figure 6.10 indicate that Spruce plywood was 17% more permeable on average than the control OSB, significant at the $\alpha = 0.05$ level. OSB made with 100% MDI was 54% less permeable than the control, statistically

different from both the control and the spruce plywood. Differences in permeability are likely due to numerous reasons, including density, resin and wax content, and surface characteristics. The more significant point evident comparing the two OSB products is once again that not all OSB is equal. The OSB made with only MDI resin is very different from the control made with both PF and MDI.

7.1.9 Permeability Summary

The permeability of OSB can vary several fold as a result of variation in the manufacturing parameters at the mill. Further, it varies significantly when subjected to cycles of wetting and drying or after being exposed to cycles of high relative humidity. Thus, as Figure 7.11 indicates, not all OSB is the same.

Permeability of All Series Tested
Second RH step (29% cup - 50% chamber)

	Control	1-Cycle soak-dry	3-Cycle soak-dry	8-Cycle soak-dry	Sanded Top Sfc	Sanded Bottom Sfc	5 RH Cycles (100%-	100% MDI Resin	Spruce Plywood (3-ply)	Resin	42.9 Density	34.5 Density	Top Surface	Core	Bottom Surface
□ Series1	1.23	2.97	3.10	3.83	1.66	1.87	2.12	0.56	1.44	0.99	0.88	2.25	0.60	2.99	1.16
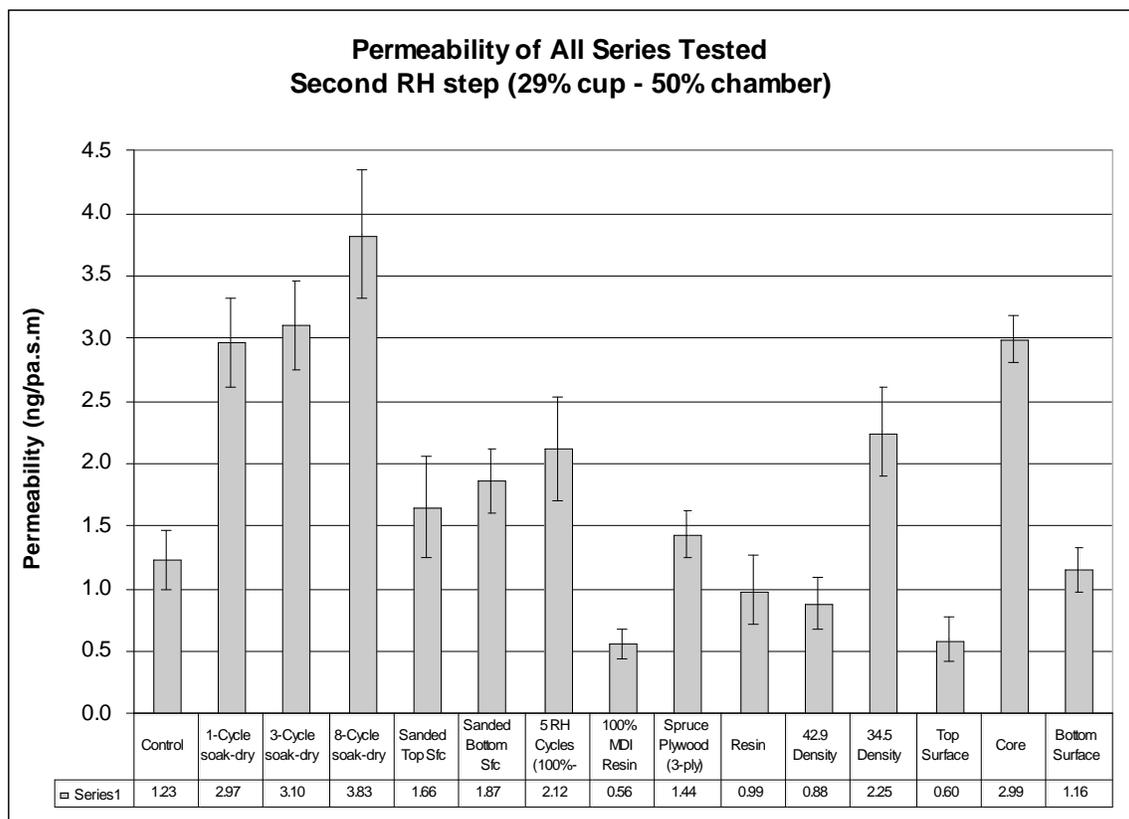
Figure 7.11: Permeability Summary of All Groups with +/- 1 Standard Deviation at the Second RH Step (29% Cup – 50% Chamber).

This strongly suggests that in addition to virgin material moisture properties, those which result from exposure to wetting and drying should be considered in design and analysis. A simple factor such as whether or not the OSB has been sanded or not, may further alter the permeability, depending on the degree of sanding. When wall, roof or floor systems are designed with OSB, these variations in permeability may have an impact on the overall moisture performance of the wall system, and ultimately on whether or not mould, mildew or rot will develop under adverse service conditions. Ultimately, both the designer and the OSB manufacturer can take advantage of these variations in permeability in order to optimize building systems for occupant health, efficiency and durability.

7.2 Water Vapour Sorption Testing Analysis and Discussion

Sorption tests were carried out for 12 specimen types, some in several formats (full thickness, slices and discs), (Table 6.4), over the whole relative humidity range, from 28% relative humidity up to 85% relative humidity (Table 6.3), as described in Section 6.2, and some specimens were water soaked for a final tests. Tests were also conducted on planer shavings. All testing was conducted at 25°C, and desorption tests were not conducted for reasons of time and space constraints. For OSB, as well as most other building materials, the effect of temperature on the sorption isotherms in the range of 20 to 70°C can be ignored (Kunzel, 1995), (Nevander, 1981). This is because in terms of adsorbed water, although the rate of water molecules landing on the material surface increases with temperature, so does the rate at which they leave the surface. The equilibrium adsorbed molecular thickness remains almost unchanged. In terms of capillary water, as illustrated by the Kelvin equation, because the ratio of vapour pressure over saturation vapour pressure, or relative humidity is inversely related to temperature, the effects of temperature cancel. The effect of temperature on the mass of water vapour has no effect.

Also, the hysteresis between adsorption and desorption curves is relatively small for most building materials, and thus the moisture storage function can usually be represented accurately enough just by the adsorption isotherm. Where the hysteresis is more pronounced and more accuracy is desired, the effect can be calculated from the average between the adsorption and desorption isotherms (Kunzel, 1995). RH cycling of OSB specimens does however have a significant effect on permeability as shown in this work.

7.2.1 Density and Sorption

No large differences in sorption moisture content were detected between the 688.6 kg/m^3 (42.9 lbs/ft^3), 626.0 kg/m^3 (39.0 lbs/ft^3) and 553.8 kg/m^3 (34.5 lbs/ft^3) target density / unit weight panel groups either in the sliced specimen format as illustrated in Figure 6.13, or the full thickness disc specimen format in Figure 6.14 throughout most of the relative humidity range tested. The lower density specimen did however achieved a slightly higher resultant moisture content for a given relative humidity level. That is, equilibrium moisture content (kg water / kg dry wood mass) is inversely proportional to OSB density (kg dry wood mass / m^3). These results are in agreement with the findings of Wu and Ren (Wu, Ren, 2000). However, Wu and Ren only studied the effect on single-layer, (cold-pressed and then heated to cure) laboratory made OSB panels. They unfortunately had the added complication or processing factor of varying pressing times for each density of panel manufactured (pressing time was not maintained constant as density was varied). In this study, pressing time was maintained constant throughout the study, no matter what the panel density or resin addition.

For the sliced specimens, which density group differs from which depends on the relative humidity. At the first step, the high density specimens have a significantly lower equilibrium moisture content than both the medium and low density groups at the significance level of $\alpha = 0.05$, but there is no statistical difference between the medium and low groups. At the second and third steps, the low density group has a higher equilibrium moisture content than the medium

and high density groups at the significance level of $\alpha = 0.05$, but there is no statistical difference between the medium and high. At the fourth step, only the low and high density groups differ. At the fifth step (not EMC with water vapour), no statistical difference exists among any of the groups. And at the sixth, water soaked step, the low density differs from the medium and high at the significance level of $\alpha = 0.05$, but no statistical difference exists between the medium and high.

With respect to the full thickness disc specimens, differences in equilibrium moisture content depend on the relative humidity. At the first and third relative humidity step, no statistical difference exists. At the second step and fourth steps, only the low and high density groups differ. At the fifth relative humidity step, the high density differs from both the medium and low density groups, but no statistical difference is seen between the low and medium density groups.

Another way of looking at the relationship between density and moisture content is to plot the densities of individual specimens and their corresponding moisture contents (%), as shown in Figures 6.15, 6.16 and 6.17. On all three plots, the relationship seems to be one of a slight decrease in sorbed moisture content with increasing density. That is, there is a slight inverse linear relationship between OSB density and sorbed moisture content at any given relative humidity. This is in general agreement with what is seen in Figures 6.13 and 6.14.

One might at first intuitively have thought that the relationship should have been the other way around, such that the higher the density, the higher the equilibrium moisture content, on the basis that the higher density panels have more wood mass, internal wood surface area and thus sites for moisture to be adsorbed. However as moisture content is measured on a dry mass of OSB basis, [(wet mass – dry mass) / dry mass] x 100%, each group, whether it be the high density / unit weight (689 kg/m^3 / 42.9 lbs/ft^3) group or the low (554 kg/m^3 / 34.5 lbs/ft^3) group, all have the moisture content based on the same mass of OSB. In other

words, because moisture content is measured as mass of water per mass of oven dry wood material, the actual mass of each specimen has been removed from the measure and is not a factor. Thus, the results show that per kg of oven dry material, the lower density material absorbs more moisture than the high density material. This may be again due to lower density specimens having more internal space for capillary water at the higher RH levels.

Besides the differences in density and internal space, there may be other factors which account for some of the differences. Although all variables were kept constant between the different series from species mix to resin content and pressing time, other differences may have arisen during pressing due to density-induced changes to heat and mass transfer. These could involve properties such as the degree of resin cure and ultimate temperatures reached within the mat, resin and wax migration and the vertical density profile to mention a few. Another factor directly related to density is the residual stress, or compression-set achieved during pressing, as it has been shown that wood under compression has a lower hygroscopicity than unstressed wood (Skaar, 1988, Barkas, 1949). This factor could also account for some of the difference between the more highly compressed and densified surface layers and the less compressed core.

The relationships from the best fit curves (lines) (linear regression analysis) are as follows in Table 7.3, for both slice and full thickness disc specimens, with corresponding R^2 values (the data plots can be seen in Figures 6.15, 6.16 and 6.17).

Table 7.3: Linear Regression Analysis Equations for Moisture Content and Density Relationship.

RH Step	Specimen	Equation	R^2 value
1: 2% - 28%	Slice	Y = -0.0037x + 7.94	0.52
	Disc	Y = -0.0026x + 7.64	0.64
2: 29% - 50%	Slice	Y = -0.0028x + 9.15	0.32
	Disc	Y = -0.0035x + 9.95	0.71
3: 53% - 60%	Slice	Y = -0.0044x + 11.85	0.49
	Disc	Y = -0.0028x + 11.23	0.54
4: 64% - 70%	Slice	Y = -0.0025x + 12.93	0.26
	Disc	Y = -0.0041x + 14.19	0.64
5: 75% - 85%	Slice	Y= 0.0003x + 17.69	0.01
	Disc	Y = -0.0086x + 22.95	0.33
6: Saturation	Slice	Y = -0.1314x + 211.79	0.84

Where: y = moisture content (%)
         x = density (kg/m^3)

It should be noted that even though the regression line fit appears to be fairly good, some of the R^2 values are low.   This is because the slopes of the regression lines are low, indicating that the impact or effect of density (x) on permeability (y) is rather low. In other words, density is not a very good predictor of equilibrium moisture content.   In the extreme case as when taking limits in mathematics, if the slope were flat (zero) with a perfectly horizontal regression line, then even if the fit were perfect with every point on the regression line, over a range of density (x) values, density would not be related at all to moisture content, and the R^2 value would be undefined (zero divided by zero).

What is most interesting to note, however, is the change in the slope of the regression line of the full thickness disc specimens at the highest relative humidity step (85% RH), in relation to the other four lines at the lower relative humidity levels. At the lower relative humidities, the slopes, and thus the effects

of density, are much less than at the high humidity step of 85% RH. This relationship is not duplicated in Figure 6.15 for the sliced specimens at the first five RH steps, and this may be due to the effects of cutting the material up into small slices. However, the effect is pronounced in Figure 6.16 where the specimens were soaked in water for 24 hours. What can be seen here again, as mentioned with respect to the points of the sorption isotherms merging in Figure 6.13, is the appearance of capillary water within the OSB specimens. It must be noted however, that this is now absorption of liquid water, and not adsorption. The lower the density, the more space for capillary water, and this is why at the sixth step where the specimens were soaked the effect is most pronounced. The relationship between density and moisture content changes, with the lower density specimens having more free internal space for capillary water to occupy. Thus, the slope of the line changes, and the lower density specimens equilibrate to a higher moisture content.

Volumetric Moisture Content

Another way to look at the relationship is to calculate moisture content on a volumetric basis, which gives an entirely different picture, as illustrated in Figures 7.12 (full thickness OSB disc specimens) and 7.13 (sliced OSB specimens). The "volumetric moisture content" is a measure of mass of water (kg) per unit volume of OSB (m^3), rather than the more traditional gravimetric measure of moisture content as mass of water (kg) per dry mass of OSB (kg).

Full Thickness Disc Volumetric Moisture Content vs. Relative Humidity

Legend:
- 34.5 Dens
- 39.0 Dens
- 42.9 Dens

X-axis: Relative Humidity (%)
Y-axis: Volumetric Moisture Content (kg H2O/m^3 OSB)
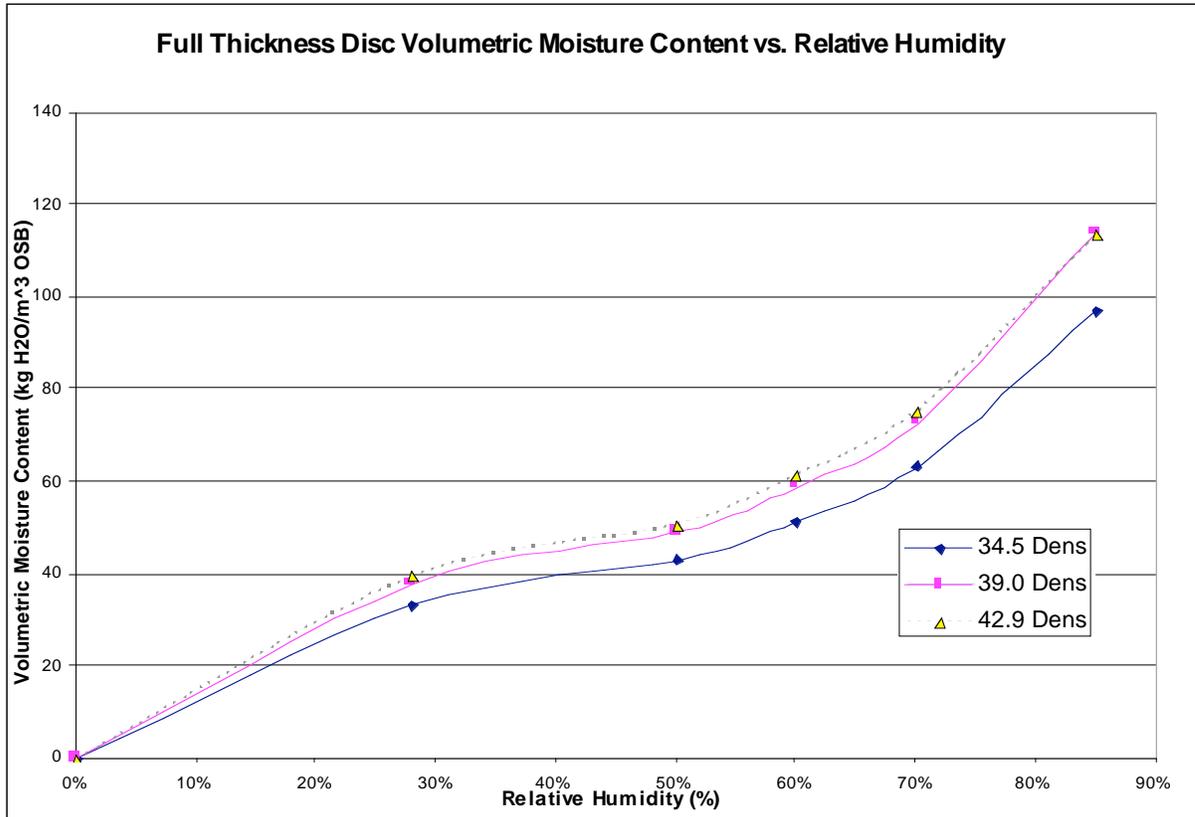
Figure 7.12: Sorption for Different Densities of Full Thickness Disc Specimens, Volumetric Moisture Content Basis, 3-Specimens Each.
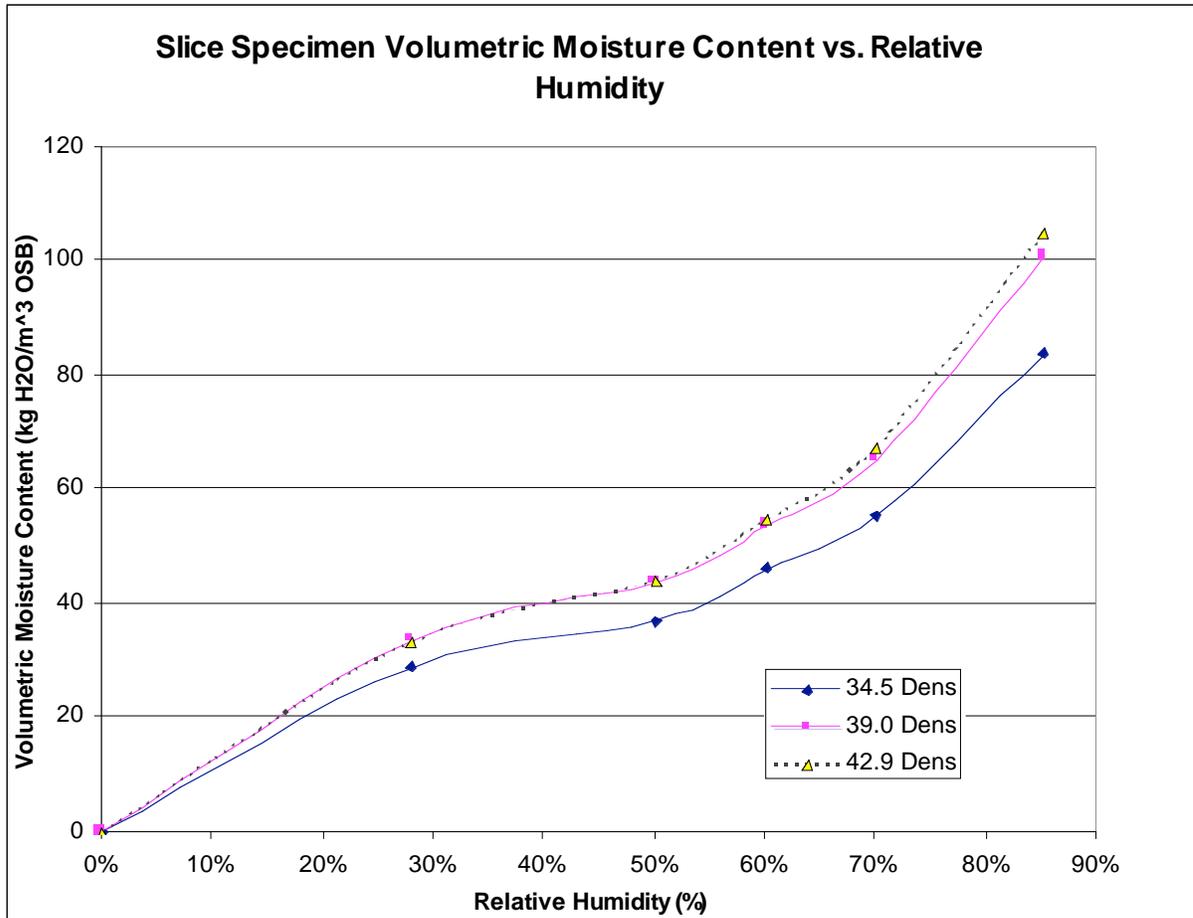
Fig. 7.13: Sorption for Different Densities of Sliced Specimens, on a Volumetric Moisture Content Basis, 10-Specimens Each.

These volumetric sorption isotherms illustrate the mass of sorbed water (kg) per volume of OSB (m^3) at a given relative humidity.

For the full thickness disc specimens, the low density specimen group is lower than the medium and high density groups at the significance level of $\alpha = 0.05$, but the two higher density groups are not significantly different from one another.

The slice specimen sorption curves showed similar results to the full thickness disc results, indicating that from RH steps one through five, the low density group volumetric moisture content again is statistically lower than the medium and high density groups, but no difference exists between the medium and high.

The effect of density on moisture absorption is apparent in these volumetric moisture content analyses. Here, the higher the density of OSB, the more wood mass there is, and thus more internal surface area and sorption sites for storage of adsorbed water. This is illustrated in the relative position of the curves, with the highest density series (42.9 lbs/ft^3) having the highest moisture content, and the lowest density series (34.5 lbs/ft^3) having the lowest.

Volumetric Moisture Content and Volume Correction using Swollen Volume
Figure 7.14 shows the volumetric moisture content of sliced specimens of various densities, extended to include the final step where the specimens were soaked in liquid water designated 100% RH. It must be noted again that this final step is not in the strictest sense a continuation along the same relative humidity range, as it involves soaking in liquid water. Theoretically, if exposure to 100% relative humidity water vapour were achieved, it would approach soaking in liquid water, because in conditions of 100% RH, condensation would occur.
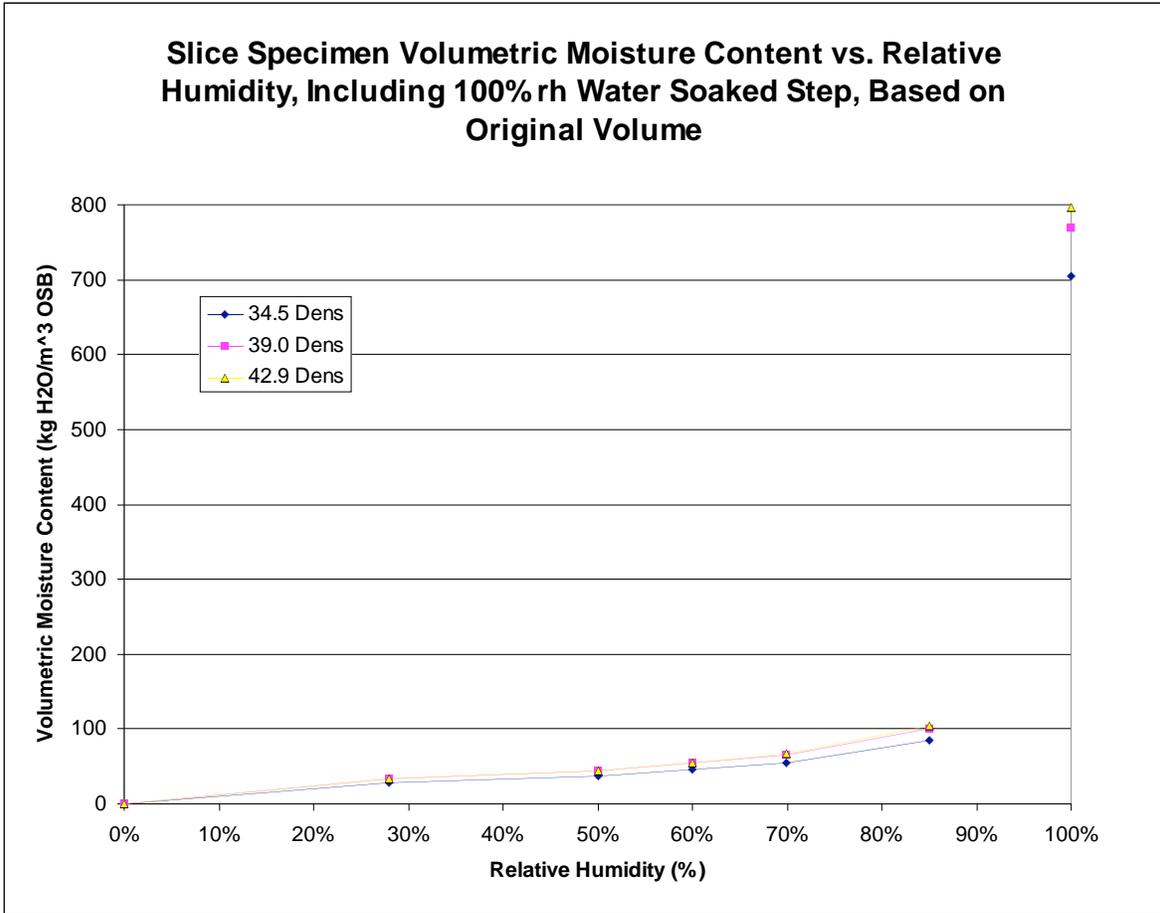
Figure 7.14 : **Slice Specimen Volumetric Moisture Content vs. Relative Humidity Including Water Soaked Step, Based on Original As-received Pre-testing OSB Volumes, 10-Specimens Each.**

However, Figure 7.14 does not show lower density specimens storing more capillary water at the extreme end of the RH scale. This may be because it can not account for the volume changes due to swelling, and instead uses the initial unexposed volume. The higher density specimens swell more than the lower density specimens, as illustrated in Figure 7.2, "Mean bulk densities of full thickness disc permeance test specimens, pre and post permeance testing", Figure 7.10, "Thickness swell of full thickness permeance disc specimens from initial condition to after permeance testing", and Figure 7.15, "Thickness swell of sliced specimens, oven dry to water soaked",
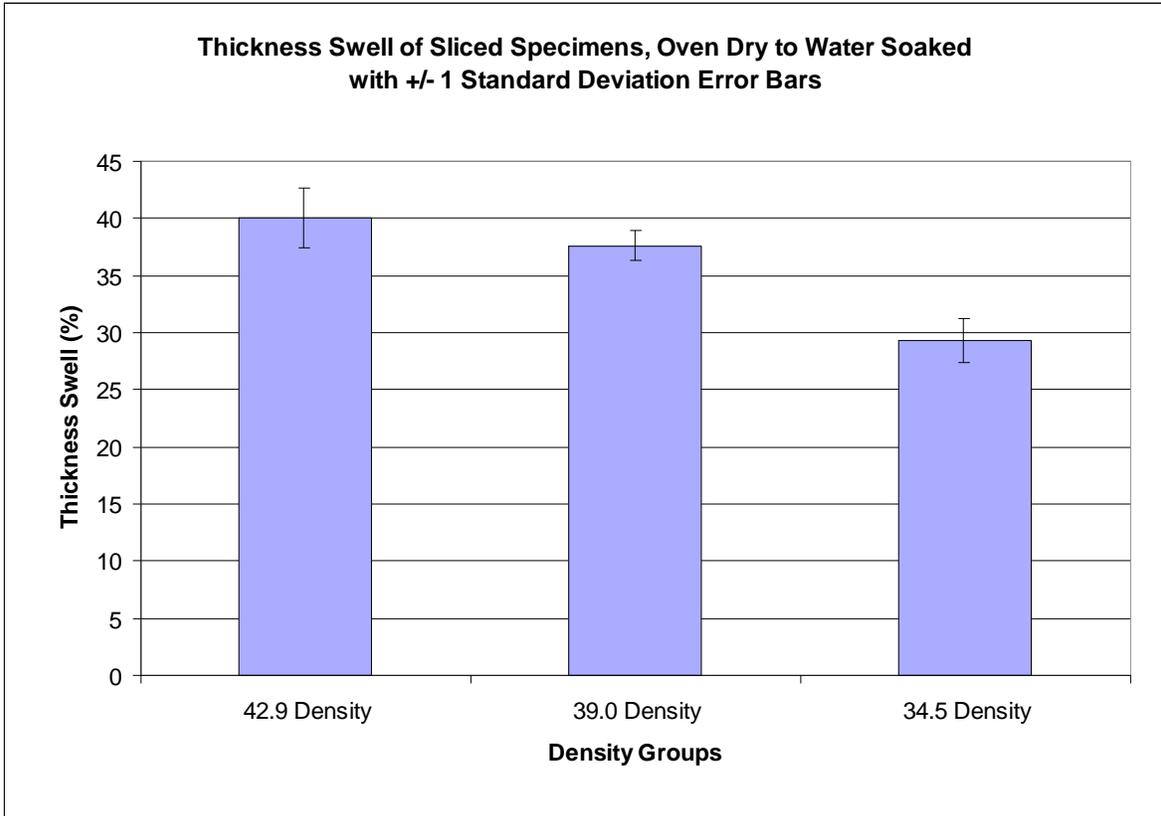
Figure 7.15: Thickness Swell of Sliced Specimens, Oven Dry to Water Soaked.

The approach of correcting the specimen thickness to account for swelling at each different relative humidity step would be another and perhaps more refined methodology for calculating both volumetric moisture content, as well as water vapour permeability. However, as in this study, the most common method is to base measurements on the original un-swollen dry or as-received thickness. Such measurements and their effect would be a good topic for future research.

It should be noted that the thickness swell values in Figure 7.15 are higher than one would expect for larger OSB specimens. This is because standard thickness swell specimens are larger (approximately 150 mm x 150 mm) and are not on the edge, but according to standard tests approximately 25 mm from the edge, which should result in lower thickness swell values for 24 hours of water soaking. The values stated are for the much smaller (5 mm width) sliced specimens, in effect

measured directly on the edge. Larger specimens also do not swell as much due to a size effect whereby water cannot penetrate to the centre as easily, and also the larger size provides cohesive support to the edges reducing their overall swell.

7.2.2 Specimen Size Effect on Sorption

The effect of specimen size on sorption was studied by running concurrent sorption experiments in the same chamber on different sizes of specimens, through the entire relative humidity range, comparing full thickness OSB discs to smaller sliced OSB specimens. The resulting sorption isotherms are plotted in Figures 6.18, 6.19 and 6.20.

Comparison of the full thickness disc specimens to the smaller slice specimens (Figures 6.18, 6.19 and 6.20) shows that in each density case, the larger disc specimens exhibited a higher resultant moisture content for any given relative humidity than did the corresponding sliced specimen. Statistical analysis using an independent sample two-tailed t-test at the significance level of $\alpha = 0.05$ indicates that for the low density / unit weight (554 kg/m^3 / 34.5 lbs/ft^3) comparison of disc vs. slice specimens, the moisture content curves are statistically different for all steps except three. For the medium control (626 kg/m^3 / 39.0 lbs/ft^3) disc vs. slice comparison, the moisture content values are different at all RH steps, and for the high (689 kg/m^3 / 42.9 lbs/ft^3) density / unit weight disc vs. slice comparison, the two sorption curves are statistically different at all RH steps except the fifth. Thus the larger disc specimens with a smaller surface area to volume ratio absorbed more moisture at a given relative humidity than did the smaller, higher surface area to volume ratio slice specimens. At each step, specimens reached equilibrium with the chamber, such that sorption rates should not be a factor.

One might have expected the opposite result, with the smaller specimens equilibriating to a higher moisture content than the larger specimens. This could

have been explained by a larger degree of relaxation of compression stresses in the smaller sliced specimens, due to their larger surface area to volume ratio, or more edge exposed for a given volume. The same effect can be seen when comparing the thickness swell on the flared edges of OSB specimens to the swell in the middle of a specimen. The outermost edges are unsupported by adjacent material, because they are on the edge. This would in turn allow for a greater sorption moisture content at any given relative humidity, as explained in the next section under analysis of the size effect on planer shavings. However, the finding were contrary to what was expected, and further work is needed in this area to verify and explain the results.

Planer shavings

Another specimen size effect experiment was conducted concurrently, again through the entire relative humidity range, comparing sliced specimens to planer shavings (Figures 6.21, 6.22 and 6.23).

In the comparison of the individual layer OSB slice specimens to the corresponding layer planer shaving specimens, the planer shavings exhibited a higher resultant moisture content for any given relative humidity than did the corresponding slice specimen. Statistical analysis using an independent sample two-tailed t-test at the significance level of α = 0.05 indicate that for the top surface slice vs. planer shavings sorption curve comparison, the two are different at all but the fifth RH step. Comparing the core layer slice vs. shavings, the two are different at all five RH steps. For the bottom surface, the slices are statistically different from the shavings at the third through fifth steps. Here the larger slice specimens with a proportionately smaller surface area to volume ratio absorbed less moisture at a given relative humidity than did the smaller, higher surface area to volume ratio planer shaving specimens.

The effect of stress on the equilibrium moisture content (EMC) was discussed by Skaar (Skaar, 1988), and previously by Barkas (Barkas, 1949). They found that

wood with applied compressive stresses exhibited lower EMC values, and the reverse for wood which had experienced tensile stresses. The effect was most pronounced when the stresses had been applied perpendicular to grain, in the direction where the greatest swelling takes place (tangential).

The effect of planing OSB likely has the same effect as described by Skaar. Planing will relieve the compressive stresses locked into the OSB during the manufacturing, when the OSB is densified under heat and pressure. The resin acts like many tiny spot welds, holding the OSB in a compressed state wherever there is a resin droplet. Upon planing, many of the spot welds are broken, and the OSB shavings are able to expand, relieving the built in compressive stresses, revealing OH (hydroxyl) group sites and surface area for sorption, and larger capillary volume for capillary water. The effect of compression set can also be observed without the use of resin, with exposure to just heat and pressure. The compression set may also be reversed or relieved when exposed to water.

The initial objective in analyzing the water vapour sorption of planer shavings as compared to full thickness specimens was to investigate whether the shavings could serve as a means of carrying out a rapid sorption test. The results indicate that the time to reach equilibrium moisture content with the shavings was significantly less, taking approximately 24 hours, as compared to approximately one month for the full thickness discs. When a sorption isotherm is needed over a whole RH range and time is limited, the use of smaller specimens such as the shavings could serve as a viable alternative saving months of time. However, a correction factor may have to be applied to the shaving sorption isotherm, and will depend on the relative humidity and the density of the OSB.

7.2.3 RH Cycled Specimens

The effect of cyclic exposure to elevated relative humidity conditions on sorption moisture content was investigated at room relative humidity conditions of $22^{o}C$ and 48% RH, and compared to the non-RH cycled control series labelled 39.0

Dens on Figure 6.24, "Full Thickness Disc Volumetric Moisture Content vs. Relative Humidity, with RH Cycled Specimens".

The RH cycled specimen series moisture content point falls statistically below the control (39.0 lbs/ft^3 or 626 kg/m^3) series at the α = 0.05 level. Since the RH cycled specimens were prepared from control (39.0 lbs/ft^3 or 626 kg/m^3) material, the effect of RH cycling is demonstrated. Most of the difference is likely due to thickness swelling, and thus a reduction in bulk density, because the moisture content here is on a volumetric basis, with the volume measured after RH-cycling. The volume was also measured after oven drying, but was found to be statistically the same as the post-RH cycling volume.

On the more traditional gravimetric moisture content basis plotted in Figure 6.25, the RH cycled specimen series also lies below the control (39.0 lbs/ft^3 or 626 kg/m^3) series (lower EMC) at the statistically significant level of α = 0.05. In this case the difference is independent of thickness swell, as the moisture content is on a mass basis, and must be explained in terms of changes incurred during relative humidity cycling. The RH-cycling effect which most likely had the greatest impact on sorption moisture content was stress relaxation caused by moisture induced swelling, resulting in the exposure of more surface area and sorption sites to water vapour sorption. The effect of stress relaxation is described in Sections 7.1.5 "Effect of Cyclic Soaking and Drying on Permeability" and 7.1.6 "Effect of Relative Humidity Cycling on Permeability". The resulting implication is that exposure history can have a significant impact on sorption and permeance properties, and that relying on properties determined on virgin material can lead to errors.

7.2.4 Effect of Oven Drying on Sorption Isotherms
The effect of oven drying before beginning the sorption testing was examined by comparison of two sets of slice specimens, cut from the same 39.0 lbs/ft^3 (626 kg/m^3) control panel, where one set was oven-dried at the standard 102°C +/-

1°C temperature for 24 hours, while the other set was not. Both sets were then tested for moisture sorption throughout the entire relative humidity range concurrently.   The resultant sorption isotherm curves are displayed in Figure 6.26.

The results indicate that the oven dried sorption isotherm lies below the non-oven dried. That is, for a given relative humidity, the oven dried specimens exhibited a lower moisture content and thus were not able to hold as much moisture as were the non-oven dried specimens. This is due to the effect of heating on the hydroxyl groups on the wood surface, rendering some of them unavailable for water molecules to bond to. The difference between the oven-dried and not oven-dried control sorption curves was significant at the α=0.05 level at all RH steps except for the third, as found using a paired, independent sample two-tailed t-test.

Skaar (1988) states that some of the reduction in the hygroscopicity of wood due to heating at elevated temperatures is due to the partial decomposition of the wood structure, and specifically the hemicellulose, which is the most hygroscopic component. He also states that this effect is permanent, non-recoverable, and that the magnitude of the effect depends on both the elevation of the temperature and the time for which the specimen was exposed to that elevated temperature. It is also possible that because OSB contains resin and wax and was manufactured under heat and pressure, secondary effects such as flow of wax in the panel could also change the sorption characteristics, but this was not part of the scope of this study. The objective was to find whether or not heating the specimens before testing for moisture-related properties had an effect on the results.

This finding, that there is a significant difference in sorption between oven-dried and non oven-dried specimens, illustrates the importance of not oven-drying wood based test specimens before testing for moisture-related properties where the goal is to apply the results to real world situations. For any study where one

of the goals is to develop OSB material data which can be use for simulations and design decisions for real building systems, it is important that none of the test specimens be oven dried before testing. Specimens in this study were not oven-dried before testing, but rather started at room equilibrium moisture content. Specimens were however oven-dried after testing was complete, in order to determine the dry mass needed for further calculations such as moisture content and bulk density.

7.2.5 Sorption Isotherms for Different Component Layers of OSB

Individual component layers of OSB were prepared from 626 kg/m^3 density (39.0 lbs/ft^3) control full thickness OSB by running full thickness strips through the planer until only the target component layer remained. Sorption test results for the three component layers are displayed in Figure 6.27.

The results indicate that the sorption isotherm for the core component layer lies slightly above both the bottom and top surface layers, throughout the relative humidity range. Statistical analysis by one-way ANOVA indicates that the core layer moisture content through the whole RH range tested is statistically higher than both the top and bottom surface layers, but no significant difference exists between the two surface layers, at $\alpha = 0.05$. At the lower end of the range, below 60% relative humidity, the bottom surface component layer isotherm lies slightly above the top surface component layer isotherm, but above 60% the isotherms cross, and the top surface component layer isotherm lies slightly above the bottom surface layer. In other words, for any given relative humidity, the core layer exhibited the highest resultant moisture content, followed by the two component surface layers.

The sorption characteristics of the individual component OSB layers were also determined using planer shavings, made at the same time as the individual component layers for the slice specimens were being prepared. The results are plotted in Figure 6.28.

The planer shaving results agree with those from the sliced specimens. The sorption isotherm for the core component layer lies above those of both surface layers, throughout the relative humidity range, with the exception of at the high relative humidity range, where the bottom surface layer sorption isotherm just crosses the core isotherm at about 80% relative humidity. At the lower relative humidity range, both the top surface and bottom surface component OSB layer sorption isotherm curves lie very close together, but at the higher relative humidity range at above approximately 60% relative humidity, the bottom surface sorption isotherm rises above the top surface isotherm. A one-way ANOVA statistical analysis with $\alpha = 0.05$ reveals that at RH step one, the core layer planer shavings series has a statistically higher EMC than both the top and bottom surface planer shaving series. At step two and three, no statistical difference is evident. At step four, the core is statistically different from the top surface only, with both surfaces not different from one another. And at RH step 5, the top surface is different from the core and bottom surface, but there is no difference between the core and bottom surface.

The overall conclusion that can be drawn from the plots of both the sliced specimens and the planer shaving specimens of the different component OSB layers, is that the core layer reaches a higher equilibrium moisture content throughout the RH range than either of the surface layers. The exception is in the case of the bottom surface component OSB layer planer shavings at the high relative humidity range, when looked at on a gravimetric mass basis of moisture per mass of oven dry OSB. This may be partly due to the higher resin and wax content in the surface layers as compared to the core, and the higher density of the surface layers. The resin and wax occupy space within the wood structure, occupy OH group sites which might otherwise be available for water molecules to attach to, and bind the wood together, reducing the degree of swelling expansion and thus reducing the ability for water molecules to penetrate the structure of the OSB. And as mentioned, Skaar by experimentation demonstrated the same effect by mechanically restricting wood from swelling, observing that the resultant

sorption moisture content was lower than for matched unrestrained wood (Skaar, 1988). Another possible factor is the fact that both the surface and core layers, being closer to the press platens than the core layer, experience higher temperatures during pressing (see Figure 5.1, plotting matt temperature and gas pressure during pressing), and therefore will have less active sorption sites for water molecules to bind to as explained in the oven-dried vs. non-oven-dried comparison.

7.2.6 Resin Content Effect on Sorption

The effect of the resin alone was studied by examination of the high resin content OSB specimens (called "Resin") in comparison to the control (39.0 lbs/ft^3 or 626 kg/m^3) specimens. Two sets of high resin specimens were studied, the first as sliced specimens shown in Figure 6.29, and the second as full thickness OSB disc specimens in Figure 6.30. In both cases, the high resin content specimen sorption isotherm curves lie above the control group (39.0 lbs/ft^3 at standard wax and resin addition rate) curves.

The exception is with the highest relative humidity point on the disc specimen plot, where the curves cross and the high resin series shows a lower moisture content than the control. This is in the range where capillary water could be present, and perhaps the effect of the resin through reducing swell, excludes some amount of water. Statistical analysis of the slice specimens by independent sample t-test for equality of means at a significance level of $\alpha = 0.05$ revealed that there was a significant difference between the control and high resin sorption moisture content values through all RH steps tested. Analysis of the full thickness disc series by independent sample t-test indicates that at RH steps one, two and five, there is a significant difference between the control and high resin mean sorption moisture content values. At steps three and four, no significant difference was found. Examination of the data on a volumetric moisture content basis was also done, but the results were no different from the mass basis moisture content as presented, as the densities of the resin and

control groups were similar. One would have intuitively expected the opposite effect, as postulated in the discussion of the core vs. surface layers, where the resin may occupy OH sites and internal space, thus reducing the moisture content at any given relative humidity. Perhaps the resin has its own affinity for moisture sorption, but no literature was found to verify or support an explanation at this time. Further work may be needed in this area.

7.2.7 *Comparison of Sorptions of Spruce Plywood, Pine, Western Red Cedar*

Figure 6.31 compares the sorption isotherm of the control 626 kg/m^3 density (39.0 lbs/ft^3) OSB to the high resin OSB, 100% MDI resin OSB, western red cedar, spruce plywood and pine slice specimens. The 100% MDI curve lies at the bottom of the moisture content range, exhibiting the lowest resultant moisture content per given relative humidity throughout the range (with the exception of the very highest relative humidity step. The highest moisture content series vary from red cedar at the low relative humidity range, then pine at the middle range, and finally spruce plywood at the very high end of the relative humidity range. At any given relative humidity point, there is a two to four percent moisture content difference between the lowest and highest sorption isotherm curves.

In general, the moisture content curves for these various wood-based materials all fall within 4% moisture content of one another for any given relative humidity. The solid pine and the spruce plywood specimens are at the top of the moisture content range for any given relative humidity, including the highest range, and consistently above the control OSB and the 100% MDI OSB. One of the reasons for the 100% MDI OSB having a low sorption curve is because the MDI resin binds with OH groups in wood, leaving them no longer available to bond with water molecules. If one were then to use these moisture content curves to predict which materials would first provide conditions capable of supporting the growth of microorganisms, it would appear that based on moisture content, the

solid pine and spruce plywood would first experience growth, before any of the OSB types.

7.2.8 Sorption Analysis Summary

The sorption isotherms, or plots of moisture content vs. relative humidity, both on a traditional mass of water per mass of oven dry material basis as well as on a volumetric basis as kg of water per cubic meter of dry material have been examined for a range of OSB and other wood based materials. Ultimately these curves or relationships indicate how much moisture is stored in the material, in the combined forms of adsorbed water, water vapour and liquid capillary water, once it has equilibrated with the water vapour in the air. The effects of density, resin content and exposure histories, as well comparisons of the various component layers, and comparison of OSB to various other wood materials have been studied. The practical implication is that moisture content can impact the performance of OSB through a multitude of mechanisms, including swelling and shrinkage and the related stresses, water vapour permeability, and the growth of microorganisms such as mould and wood rotting fungi.

Chapter 8

Hygrothermal Modeling Analysis

8.1 Hygrothermal Modeling

In order to put the results of this study into perspective, it is necessary to investigate the impacts of the variations in the studied moisture-related properties (water vapour permeance and sorption) of the OSB types analysed on the moisture-related performance of building components. One approach would be to select a range of climates across this country, then in each climate to select a commonly used wall design and build variants of the design each using OSB sheathing with different moisture properties. Then after a period of time, likely several years, one would disassemble the walls and analyse them for deterioration (mould, rot etc.). Although this procedure would be the most

realistic approach, the drawback is the time involved (years) and the costs involved in building, instrumenting, and monitoring the assemblies or buildings. It is difficult to generalize or apply the results for a given field study to other combinations of climates, both indoor and outdoor, constructions and materials, such that with even the best resources, it would not be possible to cover all of the various combinations (Zarr et al., 1995). Fortunately, tools have been developed in recent years which allow for the simulation of the same experiment via hygrothermal computer modeling.

One such model is called WUFI, which is a Windows-based finite element computer program for modeling one-dimensional simultaneous heat and moisture transport through multi-layered building components. It was developed by Hartwig Kunsel, with the help of Kiessl, Krus and others at the IBP (Fraunhofer-Institut fur Bauphysik). A copy of the software was generously given to the author for the purpose of this study by Dr. Kunzel of the Fraunhofer Institute for Building Physics, in Stuttgart, Germany. The software allows the user to construct a wall, roof or other building enclosure assembly from a library of materials, and then subject it to various climates based on actual weather data. The materials from which the building assemblies are constructed can be either from the materials already in the program material database, or from materials created by the user from material data, such as was done in this study for OSB of different types. The user then selects an exterior climate from real climate data for a series of North American or European cities within the weather database, and an interior climate to act across the building assembly. Numerous other factors are also specified by the user such as orientation, inclination, and height of the assembly, whether it is to be wetted by rain, the absorptivity and emissivity of the surfaces, the duration of the simulation, as well as many other factors pertinent to the simulation. After the simulation for a given wall assembly constructed of specified materials, with specific interior and exterior climates, the results are reviewed and analysed in terms of relative humidities, temperatures, and moisture contents at various locations and points in time specified by the

user within each assembly. In the case of this study, where moisture-related performance and durability are of concern, the results are analysed with respect to conditions which are conducive to mould growth and rot.

For the purposes of this study, the lower limits for the expected onset of mould will be set as 80% RH and temperatures above 10°C for a minimum period of one month. Some recent hygrothermal analysis software programs are combined with a numerical mould growth index, which calculates the numerical index for the likelihood and degree of mould growth under given conditions of relative humidity, temperature and duration of exposure to the conditions, however WUFI does not do this at the time of performing these analyses.

8.2 OSB Materials Data for Modeling

From the results of this study, it was possible to create five new OSB materials in the WUFI material database: low (553.8 kg/m^3 or 34.5 lbs/ft^3), medium (the control) (626.0 kg/m^3 or 39.0 lbs/ft^3), and high (688.6 kg/m^3 or 42.9 lbs/ft^3) density materials, high resin content made at control target density 626.0 kg/m^3 (39.0 lbs/ft^3), and an RH cycled OSB from control 626.0 kg/m^3 (39.0 lbs/ft^3), subject to five cycles from 100% RH to room RH (42%), 24 hours in each environment. Each of these were tested for water vapour sorption and permeance over the full RH range. As the data points for low and high density groups at the highest RH step were not available, but the data were available for the middle density series, these two points were extrapolated based on the equation for the line for the existing data and the shapes of the permeance vs. relative humidity curves, as illustrated in Figure 8.1
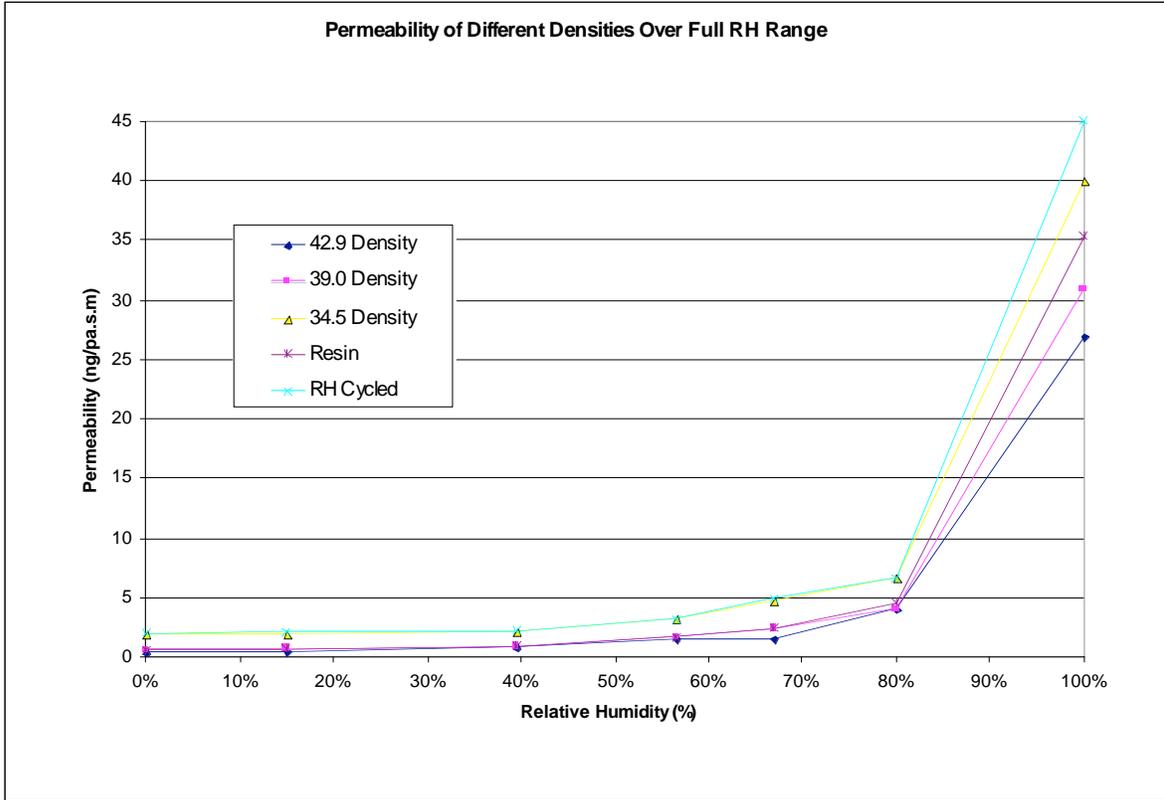
Figure 8.1: Permeability for Three Different Densities over Full RH Range, 100% RH Points Estimated Based on Data, 5-Specimens Each.

In order to create a new material in the WUFI material data base, for hygroscopic materials a sorption isotherm as well as permeability values at several RH levels are needed. Due to the time and experimental space constraints within the chamber, only four full-thickness materials were tested through the full RH range for sorption and permeance testing, which were the 554 kg/m^3 (34.5 lbs/ft^3), 626 kg/m^3 (39.0 lbs/ft^3), and 688.6 kg/m^3 (42.9 lbs/ft^3) density (unit weight) panel groups, and high resin content (at 626 kg/m^3 or 39.0 lbs/ft^3) group. However, numerous permeability investigations were carried out at the middle RH range (50% RH in the chamber to 29% RH in the cup). These results can be extrapolated across the full RH range, for both permeance and sorption, using the relationships developed based on the other OSB types carried through the full range of testing. Permeance values based on specimen density at each RH range were developed by regression analysis (Figure 7.6, Permeability vs. Density for Various Relative Humidity Ranges, and Table 7.1: Permeability vs.

Density regression analysis logarithmic trend lines with calculated R^2 (coefficient of determination) values)).

One such group was the "RH cycled" series, made from 39.0 lbs/ft^3 (626 kg/m^3) control specimens by being subject to 5 cycles from 100% RH to room RH (42%). It was found that at 50% RH (Figure 7.2), the average specimen volumetric moisture content (43.08 kg water/m^3) was within 0.1% of the average 43.00 kg/m^3 moisture content of the 34.5 lbs/ft^3 (554 kg/m^3) full thickness specimen series. Assuming that the general shape of the sorption isotherm is the same for all the other OSB types tested, then one can use the sorption isotherm of the 34.5 lbs/ft^3 (554 kg/m^3) full thickness specimen series to accurately represent the RH cycled full thickness specimen series.

Permeability for the RH cycled full thickness specimen series at the RH gradients not measured was predicted from the specimen density. The predicted permeability at the 50-29% RH step from the equation y=-5.278 Ln(x) + 35.491, (where y is permeability in ng/pa·s·m and x is density in kg/m^3), from the corresponding five specimen average density of 541 kg/m^3 is 2.27 ng/pa.s.m, and the actual measured permeability was 2.12 ng/pa.s.m, (a difference of 6% between measured and predicted).
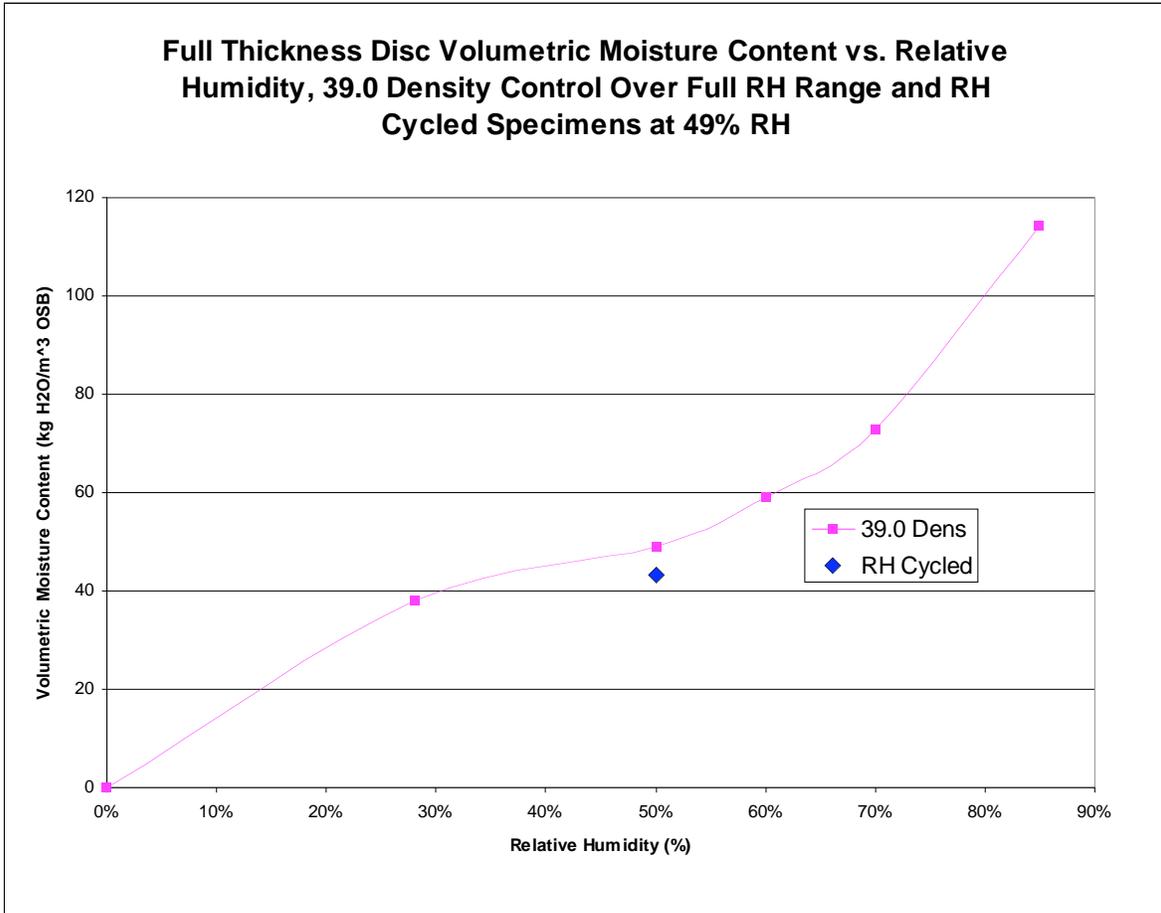
Figure 8.2:   Full Thickness Disc 3-SpecimenSorption Isotherms, Volumetric Moisture Content vs. Relative Humidity, With One RH Cycled 5-Specimen Average Point.

Further work in the area could be conducted to verify the agreement between actual measured permeability and that predicted based on density by the relationship established here for RH cycled specimens (cycled for various numbers of cycles), as well as for water soaked specimens, through the whole RH range.

For the material properties not measured in this study, but needed for completing a material in the WUFI database, the property values were kept the same as for the OSB material supplied in the software. These properties include the thermal conductivity, specific heat capacity, and the liquid transport functions for suction and redistribution.

8.3 Modeling Structure

The last overall objective of this study was to investigate how variation in OSB hygrothermal properties affects the performance of walls through hygrothermal modeling. To this end, three climates were selected form the real weather files available in WUFI. For each climate, two variants of common wall design currently in use in those climates were chosen. And each wall design was tested with four types of OSB, and some with plywood for comparison, to investigate the impact of the OSB type on moisture performance.

The climates selected to provide a wide range of weather were Vancouver, British Columbia, Anchorage, Alaska, and Toronto, Ontario. The two variants of the chosen wall design in each climate were: wall 1, with a polyethylene vapour retarder installed between the gypsum board and the interior stud faces; and wall 2, without a polyethylene vapour retarder. The OSB types tested on each wall type in each climate were: low density 554 kg/m^3 (34.5 lbs/ft^3); high density 689 kg/m^3 (42.9 lbs/ft^3); high resin content at control density, 626 kg/m^3 (39.0 lbs/ft^3); and RH cycled, made from control density 626 kg/m^3 (39.0 lbs/ft^3). A comparison simulation was also conducted with 500 kg/m^3 density plywood in the Anchorage and Toronto climate with both walls 1 and 2. All other simulation factors were kept constant, which included the interior climate (medium), wall orientation (west), building height (short or up to 10 m), simulation duration (3 years, starting January 1), etc. In all, eight or more wall configurations were tested in each of three climates, for a total of 28 simulations. Details of each simulation follow.

Vancouver, BC

The wall selected for simulation in the Vancouver climate is typical of the 1980s and 90s residential construction, and considered to be "energy efficient" (Lstiburek and Straube, 2006). It is a 2 x 6 (38 mm x 140 mm) wood frame wall with fibreglass batt insulation in the stud cavity (R-20 or RSI 3.5 m^2·K /W). Inside sheathing is ½" (12.5mm) gypsum board with one coat primer and one coat latex paint. Outboard of the studs and insulation is 7/16" OSB sheathing, a single

layer of 30 minute building paper, and ¾" (19 mm) of stucco. Version one called "Vancouver wall 1" included a 6 mil polyethylene vapour retarder outboard of the gypsum board (illustrated in Figure 8.3), whereas "Vancouver wall 2" does not.

Anchorage, Alaska

The wall selected for simulation in the Anchorage Alaska climate is an EIFS 2 x 6 stud wall, identical to one modeled by NRC in their study "Application of Hygrothermal Analyses to Optimize Exterior Wall Design", except for the addition of one inch (25.4 mm) to the thickness of the extruded polystyrene (Mukhopadhyaya et.al., 2003). It consists of a 2 x 6 (38 mm x 140 mm) wood frame wall with batt insulation in the stud cavity (R-20 or RSI 3.5 $m^{2.}K$ /W). Inside sheathing is ½" (12.5mm) gypsum board with one coat primer and one coat latex paint. Outboard of the studs and insulation is 7/16" OSB sheathing, one layer of spun bonded polyolefin house wrap, a 1 mm invented air gap, and 2" (50 mm) expanded polystyrene insulation with 5mm of stucco. Version one called "Anchorage wall 1" (illustrated in Figure 8.4) included a 6 mil polyethylene vapour retarder outboard of the gypsum board, whereas "Anchorage wall 2" did not.

Toronto, Ontario

The wall selected for testing in the Toronto climate was the same stucco wall as tested in Vancouver, without any modifications. Version one called "Toronto wall 1" (illustrated in Figure 8.5) included a 6 mil polyethylene vapour retarder outboard of the gypsum board, whereas "Toronto wall 2" did not.
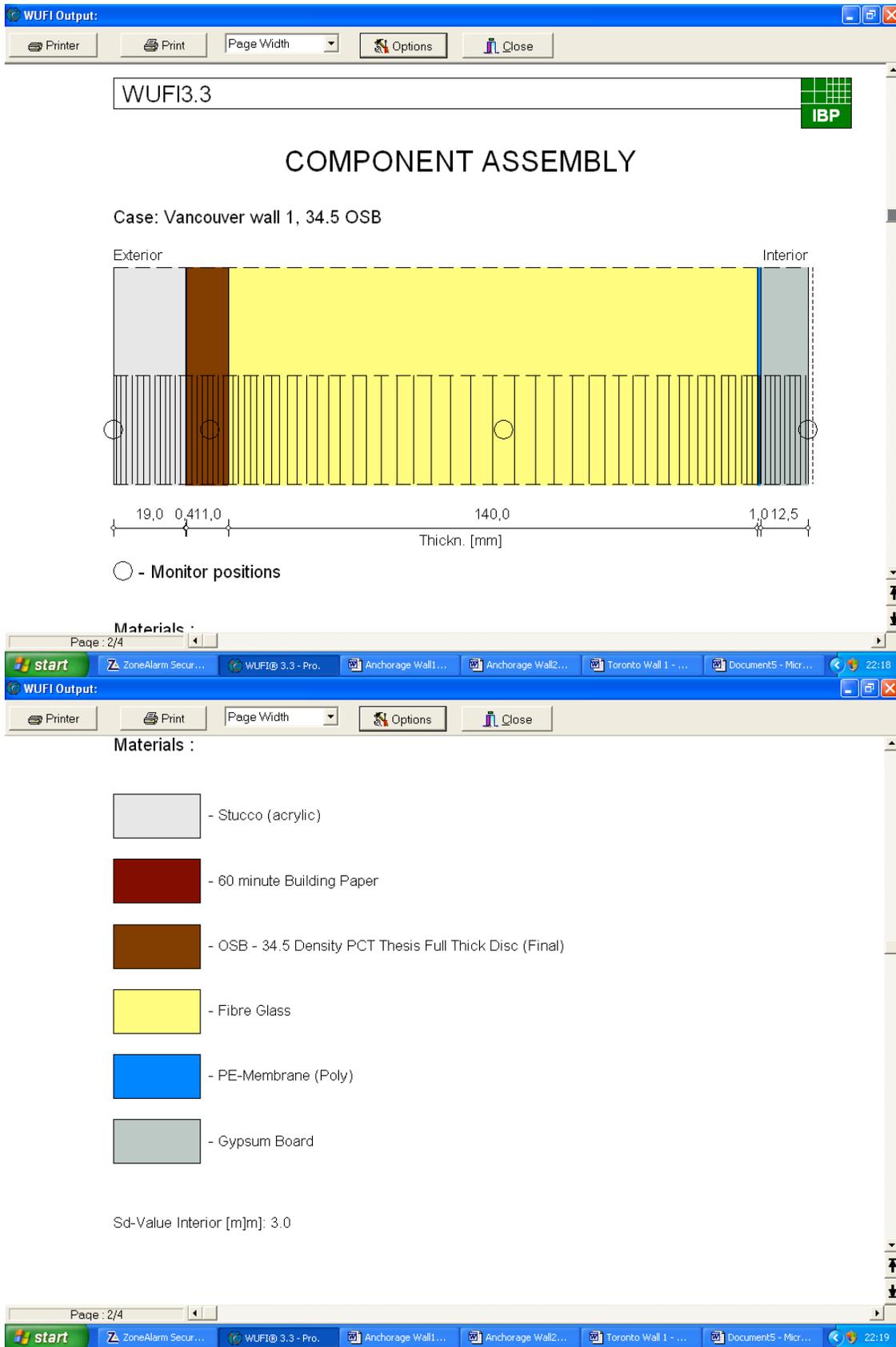
Figure 8.3: Vancouver Wall 1 from WUFI.
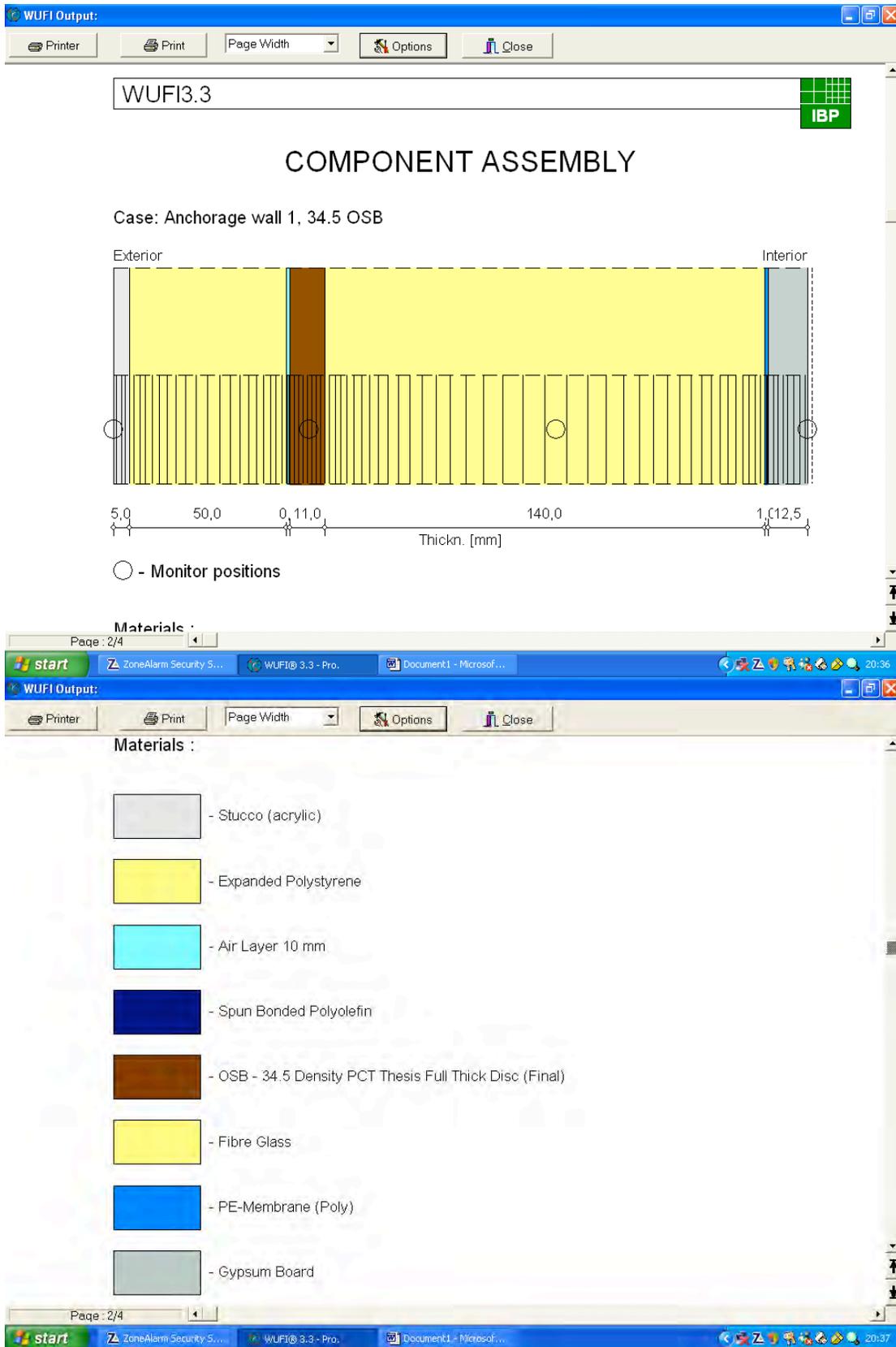
Figure 8.4: Anchorage Wall 1 from WUFI.
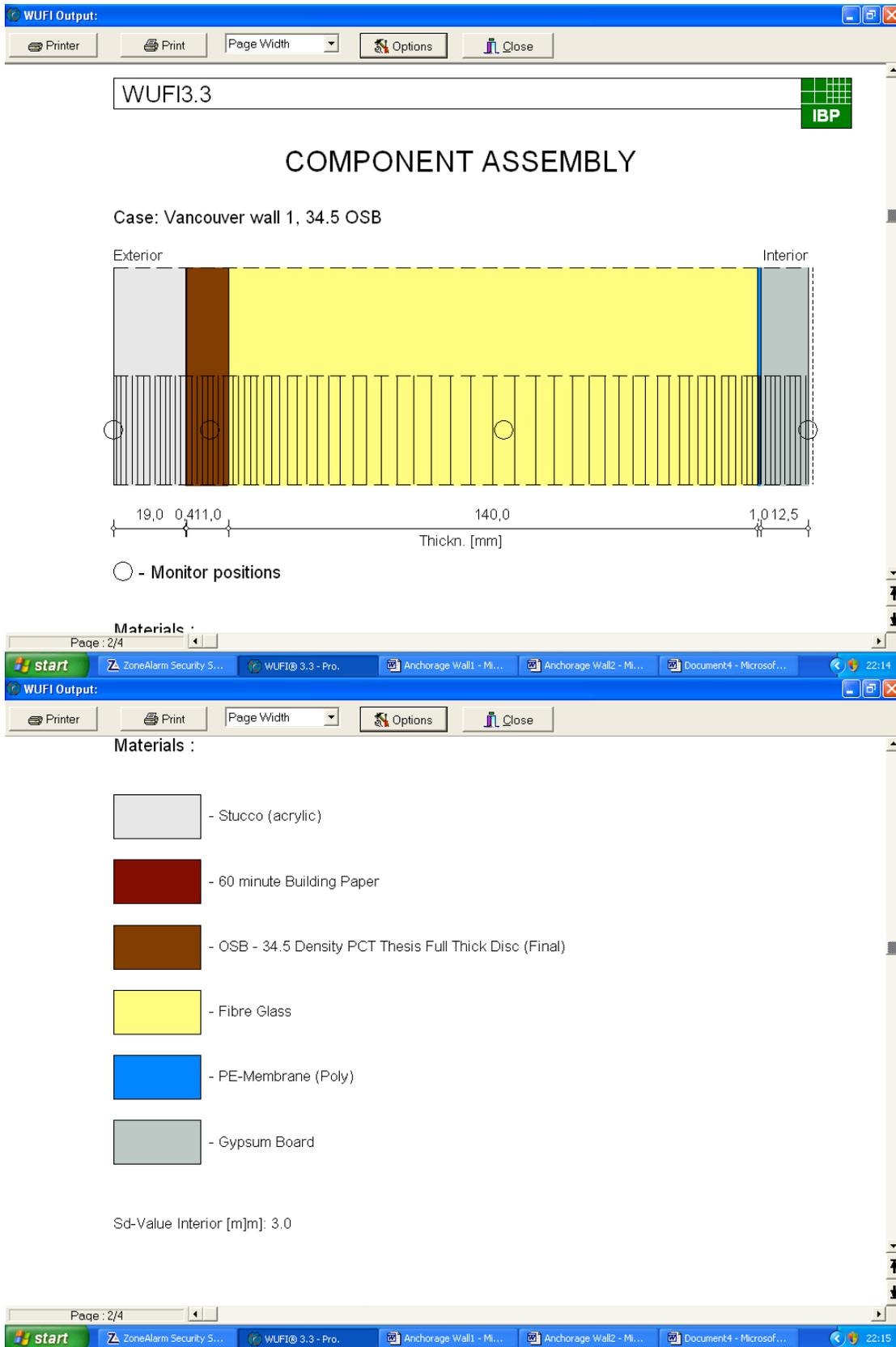
Figure 8.5: Toronto Wall 1 from WUFI.

8.4 Hygrothermal Modeling Results and Discussion

Sample summary graphs from WUFI simulations showing temperatures and relative humidities for the different cases are presented in Appendix B, and the WUFI output files in both WUFI format and ASCII format for all simulations are included on the attached CD.

8.4.1 Vancouver

The Vancouver 2 x 6 wood frame wall with batt insulation and stucco did not perform well with respect to the moisture criteria outlined. The OSB sheathing spends considerable time in conditions conducive to microorganism growth.

There was no observable difference between wall one with the polyethylene vapour retarder and wall two without for any of the OSB types tested. In both wall one and wall two, all of the OSB types reached over 80% relative humidity for seven months of the year, extending from the beginning of November to the end of May, at temperatures ranging from a low of 1°C to a high of about 20°C. The only slight difference observed was that the RH cycled OSB reached a peak relative humidity of 88% in both walls one and two, as compared to a peak relative humidity of 86% for the low 553.8 kg/m^3 density (34.5 lbs/ft^3), high 688.6 kg/m^3 density (42.9 lbs/ft^3), and high resin made at control 626.0 kg/m^3 density (39.0 lbs/ft^3) OSB types.

The observed difference between the OSB types simulated, either with or without a polyethylene vapour retarder are negligible and insignificant. The simulation results indicate that conditions necessary for the growth of microorganisms, mould more probably than wood destroying fungi, would be encountered for an extended period of time each year.

8.4.2 Anchorage

The EIFS wood frame wall simulated in the Anchorage Alaska climate performed relatively well in terms of moisture. None of the results indicate conditions conducive to the growth of microorganisms. The simulation results did however

indicate a difference between wall type 1 with a polyethylene vapour retarder, and wall type 2, without.

For wall type 1, the maximum relative humidity reached in the low density, high density and high resin OSB types was 57%, and 58% in the RH cycled OSB, all well below the threshold of 80%, and at below zero temperatures.

For wall type 2, the maximum relative humidity reached by all four types of OSB was 85% for the period from start of December to the end of April, which are above the 80% threshold. However the temperatures at that time were between 0 and -5, which are too cold for microorganism growth. By the time the temperature in the OSB rose above zero, the walls had dried out to below 80%. The difference between the RH cycled and the other OSB types is not significantly different in terms of any performance criteria.

8.4.3 Anchorage Climate with Plywood

In order to put the performance of the OSB sheathing better into perspective, a comparison simulation was run with plywood instead of OSB for the Anchorage walls 1 and 2. The plywood was selected from the WUFI material database, and had a bulk density of 500 kg/m^3. Wall 1 with plywood performed not much differently than with RH cycled OSB, reaching a maximum RH of 55%, well below the 80% threshold. Wall 2 with plywood however, performed significantly differently than with OSB. It reached much the same relative humidity, with a peak of 87% as compared to 85% with RH cycled OSB. But the critical difference was in the temperatures reached during the period at over the 80% RH threshold, which were from -5 to 12°C with the plywood, and extending half a month longer until mid May, as compared to -5 to 0°C with the OSB. This difference changes the outcome in moisture-related performance, from one with OSB sheathing where the conditions were not suited to microorganism growth, to one where microorganism growth is likely with the plywood.

8.4.4 Toronto

The stucco 2 x 6 wood frame wall simulated in Toronto did not perform much differently than it did in Vancouver. Both walls 1 and 2 reached a maximum RH of 86% with the low density, high density and high resin OSB types, and 88% RH with the RH cycled OSB. A slight difference was that the Toronto walls remained above the critical 80% RH for slightly longer (15 days to one month longer) than the Vancouver walls, but at an average temperature of about 5°C colder. However, the difference in performance is insignificant, as both walls were wet enough, long enough and at temperatures high enough to experience the growth of microorganisms.

8.4.5 Toronto Climate with Plywood

In order to put the performance of the OSB sheathing into perspective, a comparison simulation was run with plywood instead of OSB for the Toronto walls 1 and 2. The plywood was selected from the WUFI material database, and had a bulk density of 500 kg/m^3. Results indicate that the plywood performed almost exactly the same as the RH cycled OSB. Both reached 88% RH for about 8 months in wall 1, and in wall 2 the plywood actually reached 3% higher (to 91%) than the RH cycled OSB, but for the same length of time.

8.4.6 Overall Hygrothermal Simulation Conclusion

The original objective of the hygrothermal modeling simulations with the various types of OSB subject to a range of climates, was to determine whether or not the OSB type had a significant impact on the overall moisture performance of the walls. The only detectable difference between OSB types in relative humidity was between the RH cycled OSB and the other three OSB types. The RH cycled OSB was at most only two percent higher (88% vs. 86%), in the Vancouver and Toronto simulations. These differences are small and most likely insignificant in terms of the moisture-related performance of the walls.

However, when compared to plywood, there was a significant difference in the Anchorage wall 2 performance. The modeling results for wall 2 with OSB indicated that there was no danger of micro organism growth, but when plywood was substituted, the conditions changed and micro organism growth became likely. With respect to the other comparisons, in Anchorage wall 1, and both Vancouver walls, the results showed little detectable difference in moisture performance.

In conclusion, although the results of the limited hygrothermal modeling simulations conducted for this investigation do not seem to indicate any large moisture related wall performance differences with respect to the range of OSB moisture-related properties measured in this study, as applied to the wall types and climates selected for investigation, this does not mean that significant differences do not exist. It simply suggests that further investigations may be necessary with a broader range of wall designs and climates in order to discover where the range of moisture related properties do make critical moisture-related wall performance differences.

Chapter 9

Summary, Conclusions and Recommendations

9. Objectives

The first objective of this study was to investigate the effect of the variation in mill manufacturing parameters within the range for producing marketable panels, as well as post-manufacturing exposure to moisture, on the critical moisture-related properties (water vapour permeance and sorption). The properties of the individual component OSB layers were also investigated.

The second objective was to investigate the effect of the range of OSB moisture-related properties determined experimentally on the performance of selected wall designs subject to Canadian climates, using the data from this study as material data for the hygrothermal software.

Since sorption testing takes a long time (easily over one month for certain specimen sizes for each step), a third objective was to see if shavings of OSB could be used as a faster test to accurately duplicate the results of larger specimens.

9.1 Water Vapour Permeance Conclusions

Water vapour permeance testing was conducted on 19 different specimen groups, to investigate the effects of various manufacturing parameters and exposure conditions, as well as to compare the properties of the different OSB component layers. Some were tested through the whole relative humidity range, while others were tested at the second relative humidity gradient as part of various investigations.   The conclusions based on the effects of the various variables investigated on the water vapour permeance of OSB are as follows:

    i.   The characteristic effect of increased moisture content causing increased permeability in hygroscopic materials was demonstrated, with up to a seven fold increase in permeability found for some OSB types.

    ii.   The higher the density of the OSB material, the lower the permeability, for which regression analysis revealed logarithmic relationships at each of the relative humidity steps.

    iii.   The effect of density on permeability becomes more pronounced at the higher relative humidity steps where capillary water becomes a factor, again with density inversely related to permeability.

iv. Each component layer of OSB demonstrates a different permeability, with the core layer being much more permeable than either surface layer, and the top surface layer being the least permeable of all. The effect is explained in terms of density, resin and wax content, and inherent differences created during pressing, and has implications on controlling the moisture-related properties by manufacturing and surface treatment techniques. The moisture-related properties of individual layers have not previously been reported by others to the knowledge of the author.

v. When independently examined by comparing high resin specimens to control specimens at the same target density, higher resin content did not demonstrate a significant or detectable effect on permeability.

vi. Cyclic wetting and drying produced increases in permeability of 41% after one cycle, 152% after three cycles, and 211% after eight cycles of wetting and drying. The effect is most likely due to the opening of internal OSB structure by the breaking of resin bonds and the relaxation of built-in compression during the pressing during manufacturing under heat and pressure. This has not as of yet been reported by others to the knowledge of the author.

vii. Exposure to only 5 cycles of alternating high relative humidity and room relative humidity caused an increase in permeability of 72%. This also appears not to have been studied by others to the knowledge of the author. How, when and under what conditions the permeability of OSB is determined and characterized is significant..

viii. The sanding of OSB surfaces resulted in significant increases in permeability, as would be predicted from the results of testing the individual component layers of OSB. Thus mill sanded products will perform differently from non-sanded products.   Three-layer spruce plywood was slightly more permeable than the control OSB, and

OSB made with only MDI (methylenediphenyl diisocyanate) resin is about half as permeable as the control OSB.

The water vapour permeability of OSB can vary several fold as a result of variations in all of the different manufacturing parameters at the mill, discussed in detail in Chapter 3. But the most significant finding is the variation as a result of exposure to cycles of wetting and drying, or alternating cycles of high and low relative humidity. It will be emphasized again, that not all OSB performs the same.

The fact that the European Union is in the process of developing a new CEN standard 89 N 336 for permeance and permeability testing based on ISO standards, and that the ASTM E 96 standard is also currently being revised, is somewhat encouraging, as the current ASTM E 96 Standard Test Method for Water Vapour Transmission of Materials has clearly fallen behind the advances of understanding in the field and the needs of the industry. If the changes address the fact that the current standard only allows for testing at two water vapour concentration gradients (dry cup: desiccant to 50% RH, and wet cup: 50% RH to 100% RH), this will be a step in the right direction. However, if the new standards do not address the much larger effects of panel exposure history as illustrated in this study (whether the test panel is virgin, straight from the mill, or has been exposed to any range of moisture from slight RH cycling all the way to having been soaked), then the test results will be of limited use, and a comparison of test results from different sources will be very difficult. As a comparison, in concrete testing standards it is precisely specified whether or not the cylinders to be tested have been cured in the field, or in the laboratory, and whether they are 7-day, 14-day or 28-day old, because it is understood that these variables will have significant impacts on the strength results. It would follow then from the findings of this study, which show that exposing a panel to five cycles of high to low relative humidity can increase the permeability by 1.7 times or 72%, or that soaking the panel only once and then letting it dry can increase

the permeability by 2.4 times or 142%, that if measuring permeability, it would be critical to know the exact exposure history of the panels in question. If international benchmark testing standards are used to measure material properties, which are then in turn referenced by Codes and Specifications to set minimum or maximum values, it is critical to consider and specify the appropriate exposure history for the OSB panels in question. Since the primary role of a test standard is to provide test data for predicting the performance of a material in service, the test specimen should be pre-conditioned to a state as close as possible to that which it will see in service. Thus, a critical improvement to a standard test method for water vapour transmission through materials such as OSB would be to test at perhaps three easily replicated states of conditioning, for example in the virgin as-received from the mill, then after being subject to one cycle of 100% RH to 40% RH or oven dry, and finally after one cycle of soaking in water and drying. The results could then be used to determine an equation and curve for each specific type of material, from which exposures between the three points tested could be interpolated when necessary. The accuracy of hygrothermal modeling programs now commonly used to model the performance of actual wall systems and predict real-life performance such as WUFI or hygIRC would also be vastly increased with such an improvement to the test standards and a more comprehensive material data.

9.2 Water Vapour Sorption Conclusions

Water vapour sorption testing was carried out on 12 specimen types in several specimen formats (full thickness, slice or shavings) over a range of relative humidity conditions. The tests investigated the effects of density, resin content, oven-drying, OSB component layers, and specimen size. The moisture content was calculated both by the more traditional mass basis method, as well as in the volumetric basis. The conclusions based on the effects of the various variables investigated on the sorption and storage of water in OSB are:

i. At the high end of the relative humidity scale, where capillary water becomes a factor, lower density specimens exhibit higher sorption moisture contents than do higher density specimens, both for the sliced and full thickness disc specimen sizes.

ii. At the low end of the relative humidity scale, the effect of density on sorption moisture content is reduced.

iii. On a volumetric bases, the low density groups of both specimen sizes equilibrate at a lower moisture content that the high density and control specimens, reflecting the relationship between surface area for sorption and moisture content.

iv. Investigation of specimen size effect on sorption moisture content gave mixed results; however, the planer shaving specimens equilibrated to a slightly higher moisture content than did the slice specimens, due to the larger surface area exposed and available for sorption.

v. Planer shavings came to equilibrium moisture content in a much shorter period of time than larger specimens, providing a possible fast test method for sorption testing, provided an adjustment factor is used to account for the small difference in moisture content from larger specimens. This has not been studied by others, and could possibly be developed into a measurement standard for sorption testing.

vi. Relative humidity cycling resulted in unrecoverable thickness swell, a reduction in bulk density, and a reduction in moisture content as compared to the control from which they were made, at each relative humidity step.

vii. Oven drying of specimens before testing resulted in a reduction in equilibrium sorption moisture content at each relative humidity step when compared to non-oven dried control specimens. This illustrates the importance of not oven-drying wood-based test specimens before testing for moisture-related properties.

viii. Each component layer of OSB behaves differently. The core layer is lowest density and has a higher sorption moisture content compared to either the top or bottom surface layers. When compared on a standard moisture content basis (mass water / mass oven dry wood), where the effect of density is not a factor, the difference between the layers is due to other factors such as temperature during pressing, resin, and wax. Results are shown both with slice specimens and shavings. The study of component layers has not been studied by others to the knowledge of the author.

ix. The effect of higher resin content was a higher sorption moisture content, both with the sliced and full thickness disc specimens, contrary to what was expected, and no literature was found to verify or support an explanation at this time, so further work may be needed in this area.

x. In comparison to other wood based materials, the control OSB sorption curve lay below those of solid pine and spruce plywood, but above solid red cedar and 100% MDI resin OSB, which had the lowest hygroscopicity.

Overall, statistically significant differences were observed between the different types of OSB manufactured and tested, and between the different component layers of OSB. Relationships between density and sorption moisture content at different relative humidity levels were investigated and equations developed. Whether or not these differences significantly impact the moisture-related performance of OSB panels in actual or simulated wall systems has been investigated in the hygrothermal modeling section of this work.

9.3 Rapid Sorption Test Method Results

The use of different specimen sizes was investigated to determine if a faster test method was possible for water vapour sorption testing. It was found that planer shavings reached equilibrium moisture content in a much shorter period of time than larger specimens. It required close to a month for full thickness OSB discs measuring 91 mm in diameter to reach equilibrium, while the planer shavings required less than 48 hours. The equilibrium moisture content reached was found to be close to the full thickness disc moisture content and slice specimen final moisture content, but not exactly the same. Thus, shavings can provide a possible fast test method for sorption testing, provided an adjustment factor is used to account for the small difference in moisture content from larger specimens.

9.4 Hygrothermal Modeling Conclusions

The overall conclusion from the hygrothermal modeling simulations conducted in this study, with respect to the range of OSB types and corresponding moisture-related properties measured, indicates that further simulations are needed with a broader range of wall types and climates, in order to predict whether or not the specific OSB type used in the construction will significantly affect the moisture-related performance of the walls. It was demonstrated with the Anchorage, Alaska wall 2, where plywood was substituted for the OSB sheathing, caused the wall to change from durable, to non-durable, but the substitution made little effect in the other constructions and climates. There are likely instances where the differences between the hygrothermal properties of the various OSB types tested may indeed make a moisture-related performance difference.

9.5 Future Work / Recommendations

This research project has investigated the effects of a few selected manufacturing parameters, surface treatments, and exposure conditions on the water vapour permeance and sorption of commercially manufactured OSB, as

well as the properties of the individual component OSB layers. The impact of the range of water vapour permeance and sorption properties measured on the performance of walls was also investigated through hygrothermal computer modeling. During the course of the work, the following related areas have been identified as warranting further study:

i. The effect of density variation through the vertical panel thickness on permeability through porosity variation. Higher density means more wood mass per unit volume and lower porosity.

ii. Investigation of the change in permeability and sorption after exposure to a wider range of different relative humidity exposures from very mild exposure up to severe. This in turn can possibly be correlated to changes in thickness due to swelling, which could be measured in the field, ultimately improving the prediction of hygrothermal performance and influencing design.

iii. Investigation of the potential correlation between changes in permeability and changes in sorption resulting from cyclic moisture exposure.

iv. Investigation of the effects of cyclic moisture exposure on sorption and the sorption isotherm.

v. The effects of many of the other manufacturing parameters listed in Chapter three, such as the species mix, pressing temperature, pressing time and exact pressing cycle, will all have a certain effect on the final sorption and permeance properties and have yet to be studied.

vi. Further investigation of the change in permeability due to various degrees of surface sanding based on industry sanding data.

vii. Investigation of the impacts of a wide range of resin and wax addition levels, as well as types, on sorption and permeability.

viii.   Further investigation of the effect of specimen size on water vapour sorption, as the results from this study were somewhat inconclusive.

ix.   The range in moisture exposures commonly experienced by panels after leaving the mill, during transport, distributor storage, job site storage, construction and finally within the building assembly could be investigated in order to predict the possible ultimate changes in permeability and sorption properties.

x.   The data from this study and possibly others could be used to create a predictive model, predicting the permeability and sorption properties of OSB based on various manufacturing variables, surface treatments, as well as history of exposure to moisture after manufacture.

xi.   Hygrothermal simulations of a larger range of wall designs subject to a wider range of climates need to be investigated, both using the OSB moisture-related properties from this study and those of future studies in order to more conclusively investigate the effects of the OSB properties on durability. Such work could be combined with the results from studies such as by the MEWS consortium (Kumaran, M., et al., 2002) or by Lstiburek and Straube (Lstiburek and Straube, 2006) to better prescribe which wall designs are most suitable for given climates.

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Appendix A: Mill Conditions and Testing Results During Panel Manufacturing Trial

Appendix B: WUFI Hygrothermal Modeling Sample Results
Anchorage, Alaska Wall 1

WUFI3.3

IBP

COMPONENT ASSEMBLY

Case: Anchorage wall 1, 34.5 OSB

Exterior   Interior

5,0   50,0   0, 11,0   140,0   1, (12,5

Thickn. [mm]

○ – Monitor positions

Materials :

- Stucco (acrylic)

- Expanded Polystyrene

- Air Layer 10 mm

- Spun Bonded Polyolefin

- OSB – 34.5 Density PCT Thesis Full Thick Disc (Final)

- Fibre Glass

- PE-Membrane (Poly)

- Gypsum Board

WUFI3.3

IBP
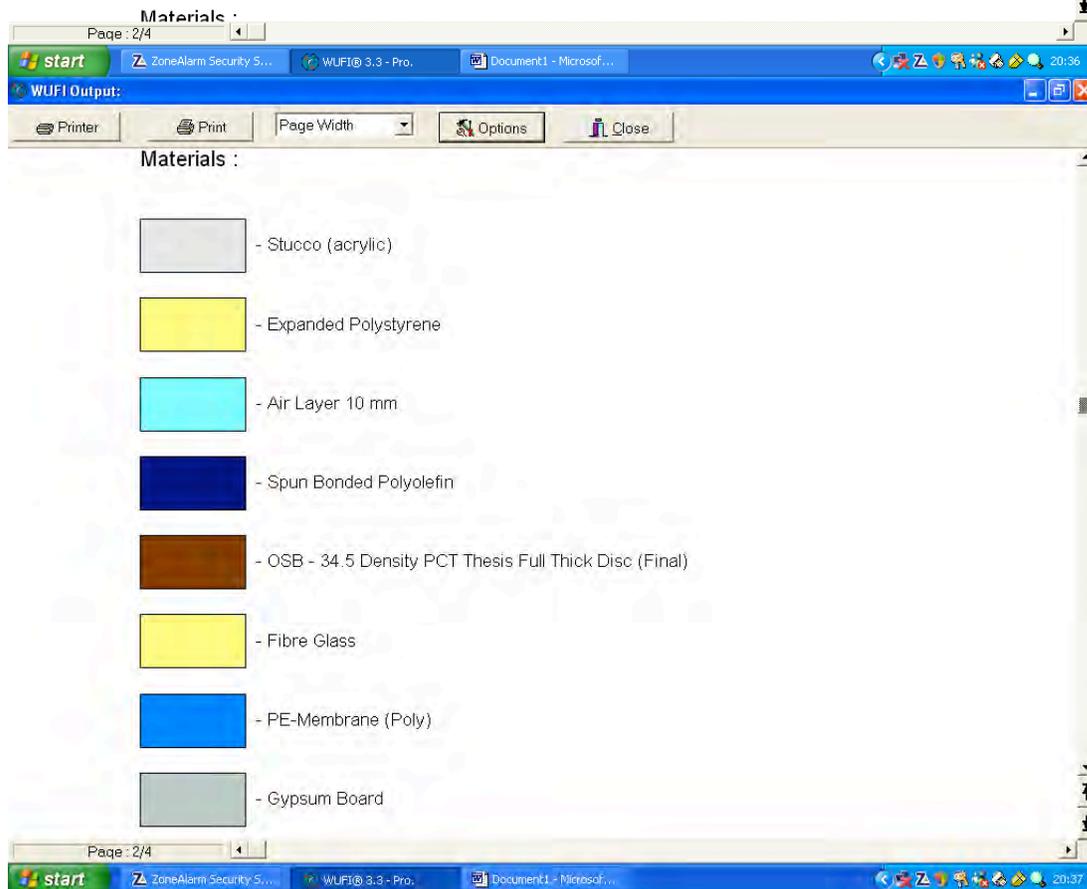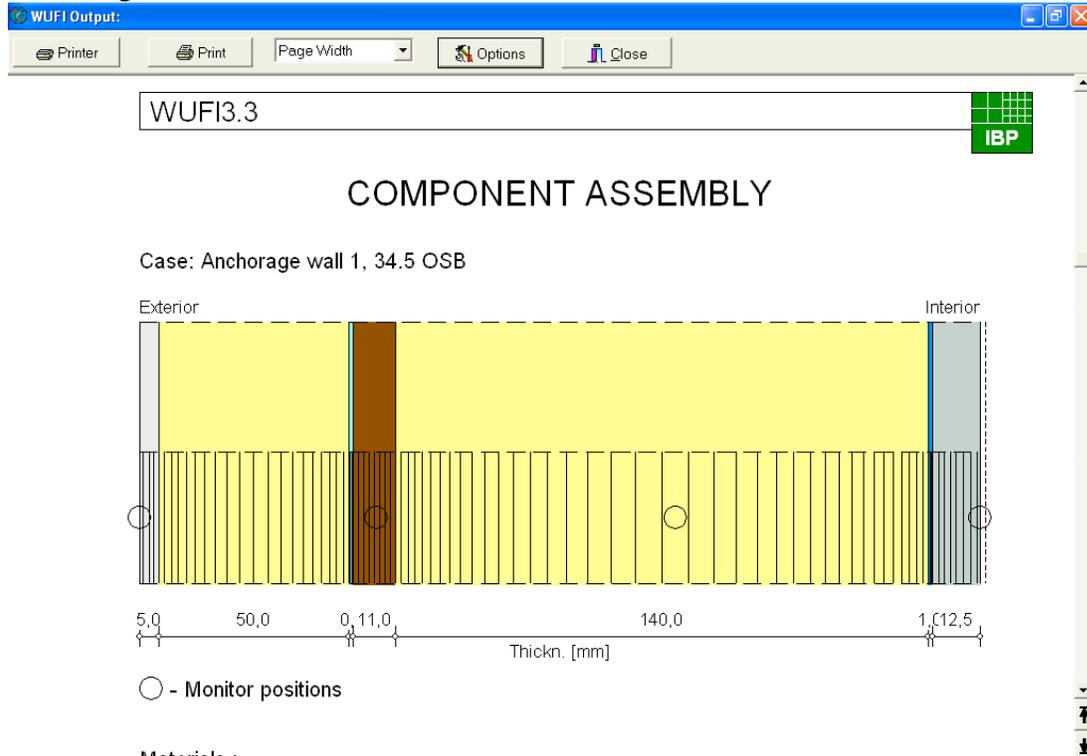
Orientation

Orientation: West

Inclination: 90°

Surface Transfer Coefficients

Exterior

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.056	Outer Wall
Sd-Value	[m]	----	No coating
Short-Wave Radiation Absorptivity	[-]	0.4	Stucco, normal bright
Long-Wave Radiation Emissivity	[-]	0.9	Stucco, normal bright
Rain Water Absorption Factor	[-]	----	According to Inclination and Construction

Interior

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.13	Outer Wall
Sd-Value	[m]	3.0	

WUFI3.3

IBP

Results from Last Calculation

Water Content [kg/m³]

Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Stucco (acrylic)	100,00	110,68	23,35	165,40
Expanded Polystyrene	0,00	1,01	0,00	1,22
Air Layer 10 mm	1,00	0,57	0,11	1,00
Spun Bonded Polyolefin	0,00	0,00	0,00	0,00
OSB - 34.5 Density PCT Thesis Full Thick Dis	25,90	46,43	24,92	48,90
Fibre Glass	0,00	0,24	0,00	0,43
PE-Membrane (Poly)	1,00	1,00	1,00	1,00
Gypsum Board	35,00	29,93	28,94	35,00

Status of Calculation

Simulation: Time and Date	26/06/2007 12:02:49
Computing Time	0 min, 59 sec.
No. of Convergence Failures	0

OSB - 34.5 Density PCT Thesis Full Thick Disc (Fin

Fibre Glass
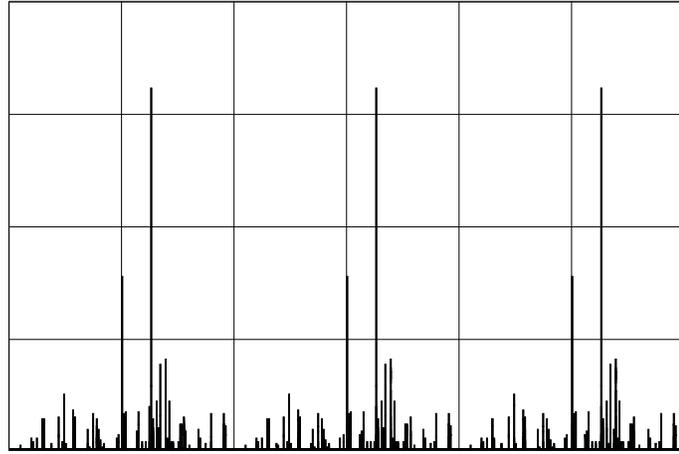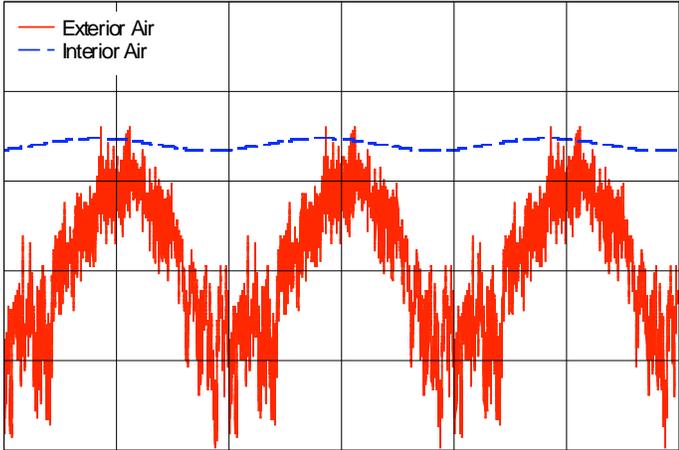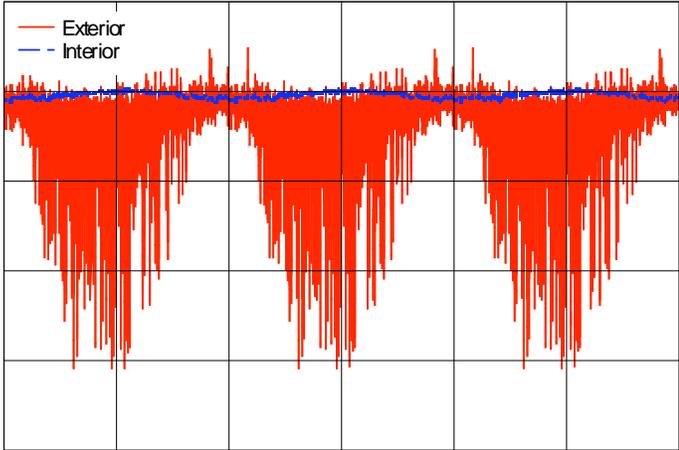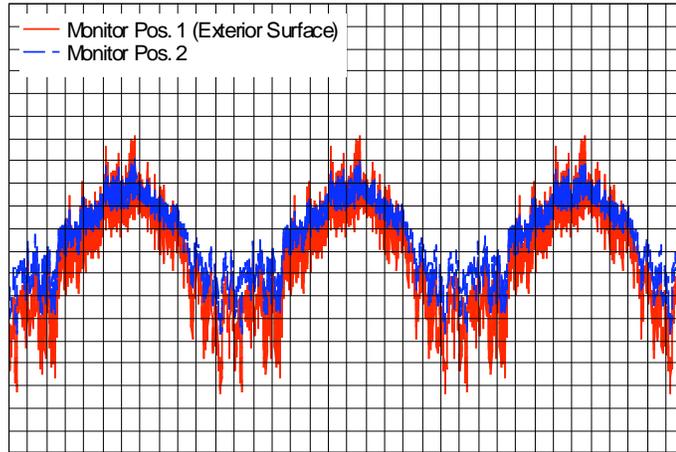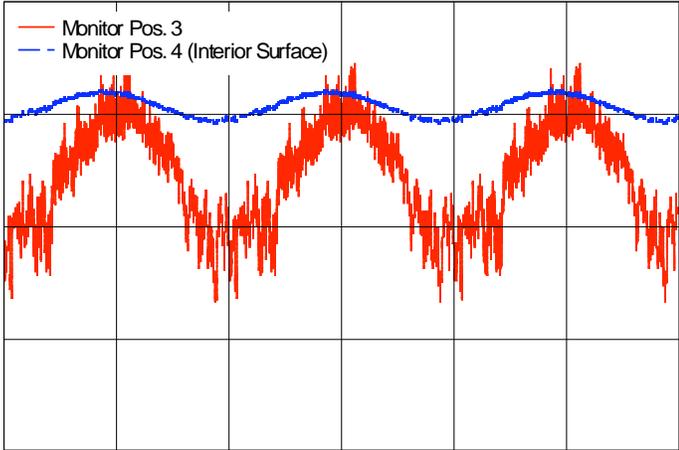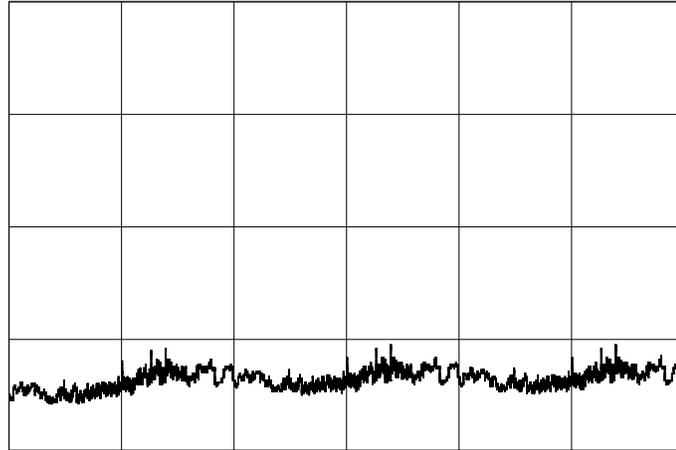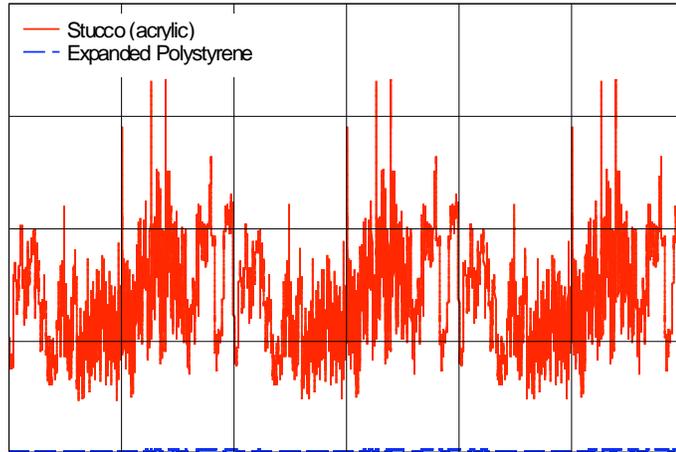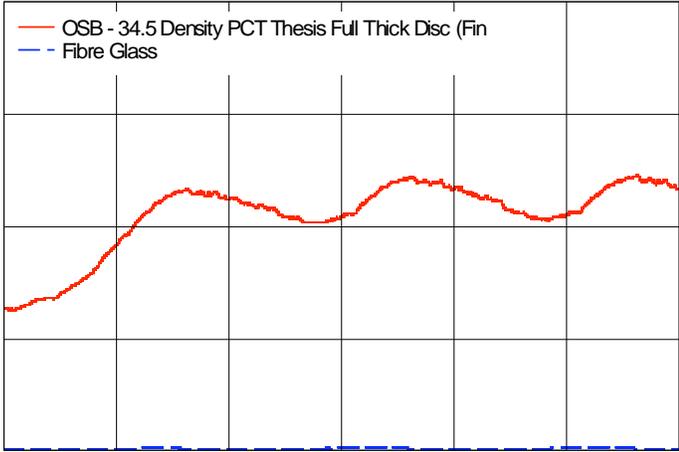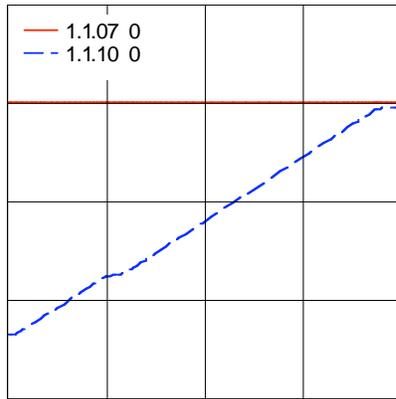
Appendix C: Water Vapour Permeance and Sorption Sample Test Raw Data

| SORPTION SPECIMEN MASS OVER TIME							
Sliced Specimens							
Step #1		**Density Equation:**		y=-0.0037x + 7.9415			
Chamber RH:		28%					
						Normalized	**MC**
39.0 Density Oven-dried before start						**for Density**	**Volumetric**
11-Sep-02	**12-Sep-02**	**13-Sep-02**	**16-Sep-02**	**13-Jan-03**	**MC**	**MC**	**(kg/m^3)**
4.77	4.76	4.76	4.76	4.77	4.84	5.77	28.40
4.68	4.68	4.67	4.67	4.68	5.17	5.83	29.43
4.59	4.59	4.59	4.59	4.59	5.03	5.87	28.15
4.59	4.58	4.58	4.58	4.59	5.28	5.88	29.43
4.80	4.80	4.80	4.80	4.80	4.80	5.77	28.15
4.85	4.84	4.84	4.84	4.84	4.99	5.76	29.43
4.83	4.82	4.83	4.83	4.83	5.23	5.77	30.71
4.58	4.57	4.58	4.58	4.58	5.29	5.86	29.69
4.94	4.93	4.94	4.94	4.94	5.11	5.72	30.71
4.71	4.70	4.71	4.71	4.71	5.13	5.84	29.18
				Mean:	**5.09**	**5.81**	**29.33**
						Normalized	**MC**
39.0 Density start at room EMC						**for Density**	**Volumetric**
					MC	**MC**	**(kg/m^3)**
4.44	4.43	4.43	4.42	4.42	6.25	5.97	33.27
4.66	4.65	4.65	4.65	4.65	6.16	5.87	34.55
4.97	4.95	4.95	4.95	4.95	5.54	5.72	33.27
5.07	5.06	5.06	5.05	5.05	6.09	5.69	37.11
4.66	4.65	4.65	4.64	4.64	5.94	5.87	33.27
4.62	4.61	4.61	4.60	4.60	5.99	5.89	33.27
4.37	4.36	4.36	4.35	4.35	6.10	6.00	31.99
4.96	4.95	4.95	4.94	4.94	5.78	5.73	34.55
4.63	4.62	4.62	4.61	4.61	5.73	5.88	31.99
4.78	4.77	4.77	4.76	4.76	6.01	5.82	34.55
				Mean:	**5.96**	**5.84**	**33.78**
						Normalized	**MC**
34.5 Density						**for Density**	**Volumetric**
					MC	**MC**	**(kg/m^3)**
3.76	3.75	3.75	3.75	3.74	6.25	6.26	28.48
4.11	4.13	4.13	4.13	4.12	5.64	6.07	28.48
4.00	3.98	3.98	3.98	3.98	6.13	6.15	29.78
4.08	4.07	4.07	4.07	4.06	6.28	6.11	31.07
3.72	3.71	3.71	3.71	3.70	6.63	6.28	29.78
4.23	4.22	4.22	4.22	4.21	6.31	6.04	32.37
3.47	3.46	3.46	3.46	3.45	6.15	6.37	26.13
3.65	3.64	3.64	3.64	3.63	6.14	6.29	27.43
3.64	3.63	3.63	3.63	3.63	6.14	6.29	27.43
4.02	4.01	4.01	4.01	4.00	6.10	6.12	30.04
				Mean:	**6.18**	**6.20**	**29.10**

PERMEANCE TESTING RAW DATA

STEP #1 STARTED JULY 6, 2002

CaCL2 Run 1

Full thickness permeance discs

CaCL2 in Chamber, Dessicant in Cup

			RH 25C	Actual RH
Chamber	CaCL2		29.00%	28.00%
Cup	Dessicant		2.00%	2.00%
Gradient				**26.00%**

Specimen Mass with Time

	Jul-06	Jul-15	Jul-24	Jul-26	Jul-27	Jul-30	Aug-08
	12:00	12:00	13:30	15:30	13:00	13:00	16:30
	0	**216**	**433.5**	**483.5**	**505**	**577**	**796.5**

…. Resin

1	337.41	337.30	337.54	337.58	337.60	337.70	338.01
2	339.41	339.43	339.88	339.95	339.99	340.15	340.62
3	335.28	335.18	335.31	335.35	335.37	335.43	335.63
4	329.67	329.58	329.71	329.73	329.76	329.80	330.00
5	321.18	321.19	321.57	321.65	321.69	321.81	322.24

… 42.9 Density

1	365.48	365.34	365.37	365.37	365.36	365.40	365.52
2	349.40	349.33	349.61	349.68	349.73	349.81	350.19
3	362.54	362.38	362.41	362.42	362.44	362.45	362.57
4	347.32	347.20	347.46	347.53	347.57	347.64	348.00
5	349.41	349.22	349.32	349.34	349.36	349.41	349.63

.. 39.0 Density

1	347.08	347.06	347.40	347.49	347.52	347.64	348.07
2	349.27	349.09	349.22	349.25	349.27	349.33	349.58
3	354.30	354.16	354.34	354.41	354.43	354.52	354.81
4	345.93	345.77	345.87	345.89	345.91	345.99	346.18
5	355.50	355.35	355.54	355.60	355.63	355.73	356.03

. 34.5 Density

|							
1	348.49	348.63	349.30	349.45	349.54	349.77	350.48
2	335.83	336.36	337.36	337.57	337.69	338.02	339.05
3	338.11	338.42	339.18	339.36	339.44	339.70	340.47
4	335.60	335.99	336.87	337.08	337.17	337.45	338.35
5	342.39	342.61	343.24	343.38	343.44	343.67	344.34

Appendix D: Constants and Formulas for Permeability Prediction and Figures 7.8 and 7.9

From Equations of Figure 7.7

Density	A	B	C
500	0.0016	-0.0759	3.25
600	0.0013	-0.0586	2.21
700	0.0009	-0.0413	1.17

"A" vs. 1/DENSITY

$y = -1365x^2 + 5.905x - 0.0048$
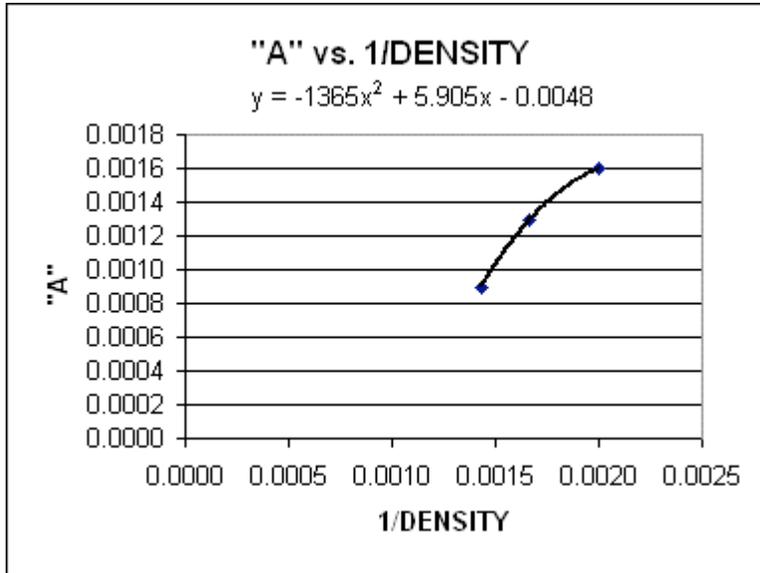
1/density	A
0.00200	0.0016
0.001667	0.0013
0.001429	0.0009

"B" vs. 1/DENSITY

$y = 36330x^2 - 185.11x + 0.149$
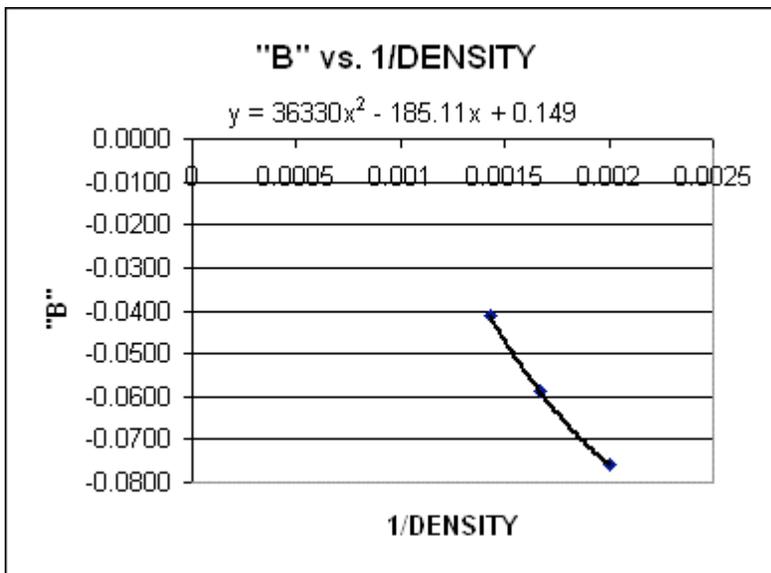
1/density	B
0.002	-0.0759
0.001667	-0.0586
0.001429	-0.0413

-0.0759

"C" vs. 1/DENSITY

$y = -2E+06x^2 + 11128x - 10.27$
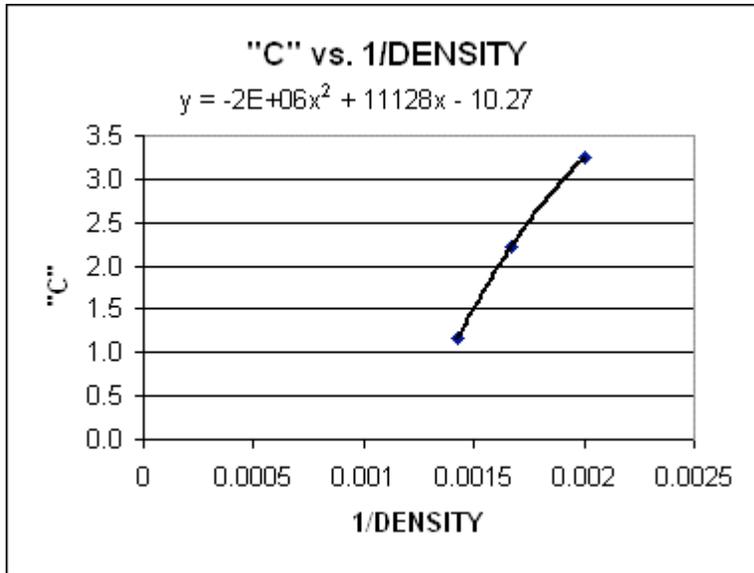
1/density	C
0.002	3.25
0.001667	2.21
0.001429	1.17

y=ax^2+bx+c

Parameter	y	a	b	c	Density?
A	0.000952	-1365	5.905	-0.0048	675
B	-0.0455	36330	-185.11	0.149	
C	1.424705	-2183000	11128	-10.27	

Permeability calculator:
Form y = Ax^2 +Bx +C where y is the permeability, and X is the average
specimen RH, Range 20% to 80% RH

Enter:	Density	AVG RH		Pemeability	
	675	80		3.88	

Model Data at Two Densities

	PERMEABILITY	
RH (%)	536.7 kg/m^3	675 kg/m^3
20	2.07	0.90
30	2.11	0.92
40	2.43	1.13
50	3.05	1.53
60	3.96	2.12
70	5.17	2.91
80	6.67	3.88

Actual Data for Comparison at Same Two Densities

	Avg. 2 pts	Avg. 2 pts
RH	537kg/m^3	675kg/m^3
15	2.12	0.79
39.95	2.37	1.05
57.5	3.35	1.86
67	5.16	2.28
80	7.03	4.42

Appendix E: Wet cup and inverted wet cup permeabilities

Wet and Inverted Wet Cup Permeability

Legend:
- Inverted Top Sfc Up
- Inverted Top Sfc Down
- Wet Cup

Y-axis: Permeability (ng/pa.s.m)