CHARACTERIZATION OF THE HYGROTHERMAL PROPERTIES OF WOOD FIBRE INSULATION BOARD

by

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B.Sc. in Civil Engineering, University of Alberta, 2011

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ABSTRACT

High thermal resistance building envelopes comprising wood fibre insulation board (WFIB) contribute to a reduction in building energy consumption associated with unwanted heat losses and gains. The long-term performance and durability of the WFIB material may perform differently than expected due to the temperature and moisture dependent material characteristics, including moisture sorption, vapour permeance, and thermal conductivity.

This research investigated the characterization of hygrothermal properties of WFIB at temperatures and relative humidities expected for a Canadian climate. The hygrothermal characteristics of WFIB were determined to have a range of values as a result of the variable nature of wood fibre materials with temperature and moisture, and the variability of WFIB materials amongst manufactured products. The variabilities of these hygrothermal properties are expected to impact the materials overall moisture storage at various in-situ temperature and relative humidity conditions, and the materials ability to transport moisture at various in-situ temperature and relative humidity conditions. Additionally, the thermal performance of WFIB is expected to vary with in-situ temperature and relative humidity conditions, with increased thermal losses/gains with increasing temperature and increasing relative humidities.

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1 Introduction

Buildings account for approximately 28% of Canadas energy consumption (2015), with residential buildings and commercial/institutional buildings comprising 17% and 11%, respectively (Natural Resources Canada, 2017). Residential buildings account for approximately 13% of Canadas greenhouse gas emissions (2015) (National Resources Canada, 2017). For residential buildings, 55% of the total energy consumption is for space heating. Concerns regarding energy use and climate change have led to an increase in the efficiency of buildings through the implementation of high thermally resistant and air tight building materials, as a result of both consumer demand and building energy requirement changes from government. Changes in building energy requirements from a municipal, provincial, and national level have been introduced in an effort to reduce building energy consumption, particularly associated with space heating energy demand. The National Energy Code for Buildings 2015 introduced maximum thermal transmittance values, and thus minimum thermal resistance values, for building envelopes categorized by the number of heating degree days. Therefore, high envelope thermal resistance through increased cavity insulation and/or increased continuous exterior insulation may be necessary to obtain compliance with building energy standards. Additionally, highly thermally resistant wall assemblies serve as a cost-effective solution for reducing building heating and cooling loads, as the material costs associated with additional thermal insulation have become increasingly economical due to escalating energy costs.

The development and application of bio-based insulation materials has grown due to increased public demand for renewable building materials with lower embodied energy relative to insulation alternatives such as expanded polystyrene and extruded polystyrene. Wood fibre insulation (WFIB) is a bio-based insulation material produced from the wood chip and shaving remnants from lumber production, and currently serves as an insulation alternative throughout Europe. WFIB manufacturing within Canada is limited, though recent studies have indicated the significant market potential for WFIB in Canada. However, it is important to consider the suitability of WFIB for use in building envelopes for a Canadian climate to ensure the long-term performance and durability of the material and the design.

The building assembly design and the hygrothermal properties associated with the selected materials are critical for determining the longevity of the building envelope, particularly for assemblies comprised of hygroscopic materials such as WFIB. If moisture within the building assembly is significant and drying is insufficient, the moisture may result in mold, material deterioration, and/or corrosion, potentially impacting indoor air quality, energy performance, and durability. However, depending on the hygrothermal properties of the materials and the quantity and duration of wetting, the performance of the building envelope materials may not be compromised due to cyclic wetting and drying of the materials. Computer software capable of calculating hygrothermal numerical simulations have been developed to predict the temperature and moisture levels in building assembly materials over time, though reliable in-situ experimental data is necessary to validate the accuracy of the simulations. Furthermore, the computer software numerical calculations rely upon material specific hygrothermal properties validated through accurate experimental data obtained through laboratory analysis. Experimentally validated material characteristic data required for accurate hygrothermal numerical simulations includes density, temperature and moisture dependent thermal conductivity, water vapour permeability, and moisture sorption-desorption isotherms. Accurate characterization of these building material properties is necessary to ensure that building assemblies are analyzed and subsequently designed to manage moisture adequately for the design climate.

1.1 Necessity for this Research

Understanding the material characteristics of thermal insulations in building envelopes is important for ensuring the longevity and performance of the control layer materials and the enclosure as a multi-layer composite assembly. WFIB is a hygroscopic material with limited research on its hygrothermal properties, particularly for the variety of products available within the category of dry process WFIB with additives of polyurethane, PMDI, and paraffin. Specifically, the effect of temperature on water vapour sorption, and the effect of moisture and temperature of vapour permeability and thermal conductively, for WFIB materials is lacking. Furthermore, further research is needed regarding the variability of WFIB hygrothermal properties within a single product and amongst the available thicknesses of a single product.

Characterizing these hygrothermal properties of commercially available WFIB will provide designers with information that can be used to optimize designs for specific climates and to best avoid moisture related issues, such as decrease in material performance or degradation due to mould and rot. Validated WFIB hygrothermal property data may be used in combined heat and moisture simulation tools to determine the long-term performance of WFIB materials for a specific climate.

1.1.1 Water Vapour Sorption Isotherms

Sorption isotherms reflect the moisture content of a material for a given relative humidity at a given temperature. This sorption isotherm reflects the combined affect of adsorption and absorption, capturing the total amount of moisture stored within the material. The moisture storage characteristics of a building assembly material are important to understand as the moisture content often impacts other material characteristics, such as vapour permeance and thermal conductivity. Additionally, the storage of high quantities of moisture within certain materials is associated with mould and fungi, potentially impacting the long-term durability of the material and assembly it is part of.

1.1.2 Water Vapour Permeance

Water vapour permeance refers to the rate of water vapour transmission through a material given a relative humidity gradient across the material. The water vapour permeance is a measure of all forms of water vapour transport mechanisms for the temperature and moisture content of the material, including vapour diffusion, surface diffusion, and capillary flow. It is important to understand the ability of moisture to transport through a material, the mechanisms of moisture transport, and to determine how the material will perform in an envelope assembly with a relative humidity gradient.

1.1.3 Thermal Conductivity

Thermal conductivity is the measure of heat transfer through a material by direct molecular contact. It is important to understand the performance of a building insulation materials thermal performance at a variety of temperatures and moisture contents to determine the insulation materials applicability for the expected temperatures and moisture scenarios the insulation material may experience throughout its service life for a specific climate.

1.2 Rational for Approach

Past research on the characterization of the hygrothermal properties of WFIB have studied water vapour sorption isotherms, water vapour permeability, and/or temperature and moisture dependent thermal conductivity. Previous research has not focused on the testing of a group of WFIB products manufactured through the dry process within a small range of densities, and the relationship of the moisture storage, moisture transport, and thermal conductivity performance of the materials. Additionally, research is needed to characterize the temperature dependence of the moisture storage, moisture transport, and thermal conductivity performance of WFIB products

1.3 Research Objective

The objective of this research is to quantify the hygrothermal characteristics of commercially available WFIB products through laboratory experiments. For this study, hygrothermal properties include temperature dependent sorption isotherms, temperature and moisture dependent vapour permeance, and temperature and moisture dependent thermal conductivity. The materials will be analyzed by studying the variability of material characteristics within a single product, variability of material characteristics amongst numerous products, variability of material across a range of thicknesses, and the variability of material characteristics with temperature.

The purpose of this research is to be able to provide data that may be used to better understand WFIB hygrothermal performance in Canadian climates. This research will add to the literature focusing on WFIB characteristics, and testing techniques for temperature dependent sorption isotherms, temperature and moisture dependent vapour permeance, and temperature and moisture dependent thermal conductivity.

1.4 Research Questions

The following research questions have been developed to support the objectives of this research:

1) What is the variability of common commercially available WFIB hygrothermal properties at temperatures representative of those in service for Canadian climates?
2) What is the variability of WFIB hygrothermal properties:
    a) Within a manufactured material?
    b) Within a manufactured material of differing thicknesses?
    c) Amongst differing manufacturers of similar materials (declared density range 110-180 kg/m^3)?

2 Literature Review

2.1 Wood

Wood is a naturally occurring renewable material that is widely used in the building industry throughout the world. Wood material characteristics vary considerably amongst different species and within the same species, depending on a variety of circumstances including geographical location during growth, environmental conditions during growth, and location of wood within the tree. The properties of wood materials are derived from the wood cell structure and composition. These properties include density, sorption, vapour permeability, fibre swelling and shrinkage, stiffness, tensile strength, and durability. For additional details regarding the wood growth and cellular and physical structure refer to Appendix A.

2.2 Wood Fibre Insulation

WFIB is an exterior rigid insulation that is primarily manufactured throughout Europe, with several manufacturers throughout North America producing higher density products. WFIB is a bio-based material that is manufactured from the wood chip by-products from raw timber. Building code changes requiring higher thermal insulation values has led to an increased demand for exterior insulations throughout Canada. Additionally, social awareness of building materials from non-renewable resources and the associated affect on global warming has increased interest in building materials that are renewable and biodegradable. WFIB is an exterior insulation that is also renewable, biodegradable, and has the added benefit of carbon sequestration, which has led to an increased interest in and use of WFIB in building construction throughout Europe and Canada.

The history of wood as an insulation materials in buildings dates back to early 20th century when wood shavings and dust were used as insulation products (Bozsaky, 2011). In 1908, the Heraklith Company in Austria came up with the idea of creating insulation panels from wood and adhesives, and magnesite. The early 1900 insulation panels had several disadvantages, including flammability and dimensional instability. The use of cellulose insulations began to appear in the 1920s in Scandinavia using forestry by-products in the manufacturing process. The manufacturing of WFIB through wet process manufacturing dates back to the 1930s in Germany, with the introduction of the dry process manufacturing system in 2004.

In general, there are two manufacturing processes for WFIB, the wet-process and the dry-process. The wet process consists of heating the wood chips using steam pressure followed by defibration of the wood chips. A fibre paste is formed by mixing the wood fibres with water and additives. The fibre paste is then formed into boards through pressing and cutting, and then dried. WFIB manufactured through the wet process has a density range of 160-350 kg/m^3, with a maximum thickness of 25mm. Thicker WFIB products manufactured from the wet process are produced through the stacking and gluing several layers of WFIB.

Similar to the wet process, the dry process consists of heating the wood chips using steam pressure followed by defibration of the wood chips. The fibres are then dried in a cyclone dryer, followed by the addition of binding agents, such as polymeric methylene diphenylene diisocyanate (PMDI) and polyurethane, and hydrophobic additives such as paraffin. The mixture is then formed into boards through pre-pressing and then subjected to heat for curing. WFIB manufactured through the dry process has a density range of 80-240 kg/m^3, with thicknesses ranging from 20-300mm.

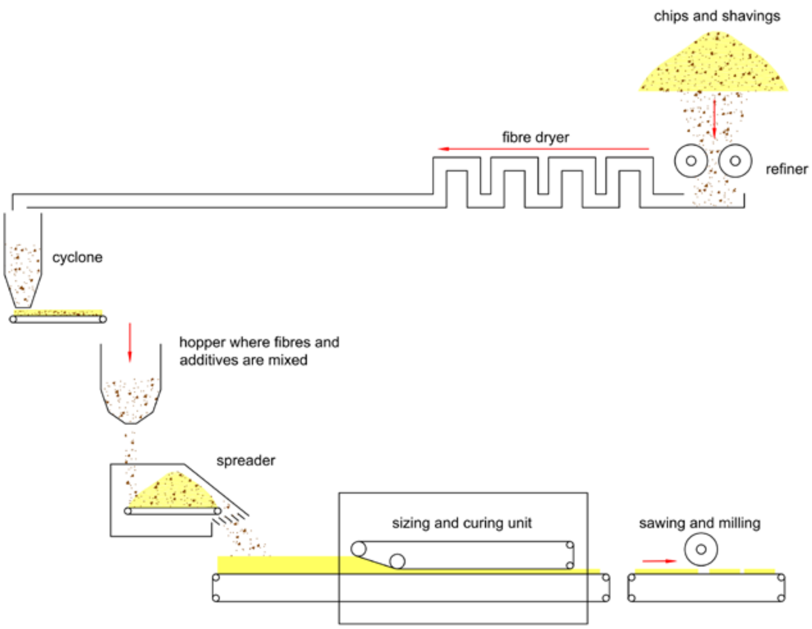


Figure 2.1 - WFIB Dry Process Manufacturing.

The manufacturing process results in a wood material which comprises fibre bundles and additives, such as paraffin, with materials properties different than wood. The porosity of the WFIB, which is the ratio of the total air volume to the total volume, comprises the air spaces of the lumens and also the air spaces of the pores between fibres and fibre bundles created throughout the manufacturing process (Ye, 2015). The pore spaces between fibre bundles are larger than the wood cell lumens. The pores and lumens of the material can be divided into voids that are 1) open, connected, and have access to the exterior, 2) voids that have access to the exterior that dead-end, and 3) closed pores with no access to the exterior.

The manufacturing process includes several mechanisms by which the properties of the wood are modified, including coating and impregnation of the material, thermal modifications, and board pressing. These mechanisms not only effect the wood fibres, but also the density distribution throughout the thickness of the manufactured material. Impregnation of the lumen and pores and coating of the fibre bundles with bulking materials, such as paraffin wax, does not react with or modify the wood molecular structure of the cell wall (Ramage et al., 2017). However, the coating and impregnation can block water pathways and therefore limit the ability of water to adsorb to wood cell walls. Thermal modification has been shown to alter the chemical composition and structure of the wood cell for processed wood products. Thermal modification of the wood cell can impact durability and mechanical properties of the wood. Industrial heat treatments have been found to be an effective means of improving wood stability and durability against biodegradation (Ramage et al., 2017). The effectiveness of impregnation and thermal modification of the wood during processing is dependent on a variety of factors. For example, the moisture content of the wood fibres during heat treatment has a significant impact on the resulting dimensional stability and hygroscopicity of the material (Altgen, Hofmann, & Militz, 2016). Board pressing impacts the density of the fibres closest to the pressure plates. Similarly, the temperature of the pressing plates during board pressing causes the greatest amount of thermal modification to the fibres closest to the pressure plates.

The vertical density profile throughout the thickness of manufactured wood materials has been extensively studied for manufactured wood products, and the effects on the physical and mechanical property of the manufactured product. Timusk conducted x-ray densitometer measurements on OSB sheathing which indicated that the surface layers were significantly more dense than the inner core of the material (Timusk, 2008). The impact of board pressing to WFIB may be similar.

Manufacturer property data for WFIB indicates that WFIB has a thermal conductivity of approximately 0.04 W/mK, which is greater than that of other commercially available exterior insulations such as EPS, rigid mineral wool, XPS, and polyisocyanurate. Vapour permeability for WFIB is approximately 65 ng/(ms Pa), which is less than rigid mineral wool, though much greater than that of EPS, XPS, and polyisocyanurate.

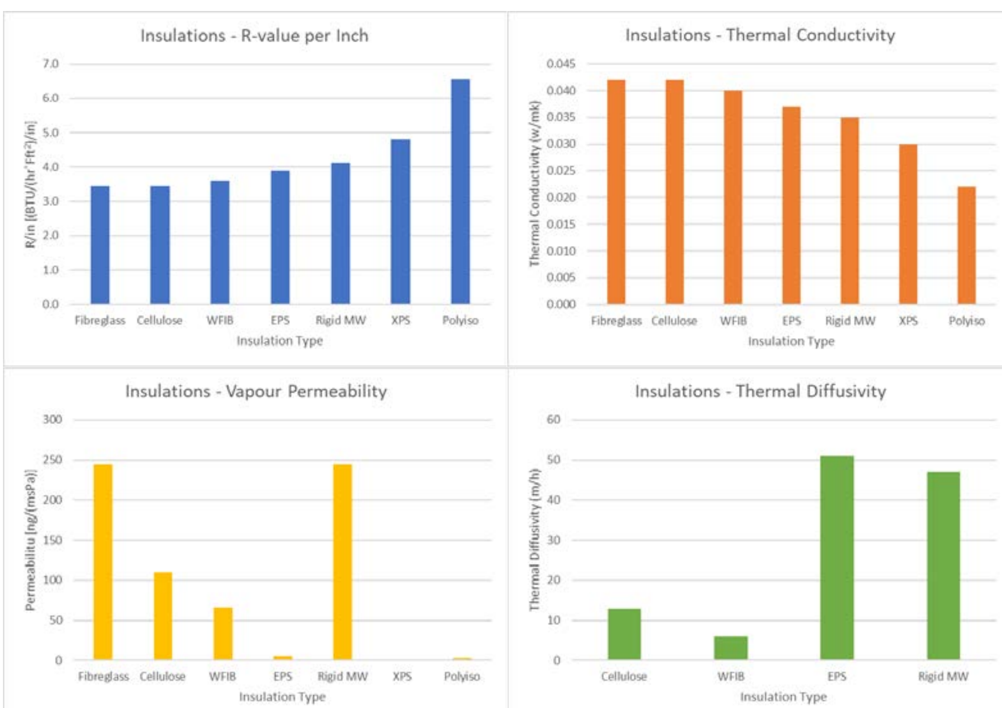


Figure 2.2 - WFIB and Common Insulation Material Properties (Straube & Burnett, 2005).

2.3 Moisture and Wood

Moisture is a critical factor affecting building envelope performance and durability, as moisture is involved in nearly all deterioration mechanisms and also impacts material characteristics such as vapour permeability and thermal conductivity (Straube & Burnett, 2005). Moisture impacts to material durability include deterioration such as mould, decay, and corrosion, and the mechanisms of freeze-thaw and swelling-shrinking of materials containing moisture. Understanding and predicting moisture movement and storage within a material is important to ensure that material performance and durability is maintained throughout the service life of the building material.

Wood is a hygroscopic material, meaning that it has an affinity for water in the vapour, adsorbed, and liquid form. The hygroscopic nature of wood and wood materials results in relatively high moisture contents at lower relative humidities, increasing the risk of performance and durability issues. Furthermore, wood is a material that contains nutrients for the growth of mould and decay. The interactions of building envelope materials and moisture must be understood to better predict the performance of wood building materials, including WFIB.

2.3.1 Water, Storage and Transport

Within building material, water can exist in all three states, solid (ice), liquid (water), and gas (vapour). Additionally, a fourth state known as adsorbed water exists, which has characteristics somewhere between vapour and liquid water. There are three different types of moisture in wood, water vapour, bound water, and free water. Water vapour is present within the cell lumens and a small amount within the cell walls. Bound water is the adsorbed water within the cell wall and on the lumen facing side of the cell wall. Free water is the condensed capillary water (liquid water) within the lumen and pores. Manufactured wood materials comprise pore spaces that may also contain water vapour, adsorbed water, and capillary water. For additional information regarding wood material including wood growth and cellular and physical structure refer to Section 2.1 and Appendix A. For additional information regarding WFIB material refer to Section 2.2.

2.3.1.1 Storage

2.3.1.1.1 Water Vapour

Water vapour is the water molecule in the gas state, which is highest energy state. The ability of air to hold water vapour is dependent on temperature, with higher temperature air capable of holding a greater mass of water vapour per mass of dry air. It is worth noting though that the density of moist air also varies with temperature. When the temperature increases, the molecular motion of the molecules in the air increases, resulting in expansion of volume and thus a decrease in density of the air. The amount of water vapour in the air at a given temperature is measured in terms of humidity ratio (kilogram of water vapour per kilogram of dry air), relative humidity (percentage), or vapour pressure (Pascals). Water vapour is stored within wood materials in the air in the pores, the lumen, and a small amount within the cell wall structure.

2.3.1.1.2 Adsorbed Water

Adsorbed water has characteristics similar to liquid water, but different in that it is more tightly held to a materials surface and is in a lower energy state than free liquid water. Adsorbed water along the pore walls of a material takes place at lower relative humidities, with hygroscopic materials adsorbing greater amounts of water than hydrophobic materials.

Within the pores, attraction of the water molecules to the solid materials molecules results in the water molecules releasing energy (latent heat of adsorption) and thus existing in a lower energy state held more tightly to the materials surface. The latent heat of adsorption, and thus how tightly the adsorbed water is held to the material surface, is dependent on the molecular structure of the material and therefore varies depending on the material. The latent heat of adsorption is less than that for vapourization/condensation. Adsorption occurs in two steps, monolayer adsorption which is a single layer of water molecules, after which multi-layer adsorption takes place (Hens, 2007).

For wood, water adsorption only occurs within the cell wall or the lumen facing surface (Skaar, 1988). Water movement through the porous wood cell wall is not capillary, but due to the large chemical forces involved the water forces its way into the cell wall spaces. As the layers of adsorbed water within the cell wall increases, the cell wall width will increase, resulting in swelling of the cell walls (Stamm, 1964). For manufactured wood materials, increased cell wall width results in swelling in the direction of the pore space. The adsorbed water within the cell wall is 'bound water', and is recognized as a distinct phase that is often referred to as a 'solid solution' (Stamm, 1964). For wood materials with additives such as paraffin, adsorption takes place within the wood cell wall and on the lumen facing surface, and on the additive material of the pore surface.

The most tightly held lowest energy water molecules are in the first layer of adsorption, and each layer of adsorption carries higher levels of energy as the layer distance from the material surface increases. The outermost adsorbed layers have higher energy levels which approach that of free liquid water. In wood, the capillary and liquid water, or 'free water', exists in the lumens. Typically 5-6 molecular layers of water can be taken up by adsorption in the cell wall structure, though this may be as low as 2 and as high as 10 molecules (Stamm, 1967). Figure 2.3 depicts the adsorption of water in wood cells from one layer, to multiple layers, to fibre saturation point, to free water within the lumen. Note that the depiction of this process is simplified, and cell and lumen sizes would vary, and the number of adsorption layers would vary. For wood materials, the presence of paraffin on wood cell surfaces would impact the adsorption process.

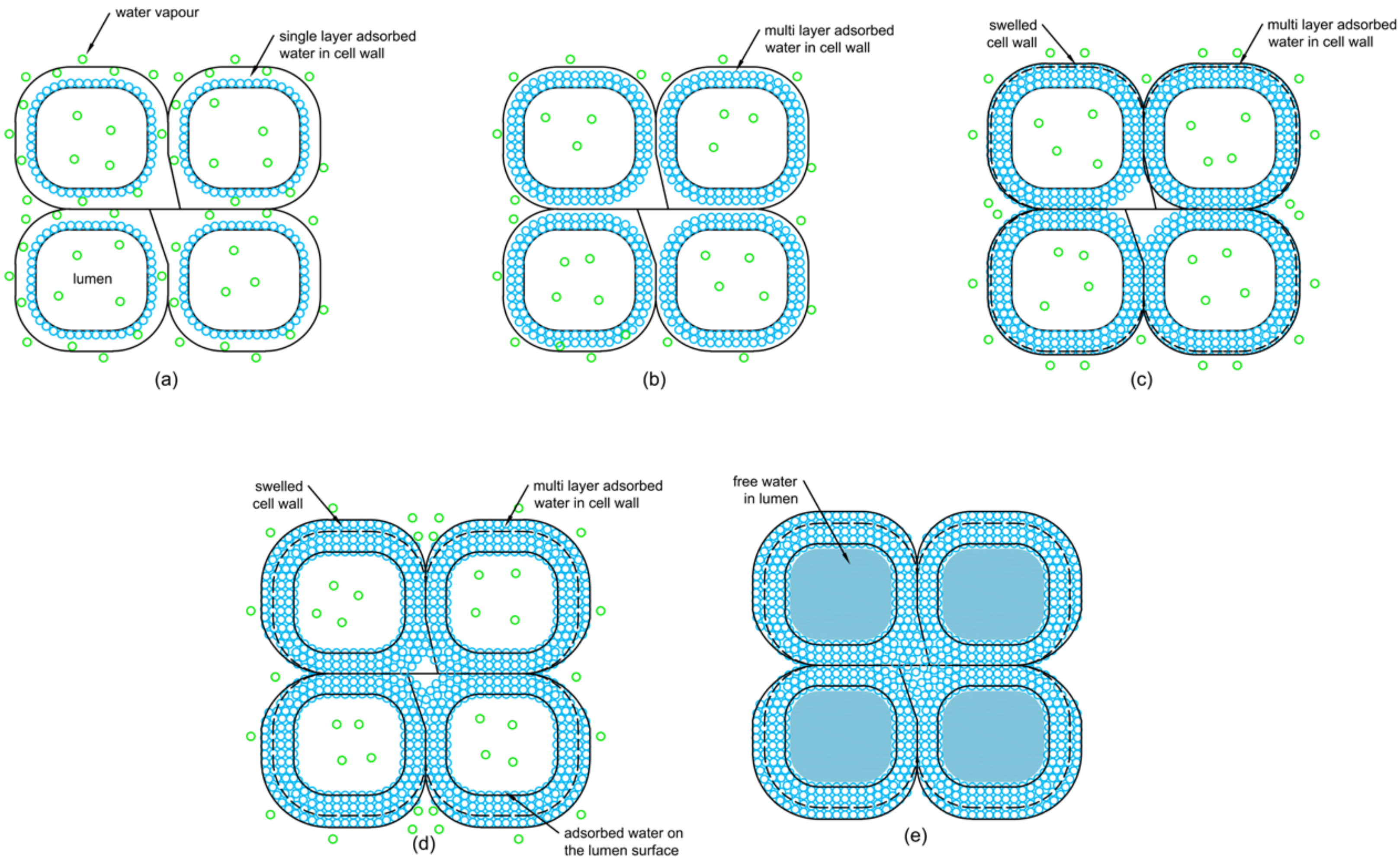


Figure 2.3 - Wood Cell Adsorption.

The sites of adsorption vary throughout a material, resulting in water molecules adsorbing in a second layer at some sites prior to some first layer sites being occupied. The number of adsorbed layers at a specific relative humidity is related to temperature, which is related to the energy. Greater temperatures have higher energy levels and therefore have sufficient energy to enter or stay in the gas phase, and adsorbed water molecules stay in the adsorbed state for a shorter period of time. The higher the water vapour content of the air at a given temperature, the higher the number of molecules that will be adsorbed. At a dynamic equilibrium for a given temperature and given water vapour content of the air, a stable quantity of adsorbed water molecules will be maintained. At the same time, there is a constant exchange of water molecules in the adsorbed state on a material surface, with any single water molecule remaining adsorbed for a very short time (Straube & Burnett, 2005).

Figure 2.4 illustrates the moisture distribution of adsorbed water for a) uniform moisture distribution and b) non-uniform moisture distribution. As previously mentioned, adsorbed water molecules are continually moving from one site to another and adsorption sites vary throughout the material, therefore it is improbable that a uniform moisture distribution would exist (Skaar, 1988).

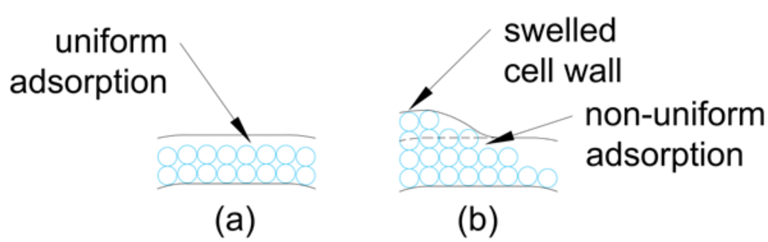


Figure 2.4 - Moisture distribution in the cell wall for case of a) uniform moisture distribution, b) non-uniform moisture distribution.

2.3.1.1.3 Fibre Saturation Point and Swelling

Fibre saturation point refers to the moisture content of wood at which the bound water (adsorbed water) is at a maximum and no free water exists in the lumens (Stamm, 1967). Below the fibre saturation point, added water within the cell wall matrix causes swelling of the cells, and macroscopic swelling of wood can be observed. Above the fibre saturation point, any increase in moisture content will occur as free water within the cell lumen, and therefore cell walls will no longer swell. Since cell sizes vary depending on characteristics such as early wood, late wood, tracheid cell, ray cell, heartwood, and sapwood, fibre saturation at a particular cell may occur at a higher or lower moisture content than another cell (Berry & Roderick, 2005). Latewood cells typically have a higher fibre saturation point than early wood, owing to the thinner wall structure of early wood cells. Sapwood cells have a higher fibre saturation point than heartwood, due to heartwood cells containing a higher concentration of extractives in the cell wall and lumen. The moisture content for the fibre saturation point of wood typically decreases as temperature increases (U.S. Forest Service, 1999).

Experiments conducted by Mantanis et al. determined that an increase in temperature resulted in an increase in the maximum equilibrium of swelling of various types of wood in water due to the available energy available for the activation energy of swelling (Mantanis, Young, & Rowell, 1994). Similarly, testing of wood fibreboard at 100% relative humidity and various temperatures indicated that the overall thickness swelling was greater for wood fibreboard at higher temperatures (Shi & Gardner, 2006).

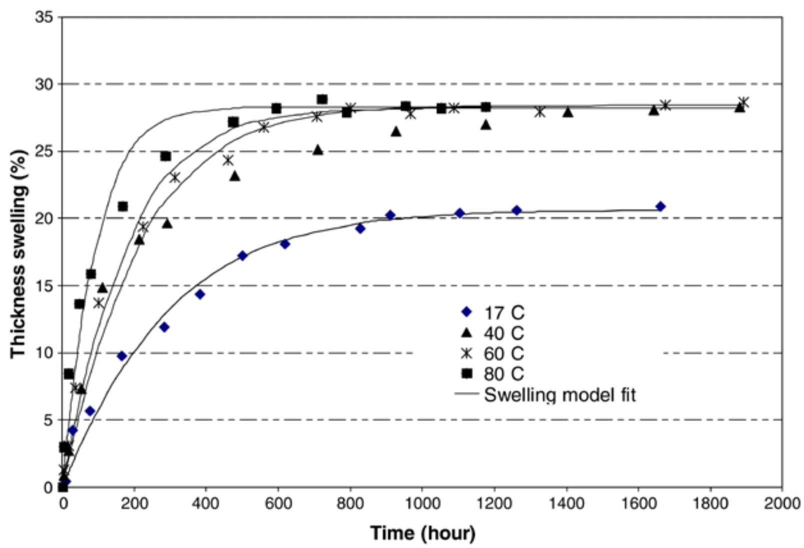


Figure 2.5 – Thickness Swelling (%) at 100% Relative Humidity at Various Temperatures (Shi & Gardner, 2006).

Previous experiments have shown that the fibre saturation point remains consistent regardless of whether the wood sample is intact or defibered through wood processing for material manufacturing (Stamm, 1964). However, experiments conducted by Geimer et al indicated that wood cell damage due to crushing and collapsing of the cells during manufacturing can result in up to a 35% increase in the amount of thickness swelling from water adsorption (Geimer, Kwon, & Bolton, 1998).

Previous experiments have shown that the fibre swelling associated with adsorption in the cell structure of WFIB continues up to approximately 85-95% relative humidity, resulting in fibre swelling and significant reduction of porosity at relative humidities between 60-95% (Ye, 2015). Additionally, study of an individual wood fibre at 40% and 100% relative humidity demonstrated swelling of 5% and 16%, respectively. Research has indicated that the lumen spaces of wood change only slightly as a result of swelling and shrinking, though the pits between lumens have been determined to decrease in size due to swelling (Stamm, 1948), (Banks & Levy, 1980).

2.3.1.1.4 Capillary Water

Capillary water, also known as liquid water, free water, or bulk water, takes place in the capillary spaces, which for wood are the lumens. For processed wood materials, capillary spaces are both in the wood cell lumens and within the pore spaces between the fibre bundles. Capillary water is in a lower energy state than water vapour, but higher energy state than adsorbed water.

In order for capillary water to occur, several conditions must first be satisfied:

1) The energy of the outermost adsorbed layer must become equal to that of liquid water. This may occur at the second layer of adsorption, or at the tenth layer of adsorption.
2) The capillary must be sufficiently small, resulting in the meniscus to form. For this reason, capillary condensation first takes place in the smallest pores and lumens. The smaller the size of the capillary, the smaller the radius of the meniscus required for capillary condensation, and therefore the lower the relative humidity at which liquid water can exist. It is often assumed that most capillary condensation occurs at or after a relative humidity of 50%.
3) The capillary tension of the condensed liquid water behind the meniscus must be less than that of the cohesive strength of water.

Capillary condensation in very small pore spaces as predicted by the Kelvin's equation was experimentally proven (Fischer, Gamble, & Middlehurst, 1981), with the resulting Kelvin equation plotted as a function of pore radius versus relative humidity in Figure 2.6 (Straube & Burnett, 2005). This indicates that capillary condensation in smaller pore spaces can occur at lower relative humidities.

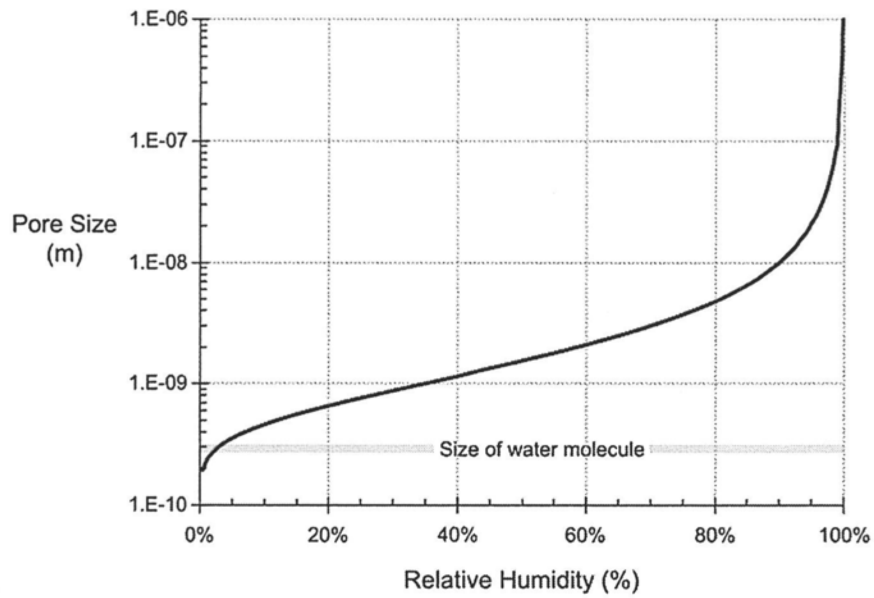


Figure 2.6 - Kelvin Equation Prediction of Capillary Condensation at Ambient Relative Humidities *(Straube & Burnett, 2005)*.

As previously noted, fibre swelling due to adsorption in WFIB impacts porosity significantly at relative humidities greater than 60%, therefore decreasing the overall capillary space as relative humidity increases. The fibre swelling associated with higher relative humidities results in decreased capillary radius and may cause obstruction of capillary paths and elimination of some capillary spaces entirely.

2.3.1.1.5 Sorption Isotherm

Sorption isotherms represent the relationship between relative humidity and the equilibrium moisture content of a specific material at a specific temperature (ASTM International, 2016a). The moisture content of a material is the mass of moisture within the material as a ratio of the dry mass of the material, multiplied by 100 to express the ratio as a percentage.

$$MC\ (\%) = \frac{M_w - M_d}{M_d} \times 100 \tag{1}$$

Where,

$MC\ (\%)$ = moisture content expressed as a percentage

M_w = mass of wet material

M_d = mass of dry material

The values from the sorption isotherm curves can be used for characterizing the hygrothermal behaviour of a material. Sorption isotherms include both adsorption and desorption isotherms.

Adsorption isotherms represent the adsorption process, where the material environmental conditions progress from low to high relative humidity conditions. Desorption isotherms represent the desorption process, where the material environmental conditions progress form high to low relative humidity conditions. Figure 2.7 is an example of a typical sorption isotherm for WFIB as measured by the author, specifically for adsorption with the exclusion of desorption. The sorption process for desorption is not included within this study. The moisture content within the material increases as the relative humidity of the environmental conditions increases, whether the water is in vapour, adsorbed, or liquid state.

The shape of a sorption isotherm curve is unique to different material characteristics and the internal structure of the material and is indicative of the different states of the water within the material at different corresponding relative humidities.

The first isotherm segment, labeled (a) in Figure 2.7, reflects the adsorption of a single layer of water molecule on internal surfaces, or in the case of wood within the cell wall. As previously noted in Section 2.3.1.1.2, adsorption is more realistically non-uniform and therefore some locations may experience no adsorption, single layer adsorption, or multi-layer adsorption.

In the second isotherm segment, labeled (b), multiple layers of adsorbed water molecules begin to form on the material surface. As noted in Section 2.3.1.1.2, each layer of adsorbed water is held less tightly and has a higher energy level, therefore the slope of the isotherm curve decreases.

The third isotherm segment, labeled (c), the increased number of adsorbed layers begin to interact, resulting in capillary condensation in pores, and in the case of wood cells within the lumens. As noted in Section 2.3.1.1.4, very small pores may experience capillary condensation at lower relative humidities. The increased condensation of capillary water in this regime is indicated through the increased slope of the sorption isotherm. As noted in Section 2.3.1.1.3, fibre swelling due to adsorption in WFIB impacts porosity significantly at relative humidities greater than 60%, therefore decreasing the overall capillary space as relative humidity increases. The fibre swelling associated with higher relative humidities results in decreased capillary radius and may cause obstruction of capillary paths and elimination of some capillary spaces entirely.

The fourth isotherm segment, labelled (d), corresponds to increased capillary condensation in the pores indicated through the increase in slope of the sorption isotherm. The supersaturated segment of the sorption isotherm is not included in Figure 2.7, as supersaturation was not included in this study. The supersaturated segment is achieved through submerging the material in water and/or forced water into the material to achieve moisture contents above the capillary saturation of the material.

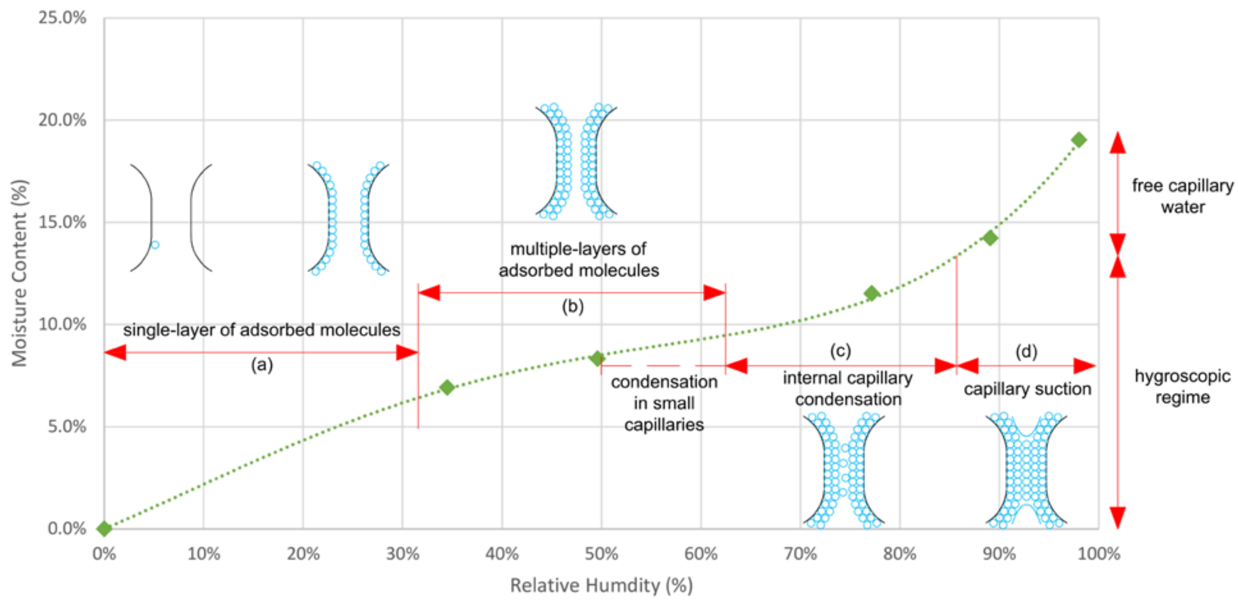


Figure 2.7 - Sorption Isotherm.

Hygrothermal material properties can be interpreted from sorption isotherms for different building materials, such as those shown in Figure 2.8. For example, the quantity of adsorption is dependent upon the number of sites available for adsorption, therefore the quantity of pore spaces and overall pore surface area. Building materials such as spruce and plywood experience higher moisture contents between 0-30%, indicating that spruce and plywood have a greater pore surface area for adsorption sites (refer to Figure 2.8). Similarly, high density wood materials comprise a high number of wood cells within which adsorption can occur. Therefore, high density wood materials often exhibit higher moisture contents at lower relative humidities than lower density wood materials.

The capillary water associated with segments c and d may be associated with moisture related issues in building materials, such as mould, corrosion, etc. Additionally, freeze thaw cycling while building materials have high levels of moisture content and liquid water, may result in deterioration of building materials. Therefore, segments c and d of the sorption isotherm curves are of particular concern for building materials durability.

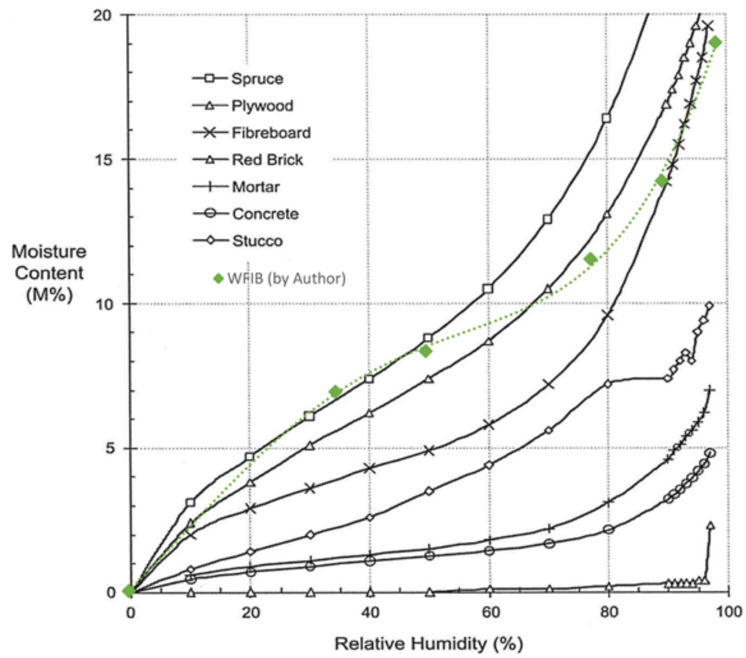


Figure 2.8 - Various Building Materials Sorption Isotherms (Straube & Burnett, 2005).

Temperature has been proven to have an impact on a materials sorption isotherm curve. A temperature increase is typically associated with a decrease in moisture content at a specific relative humidity. Water vapour at higher temperatures has greater energy levels and therefore has sufficient energy to enter or stay in the gas phase. Figure 2.9 illustrates the sorption isotherms for wood at different temperatures, with data provided from the US FPL Handbook (U.S. Forest Service, 1999).

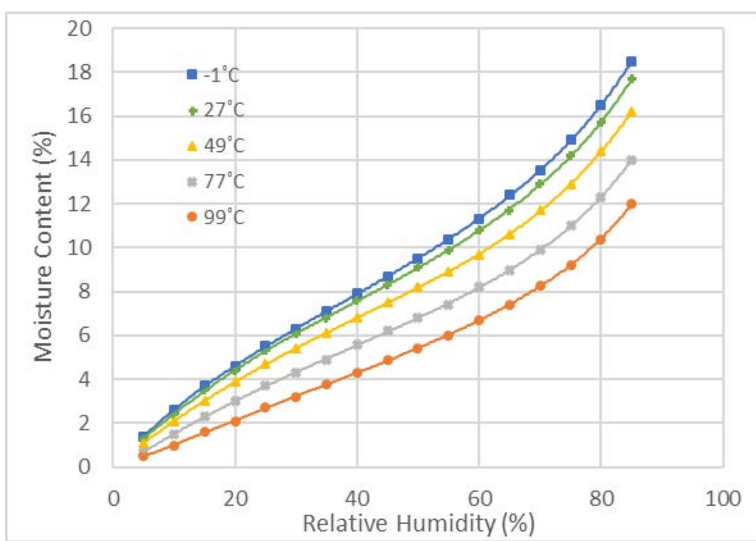


Figure 2.9 – Wood Sorption Isotherm as a Function of Temperature (U.S. Forest Service, 1999).

2.3.1.1.6 Mould Growth

Storage of high quantities of water within susceptible materials may result in mould fungi and decay fungi. Fungal growth requires spores, nutrients for spores, and specific temperature and moisture conditions for growth. Wood is a material susceptible to fungal growth due to the commonness of spores, the nutrients of wood materials, and the temperature and moisture conditions wood materials are subjected to within a building envelope.

Spores are expected among building assemblies from the outdoors and within materials from transport. Wood comprises cellulose which provides nutrients for spores. Additionally, wood is a hygroscopic material capable of relatively high moisture storage. Fungi can typically begin to thrive at relative humidities of approximately 75-80%. Wood decay can occur due to fungal growth which attacks the cellulose of the cell structure, which typically can only occur at very high moisture contents and high relative humidities (Straube & Burnett, 2005).

The combination of these wood characteristic, fungal growth mechanisms, and environmental conditions, increase the risk of wood deterioration due to mould and decay. It is important to investigate these combined factors to ensure that wood material performance and durability in the building envelope is not compromised throughout the service life of the material.

2.3.1.2 Transport

Moisture transport mechanisms comprise the movement of water vapour by diffusion, movement of adsorbed water through surface diffusion, and the movement of capillary water through capillary flow. In wood, these transport mechanisms take place within the cell wall and lumens. For processed wood materials with additives such as paraffin, the movement of water in wood is impacted due to the impregnation and surface coating of wood cells. Additionally, water transport mechanisms take place in the pores between fibres and fibre bundles created throughout the manufacturing process.

2.3.1.2.1 Vapour Diffusion

In wood, water vapour diffusion occurs in the lumens and somewhat within the cell wall. For processed wood materials that includes additives such as paraffin, water vapour diffusion also occurs in the pore spaces of fibre bundles. Water vapour diffusion is governed by a vapour pressure gradient. Water vapour diffuses from high concentration to lower concentration, therefore if there is a concentration gradient across a material due to differing environmental conditions on either side of the material or within the material itself.

At the lower end of the relative humidity scale, water transport occurs primarily through water vapour diffusion, with a small amount of adsorbed flow. Water vapour diffusion is relatively slow, therefore permeability is typically low at lower relative humidities. For materials with high porosity and a high number of interconnected pores, permeability will be greater than for materials with lower porosity and/or lower number of interconnected pores. Vapour diffusion through smaller pore spaces (radius less than 100nm) at low relative humidities with little to no adsorption will be slower than predicted by Fick's law, with vapour movement governed by a process known as Knudson diffusion (Siau, 1984), (Straube & Burnett, 2005). The rate of water vapour diffusion in the pores and lumens increases with increasing temperature, though decreases with increasing moisture. Adsorbed water diffusion occurs when the adsorbed water receives energy and returns to a vapour state.

2.3.1.2.2 Surface Diffusion (Adsorbed Flow)

For wood, surface diffusion, also known as adsorbed flow, takes place within the cell wall and along the surface of the lumen (Skaar, 1988). For processed wood materials that includes additives such as paraffin, surface diffusion also takes place within the adsorbed water on the surface of the paraffin material. As previously discussed in Section 2.3.1.1.2, the adsorbed water molecules are continually moving from one site to another, and therefore experience a non-uniform moisture distribution of adsorption. A non-uniform adsorption distribution with a relative humidity gradient creates movement of adsorbed water from the higher relative humidity part of the material towards the lower relative humidity part of the material. In other words, the adsorbed flow is from the area of the material with more layers of adsorbed water towards the area of the material with less layers of adsorbed water.

As previously discussed, the first adsorbed layer is the most tightly held with the highest binding energy and the lowest energy state, while the outermost adsorbed layer is the least tightly held with the lowest binding energy and the highest energy state. A water molecule slips from a higher adsorbed layer to a lower adsorbed layer by releasing energy. The adsorbed water molecule continues movement through lower energy states, therefore through the adsorbed layers, until the first layer of adsorption is reached. The constant movement of water vapour through adsorbed layers can be interpreted as a slipping layer of molecules adjacent to the material surface, hence surface diffusion. Surface diffusion is governed by the relative humidity gradient. Figure 2.10 illustrates the sequential movement of a water molecule during adsorbed flow.

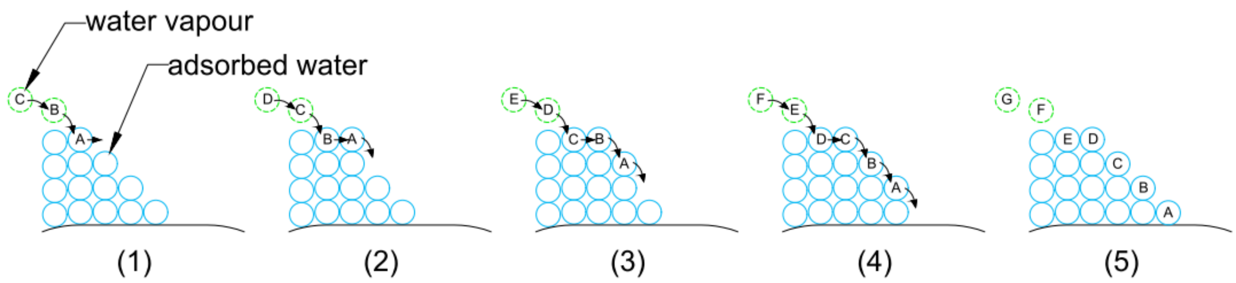


Figure 2.10 - Water Vapour Movement for Surface Diffusion.

Typically, smaller pore sizes give rise to surface diffusion at lower relative humidities. As relative humidity increases, the number of adsorbed layers increases, therefore the outermost layer of adsorbed water becomes less tightly held and thus is more mobile for surface diffusion (Siau, 1984). Additionally, surface diffusivity of multi-layer diffusion increases with increasing temperature, though surface coverage is a factor as well (Choi, Do, & Do, 2001). Similarly, bound water surface diffusion in the wood cell increases with both moisture content and temperature. In wood, bound water surface diffusion in the wood cell wall is much slower than vapour diffusion. Surface diffusion on pore surfaces is faster than vapour diffusion, and in some materials multi-layer surface diffusion is faster than capillary transport (Uhlhorn, Keizer, & Burggraaf, 1992).

As relative humidity conditions increase, and thus moisture content of the material increases, capillary water transport will begin and potentially take over from surface diffusion.

2.3.1.2.3 Capillary Flow

For wood, liquid water movement by capillary flow takes place within the lumens (Siau, 1984). For processed wood materials that includes additives such as paraffin, capillary flow takes place in the pore spaces between fibre bundles. The exact number of adsorbed layers before water is no longer considered in the adsorbed state varies. Typically, 5-6 molecular layers of water can be taken up by adsorption in the cell wall structure, though this may be as low as 2 and as high as 10 molecules. As outlined in Section 2.3.1.1.4, capillary condensation in very small pores and lumens can begin at low relative humidities, though it is common for most building materials that capillary condensation occurs at relative humidities greater than 50%. Capillary flow is typically the most efficient of the transport mechanisms and therefore is typically associated with an increased rate of water transport. Though as previously noted in Section 2.3.1.2.2, multi-layer surface diffusion can occur at a faster rate than capillary flow depending on the material characteristics. As previously noted, fibre swelling due to adsorption in WFIB results in decreased capillary radius and may cause obstruction of capillary paths and elimination of some capillary spaces entirely.

2.3.1.2.4 Permeability

Water vapour permeability is the time rate of water vapour transmission through a unit area of material of a unit thickness created by a unit vapour pressure difference between two surfaces at specified temperature and relative humidity conditions on either material surface (ASTM International, 2016b). The permeability of a material comprises all transport mechanisms, vapour diffusion, surface diffusion, and capillary flow. Often all three mechanisms will be taking place within a material at the same time due to the complexity of material structure with a variety of pore sizes and structures, and capillary paths.

The most commonly used equation for water vapour transport is Fick's law of fundamental diffusion mass flow relationship (Hutcheon & Handegord, 1995):

$$w_v = \mu \frac{dp}{dx} \tag{2}$$

Where,

w_v = mass of water vapour transmitted over time

p = vapour pressure

x = thickness of material (flow path)

μ = permeability of material

The steady-state of this equation can be expressed as follows:

$$W_v = \bar{\mu} A \Delta t \frac{(p_1 - p_2)}{l} \tag{3}$$

Where,

W_v = total mass of water vapour transmitted (ng)

A = cross-sectional area of the flow path (m^2)

Δt = time interval (s)

p_1 = vapour pressure on side 1 of the material (Pa)

p_2 = vapour pressure on side 1 of the material (Pa)

l = length of flow path (m)

$\bar{\mu}$ = average permeability of the material through the material, over the pressure gradient involved $\left({}^{ng}/_{(s \cdot m \cdot Pa)}\right)$

The permeability of wood varies significantly depending on variety of characteristics, including wood species, and the ratio of hardwood, softwood, earlywood, latewood, sapwood, and heartwood (Dinwoodie, 2000). Additionally, tracheid and ray orientation significantly impacts vapour transport, with previous research indicating that most longitudinal permeability (along the tracheids) is approximately 10,000 times the transverse permeability (along the rays) (Dinwoodie, 2000). The manufacturing process for wood products introduces further factors effecting permeability, through processes such as coating and impregnation of the wood, and thermal modifications (refer to Section 2.1). Additionally, important factors affecting the permeability of water in wood are temperature, moisture content, and density of the wood material (Dinwoodie, 2000). Whether the wood material experiences desorption or adsorption during steady state relative humidity gradient induced permeance also impacts the rate of permeability, which is discussed further in Section 3.3.2.

2.3.1.2.5 Effect of Temperature and Moisture Content on Permeability

The in-service moisture content and temperature of wood also effects the material's ability to transport water. As previously discussed, temperature and moisture content impact vapour diffusion, surface diffusion, and capillary flow. Vapour diffusion within the pore spaces and lumens increases with increasing temperature, though decreases with increasing moisture content due to decreased pore size. The surface diffusion of adsorbed water within the wood cell wall increases with increasing temperature and also increases with increasing moisture content. Similarly, surfaced diffusion in the pores increases with increasing temperature and increasing moisture content, so long as surface diffusion has not been replaced by capillary flow. The rate of surface diffusion is also impacted by the amount of adsorption coverage on the pore surfaces, though the adsorption coverage increases with increasing moisture content. Capillary condensation occurs at higher moisture contents, and therefore capillary flow typically increases with increasing moisture content.

Previous research has indicated that an increase in moisture content increases the permeability of wood (Siau, 1984), and wood products such as OSB (Timusk, 2008). Similarly, other building materials ability to transport water is also affected by moisture content. Several common building materials that experience an increase in permeability with moisture content are provided in Table 2.1.

Table 2.1 - Permeability Values for Common Building Materials (Straube & Burnett, 2005)

Material	Permeability $\left({}^{ng}/_{(Pa \cdot s \cdot m)} \right)$	
	Dry Cup (50-0% RH)	Wet Cup (100-50% RH)
Plywood (density 400-600 kg/m^3)	0.5-1.5	2-8
OSB (density 575-725 kg/m^3)	0.5-1.5	1.5-3
Asphalt sheathing paper	30-300	400-1800

Hutcheon & Handegord proposed a relationship between permeability variance with increased moisture content using dry cup and wet cup test results, as illustrated in Figure 2.11. Additional experimentation has indicated that the relationship of permeability and moisture content is much more dynamic than the relationship illustrated in Figure 2.11.

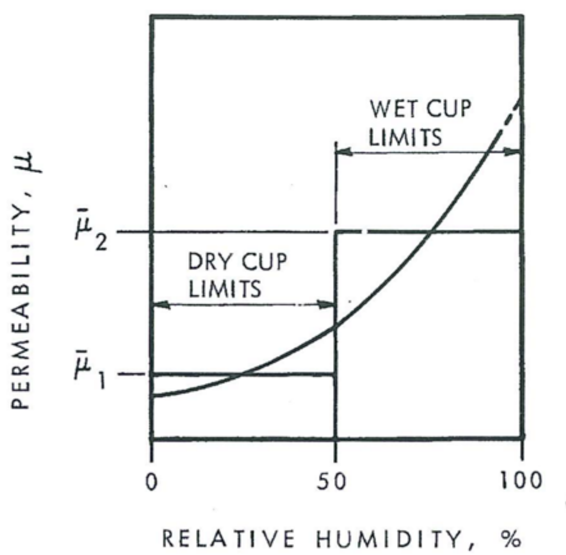


Figure 2.11 – Hutcheon & Handegord Relationship Between Dry Cup and Wet Cup Permeabilities (Hutcheon & Handegord, 1995).

Experimentation of the vapour permeability of OSB at a variety of average specimen relative humidities conducted by Timusk demonstrated a more complicated S-curve relationship for the permeability of OSB in relation to average specimen relative humidity (Timusk, 2008). Additionally, testing of several air barrier technologies through a similar technique demonstrated a small increase in vapour permeability at relative humidities less than 50%, though a steep increase of vapour permeability at relative humidities greater than 50% (Couturier & Boucher, 2011). Testing of other wood materials, including boards of spruce, pine, teak, wood fibre board, wood particle board, and wood fibre board with treatments such as asphalt impregnation, oil impregnation, and felt sheathing, indicated similar curves with greater permeability increases as relative humidity increased beyond 50% (Tveit, 1966).

Experimentation of the dry cup and wet cup vapour permeability of fiberboard and gypsum board at a variety of temperature demonstrated an approximate 8% increase in water vapour transmission rates with increased temperatures up to approximately 43˚C, reflecting the impact of temperature on dry cup and wet cup vapour permeability testing (Mukhopadhyaya, Kumaran, & Lackey, 2005).

Changes in permeability due to temperature and moisture content of the material is a result of the different water transport mechanisms, vapour diffusion, adsorbed flow, and capillary flow, at any given relative humidity within the material. As previously discussed, the water transport mechanisms are highly variable depending on moisture content, and also depending on the pore structure and size within the material. Additionally, the temperature and therefore energy associated with the water molecules impacts water transport mechanisms. Further complicating the matter, as moisture content increases and adsorption within the wood cells increases, swelling of wood fibres impacts the lumens and pores in which vapour diffusion, adsorbed flow, and capillary flow occur.

2.4 Heat Transfer in Wood

The properties associated with a material's ability to transfer heat, such as thermal conductivity, are a factor in the energy transfer and therefore overall energy consumption associated with buildings. Thermal conductivity is the measure of heat transfer through a material by direct molecular contact through a unit area, through a unit thickness, for a temperature gradient of 1 Kelvin, and is measured in terms of W/mk.

$$q = \frac{\cdot k \cdot (T_1 - T_2)}{l} \qquad (4)$$

Where,

q = rate of heat flow trough a unit area (W/m^2)

l = length of flow path (m)

T_1 = temperature on side 1 of the material (K)

T_2 = temperature on side 2 of the material (K)

k = thermal conductivity $\left({}^{W}/_{(m \cdot K)}\right)$

Thermal transmission properties of a material may vary due to the variability of a materials composition, deterioration or change of the material composition over time, the average and mean temperature of the material, and the moisture content of the material (ASTM International, 2017). Building insulation materials are specifically designed to resist heat, and therefore have a relatively low thermal conductivity.

The conductivity of wood varies significantly depending on variety of characteristics, including wood species, and the ratio of hardwood, softwood, earlywood, latewood, sapwood, and heartwood (Dinwoodie, 2000). Additionally, tracheid and ray orientation significantly impacts conductivity, with previous research indicating that most longitudinal conductivity (along the tracheid) is approximately 2.5 times the transverse conductivity (along the rays) (Dinwoodie, 2000). The manufacturing process for wood products introduces further factors effecting conductivity, as wood materials are strongly influenced by the density of the final wood product (Dinwoodie, 2000).

2.4.1 Effect of Temperature on Thermal Conductivity

The in-situ temperature of a building material in a building envelope impacts the thermal conductivity and overall thermal performance of the building material. Lower temperature materials have less energy therefore the molecules are moving slower. Higher temperature materials have more energy therefore the molecules are vibrating faster, increasing the rate of heat transfer through conduction Experimental research supports that materials experience changes in thermal conductivities with changing temperatures. Often materials experience a linear increase in thermal conductivities with increased temperatures (Berardi & Naldi, 2017), (Abdou & Budaiwi, 2005), though some materials such as polystyrene experience a non-linear change in conductivity with changes in temperature (Berardi & Naldi, 2017).

2.4.2 Effect of Moisture on Thermal Conductivity

The in-situ moisture content of a building material in a building envelope impacts the thermal conductivity and overall thermal performance of the building material. The storage of water vapour, adsorbed water, and liquid water in a material contribute to increased thermal conductivity as a result of the increased number of molecules for transferring heat and the relative higher conductivity of water compared to most insulating materials. Previous experimental research conducted for fibreglass and mineral wool correlated an increasing linear relationship between an increase in moisture content and a considerable increase in thermal conductivity (Abdou & Budaiwi, 2013). It was determined that higher density materials experienced larger changes in thermal conductivity with increased moisture content.

For wood, thermal conductivity will slightly increase with moisture content, though conductivity of the cell wall content is independent of moisture content (Siau, 1984). Though increased moisture content in the wood cell may result in cellular swelling which may increase the contact of wood cells. Processed wood materials comprise pores between fibres and fibre bundles which do not exist in natural wood, and these pores impact the thermal behaviour of the manufactured wood material from that of natural wood. Swelling of the fibres of wood and manufactured wood materials may reduce the overall porosity of the material therefore increasing the density of the material. As previously mentioned a higher density is corelated with a higher conductivity. As adsorbed water layers increase, the molecules located within the cell structure are located more closely, creating a shorter path for heat transfer.

2.5 Previous Work

Research associated with the water sorption, permeability, and moisture dependent thermal conductivity of wood and wood related products has been conducted in the past. The moisture storage and transport processes of wood have been extensively researched, with work by Alfred Stamm dating back to the early 1900's including The Capillary Structure of Softwoods (1929), Effect of Chemical Treatment on Wood Permeability (1932), Thermodynamics of The Swelling of Wood (1935), The Passage of Water Through The Capillary of Wood (1948), An Approach to the Measurement of Solid-Solution Structures in Wood and Other Cellulosic Materials (1963), Wood and Cellulose Science (1964), Movement of Fluids in Wood (1967), and so on. Additional early research of wood includes those by John Siau including Flow in Wood (1971), and Transport Processes in Wood (1984).

The research of water sorption, permeability, and moisture dependent thermal conductivity of WFIBs, specifically those manufactured through the dry process, is much more recent and less studied than wood and wood sheathing products. As previously discussed, the dry process of manufacturing WFIBs was introduced in 2004. The introduction of new products through the dry process and the increase in use of building materials from renewable resources has let to increased research into the hygrothermal properties of WFIB materials.

2.5.1 WFIB Sorption Isotherms

The moisture sorption behavior of WFIB has been studied in recent years. In 2009, Sonderegger et al. conducted extensive testing of both wet and dry processed wood fibre insulation materials, with a variety of thicknesses, densities, and additives, for a total of 28 products being tested (Sonderegger & Niemz, 2012). Of these, 2 products manufactured through the dry process with PUR-resin and paraffin additives were tested, all of which were 60mm thick and densities of 164 kg/m^3 and 240 kg/m^3. The moisture sorption isotherm testing included bot adsorption and desorption at 20˚C, with all specimens oven dried prior to testing. The adsorption testing was completed at 35%, 50%, 65%, 80% relative humidity, and the desorption testing was completed at 93%, 90%, 80%, 65%, 50%, and 35% relative humidity. Discussion indicated that products with the addition of ammonium polyphosphate, borate, and boric acid had a greater moisture content at relative humidities greater than 80% due to the impact of these additives on the saturation of the water vapour in the air.

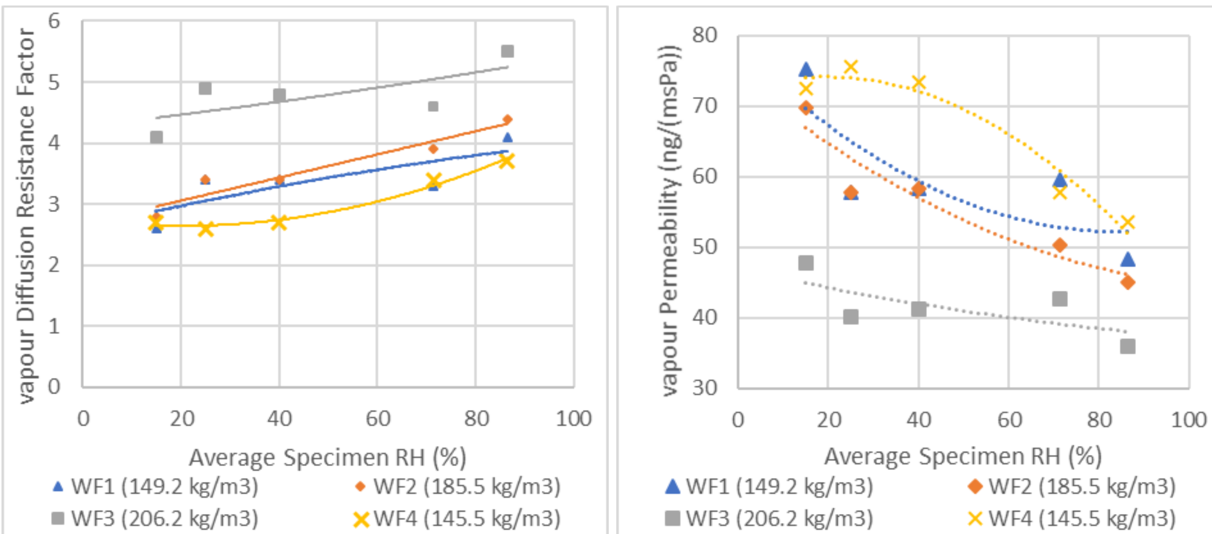
In 2010, Goto et al. conducted research on a full scale wall assembly using four different WFIB materials (149 kg/m3, 20mm; 186 kg/m^3, 40mm; 206 kg/m^3, 20mm; 246 kg/m^3, 60mm), which included the preliminary testing of the material properties (Goto et al., 2011). The moisture sorption isotherm, specifically adsorption, was completed at 0%, 30%, 50%, 80% or 90% and 23˚C. Data from testing was included, though analysis and discussion of the sorption isotherm curves obtained through testing was not included in the research study. Additionally, the volumetric moisture contents outlined in the article are considerably greater than the moisture contents obtained in other research.

In 2013, Vololonirina et al. conducted research on several wood based materials, including one type of WFIB (150 kg/m3, 20mm and 80mm), to characterize the hygrothermal properties including the adsorption and desorption isotherms at 20˚C (Vololonirina, Coutand, & Perrin, 2014). The adsorption and desorption testing was completed at 22.5%, 43%, 66%, 93%, and 97%, with the adsorption specimens oven dried prior to testing. Results and discussion indicated that the WFIB materials show a sigmoidal profile, which is a typical sorption desorption curve for hygroscopic materials, and that the hysteresis was low.

This research aims to specifically study a greater variety of products with similar densities manufactured through the dry process and in a variety of thicknesses. The current research reveals conflicting quantities for moisture sorption for WFIB products, including whether or not there exists a steep capillary free water regime at high relative humidities. This research aims to contribute additional moisture sorption data towards establishing consistent moisture sorption values for WFIB. Current research is also limited to WFIB materials that have been thermally modified through oven drying prior to moisture sorption testing. This research aims to contribute moisture sorption values for WFIB unaltered through oven drying, while also determining the impact of oven drying WFIB prior to testing. Additionally, current research lacks the impact of temperature on WFIB moisture sorption. This research aims to contribute moisture sorption data for a broader range of test temperatures envelopes may experience in a cold climate.

2.5.2 WFIB Vapour Permeance

The moisture transport behavior of WFIB has been studied in recent history. As previously mentioned, in 2010 Goto et al. conducted research that included preliminary testing of 4 different WFIB materials (Goto et al., 2011). The WFIB vapour diffusion resistance factor was tested at various relative humidity gradients, which indicated an increase in the water vapour diffusion resistance factor (decrease in water vapour permeability) as the average specimen relative humidity increase. Figure 2.12 includes the experimental results. Data from testing was included, though analysis and discussion of the vapour diffusion resistance factors obtained through testing was not included in the research study.



	Relative Humidity				
Cup	0%	0%	0%	93%	93%
Chamber	30%	50%	80%	50%	80%
Avg	15%	25%	40%	71.5%	86.5%

Figure 2.12 – WFIB Vapour Permeability as a Function of Average Specimen Relative Humidity(Goto et al., 2011).

As previously mentioned, Sonderegger et al. conducted extensive testing of WFIB products (refer to Section 2.5.1). Dry cup (cup 0%, chamber 65%) and wet cup (cup 100%, chamber 65%) testing was completed (Sonderegger & Niemz, 2012). The test results indicated that dry processed boards had a higher vapour permeability than wet processed boards. For both wet and dry processed, the wet cup vapour permeability was found to be greater than dry cup vapour permeability. The wet cup vapour permeability varied from approximately 85-135 ng/msPa, and the dry cup vapour permeability varied from approximately 55-75 ng/msPa. Note that the average permeability for dry processed boards provided in Sonderegger et al. research is for WFIB with a density range of 50-240 kg/m^3.

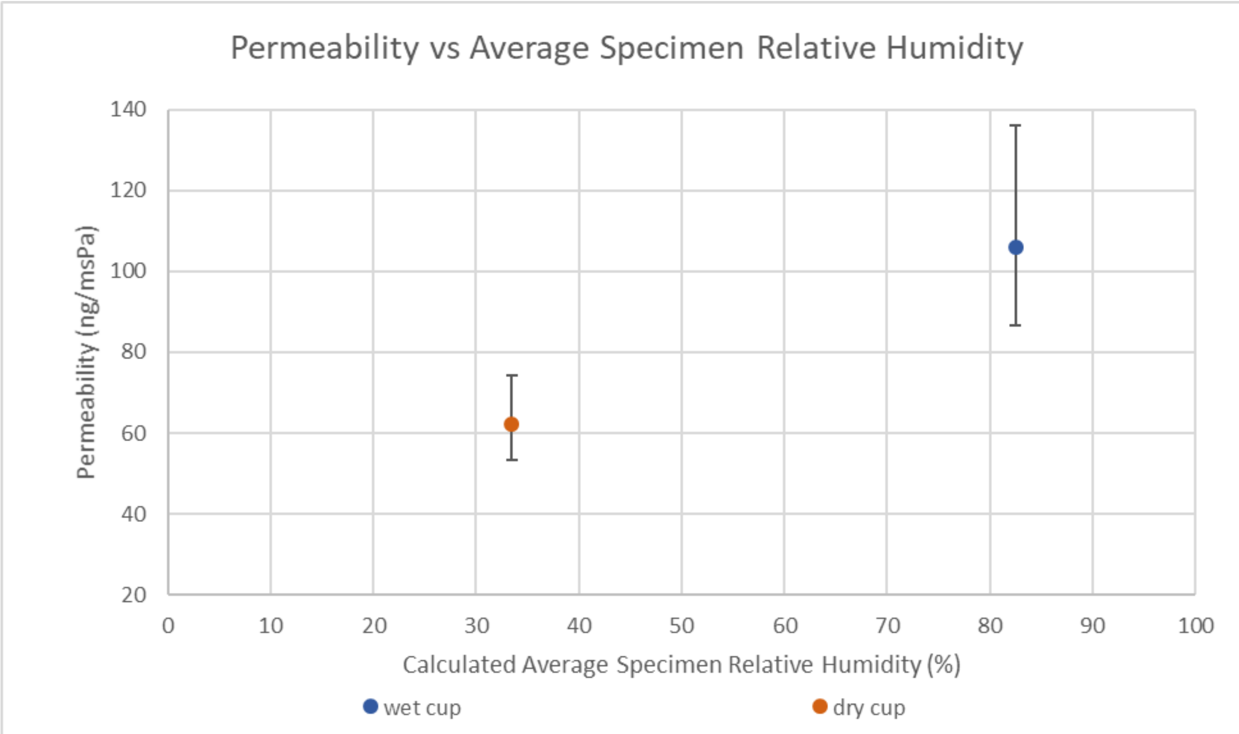


Figure 2.13 - Dry Cup and Wet Cup Permeability vs Calculated Average Specimen Relative Humidity (Sonderegger & Niemz, 2012).

Palumbo et al. conducted research on the thermal and hygroscopic properties of bio-based building materials, including wood fibre density 212 kg/m^3, and wood wool density 60.2 kg/m^3 (Palumbo, Lacasta, Holcroft, Shea, & Walker, 2016). Dry cup (cup 9%, chamber 60%) and wet cup (cup 79%, chamber 60%) testing at 20˚C was completed, and a simplified linear fitting equation between the dry cup and wet cup results indicated increase in permeability with an increase in relative humidity. The increase in permeability from dry cup to wet cup of for wood wool was 17% and for WFIB was 57%. The less dense wood wool had a greater permeability than the more dense WFIB for both wet cup and dry cup testing.

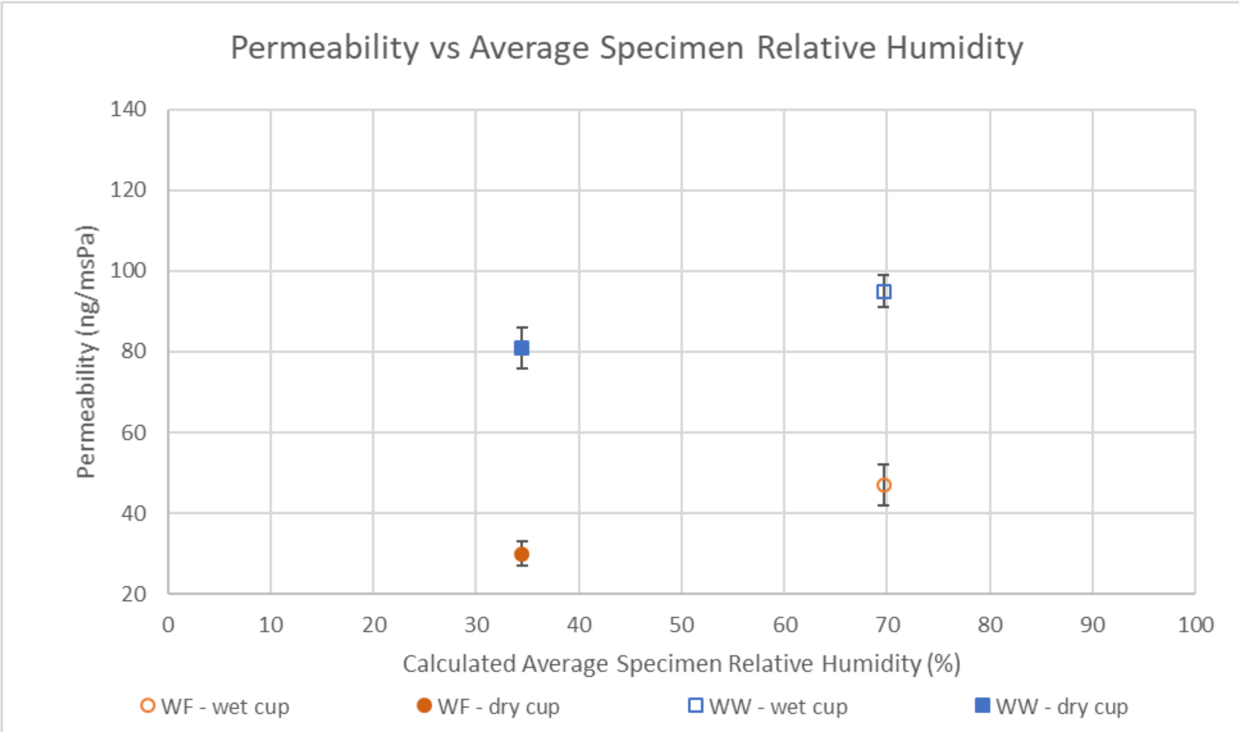


Figure 2.14 - Dry Cup and Wet Cup Permeability vs Calculated Average Specimen Relative Humidity (Palumbo et al., 2016).

This research aims to study the permeability of WFIB at numerous average specimen relative humidities, as well as dry cup and wet cup testing conditions. The WFIB products included in this study represent a larger variety of products with similar densities manufactured through the dry process and in a variety of thicknesses. The current research reveals a small amount of data for WFIB for numerous average specimen relative humidities. A larger group of similar density materials are tested in this research, including analyzing the impact of specimen thickness. Current research for wet cup and dry cup testing indicates an increase in permeability with increasing relative humidity, though impact of material properties such as density and thickness are not considered. Additionally, this research aims to contribute to the impact of temperature on WFIB permeability, which is lacking in current research.

2.5.3 WFIB Moisture and Temperature Dependent Thermal Conductivity

The thermal conductivity behavior of WFIB has been studied in recent history. Research by Kaemmerlen et al. investigated the radiative and conductive heat transfer properties of WFIB (170 kg/m^3) (Kaemmerlen, Asllanaj, Sallée, Baillis, & Jeandel, 2010). It was found that the radiative heat transfer was negligible, though it may be notable for lower density wood insulation products. The results concluded that an equivalent total conductivity is a valid means of predicting heat transfer for WFIB of density 170 kg/m^3.

As previously mentioned, Palumbo et al. conducted research on the thermal and hygroscopic properties of bio-based building materials (refer to Section 2.5.2). The research investigated the influence of relative humidity on thermal conductivity of wood fibre insulation materials with a mean temperature of 20˚C and temperature gradient of 20˚C (Palumbo et al., 2016). Wood fibre insulation materials at 20˚C and at various relative humidities were found to have a linear trend of increasing thermal conductivity with increasing relative humidity. Thermal conductivity ranged from 0.054 W/mK to 0.065 W/mK for WFIB, and 0.034 W/mK to 0.045 W/mK for wood wool, for relative humidity range of 10-90%.

As previously mentioned, Sonderegger et al. conducted extensive testing of WFIB products (refer to Section 2.5.1). Research included temperature and moisture dependent thermal conductivity using a heat flow meter at a mean temperature of 20˚C and relative humidities of oven dried, 35%, 65%, 80% RH. One specimen was studied at mean temperatures ranging from 10˚C to 30C along with the previously stated relative humidities (Sonderegger & Niemz, 2012). The tests indicated that thermal conductivity of WFIBs increased with density. Additionally, the WFIB products manufactured through the dry process are associated with higher thermal conductivities then WFIB products manufactured through the wet process. It was determined that the variation in thermal conductivity due to manufacturing process is likely related to glue process, porosity distribution, but predominately orientation of the fibres in the board as the dry process materials have more vertically oriented fibres than the wet process materials. Similar to previous research, it was determined that WFIB thermal conductivity increased linearly with increasing relative humidity.

Experiments and computer modeling conducted by Ye et al. investigated a WFIB produced through the wet process (160 kg/m3). Modeling results indicate that thermal conductivity increased non-linearly with relative humidity, inversely related to the experimentally confirmed non-linear decrease in porosity of material with an increase in relative humidity (Ye, 2015). Thermal conductivity increased from approximately 0.045 W/mK to 0.12 W/mk from 60-95%.

As previously noted, in 2010 Goto et al. conducted research that included preliminary testing of 4 different WFIB materials (Goto et al., 2011). Thermal conductivity was measured using a guarded hot plate, and specimens were at 23C and 80% RH, or oven dry prior to testing. The experimental results indicated a linear dependence of thermal conductivity on relative humidity, with a range of thermal conductivity increase by 4.4-9.8%.

Abdou et al. conducted research of various insulation materials to determine the temperature dependence performance of the thermal conductivity. The insulation materials included a wood wool material (348.2 kg/m^3) (Abdou & Budaiwi, 2005). The experimental results indicated that the thermal conductivity of wood wool at a mean temperature 4˚C, 10˚C, 24˚C, 38˚C, and 43˚C, increased linearly from 0.065 W/mK to 0.075 W/mK.

This research aims to study the thermal conductivity of WFIB at various moisture contents and temperatures. The WFIB researched includes a greater variety of products with similar densities manufactured through the dry process and in a variety of thicknesses. The current research comprises several different dry process WFIBs with similar densities to those included in this research. However, the temperature range and moisture content range of thermal conductivity testing for this research is broader than that of previous research, ensuring temperatures below 0˚C are investigated.

3 Methodology

Characterization of the hygrothermal properties of wood fibre insulation testing included testing temperature dependent moisture sorption, temperature and relative humidity dependent vapour permeability, and temperature and moisture dependent thermal conductivity. The moisture sorption specimens were tested to determine the dry density.

Table 3.1 - WFIB Test Descriptions.

Test	Variables	Description
Moisture sorption	• relative humidity • temperature	Conditioning WFIB specimens in environmental chamber at defined temperatures for various successively increasing relative humidity test conditions, weighing until steady state mass obtained.
Vapour permeability	• cup relative humidity • chamber relative humidity • temperature	Conditioning WFIB specimens in environmental chamber at defined temperatures for various cup and chamber relative humidity test conditions, weighing intermittently to determine mass gain/loss over time.
Thermal conductivity	• chamber relative humidity • heat flow meter average temperature	Pre-conditioning WFIB specimens in environmental chamber and then testing at various temperatures using heat flow meter.

3.1 Materials

As outlined in Section 2.1, WFIB is an exterior insulation that is available in a wide variety of products designed for specific construction applications (ex. roof, wall, rain screen, etc.), densities, and thicknesses. The WFIB materials tested in this research are medium-density products designed for exterior insulation in rain screen wall assemblies. A total of 6 WFIB materials in thicknesses of 40mm, 60mm, and/or 80mm were obtained from 4 different European manufacturers, for a total of 9 different WFIB materials. All materials were manufactured by the dry process. Materials 1-4 and 6 were received as full boards with a minimum quantity of 3 boards per thickness of each material. A single board per thickness of Material 5 was received, and each board was cut into thirds prior to receiving. Therefore, it is important to note that all tests completed for product 5 are for a single board for each product thickness. All materials were stored at Ryerson University. Refer to Table 3.2 for product and thickness details.

Table 3.2 - WFIB Product Details

Material #	Thickness			Material Details		
	40mm (.1)	60mm (.2)	80mm (.3)	Declared Density (kg/m3)	Raw materials	Quantity
1	1.1	-	-	140	95% wood fibres (spruce, fir), 4% polyurethane, 1% paraffin	3 boards of each thickness
2	2.1	2.2	-	145	95.5% wood fibres (coniferous), 4% polyurea, 0.5% paraffin	3 boards of each thickness
3	3.1	-	-	110	wood fibres (coniferous), polyurethane, paraffin, ammonium sulfate*	3 boards of each thickness
4	4.1	4.2	-	180	wood fibres (coniferous), polyurethane, paraffin, ammonium sulfate*	3 boards of each thickness
5	-	5.2	5.3	140	95.2% wood fibres, 4% PMDI, % paraffin	1 board of each thickness
6	-	6.2	-	180	94.5% wood fibres (spruce, fir), 4% polyurethane, 1.5% paraffin	3 boards of each thickness

*component percentages not known

3.2 Temperature Dependent Water Vapour Sorption

3.2.1 Material Selection and Specimen Preparation

From the WFIB materials obtained, 7-13 moisture sorption specimens for each material were cut to approximately 75mm x 75mm using a bandsaw. For materials 1.1, 2.1, 2.2, and 6.2, 7 specimens were cut from 3 boards, with 2-3 specimens from each board. Due to the scheduling of testing and the timing of receiving materials, for materials 3.1, 4.1, 4.2, and 4.2, it was required that 13 specimens were cut from 3 boards, with 4-5 specimens from each board (refer to Section 3.3.2). Due to the scheduling of testing, timing of receiving materials, and limited material quantities, for materials 5.2 and 5.3, it was required that 13 specimens were cut from a single board (refer to Section 3.3.2).

Table 3.3: Material Selection for Moisture Sorption Specimens

Product	Specimen No.	Product Board No.
1.1, 2.1, 2.2, 3.1(B), 4.1(B), 4.2(B), 4.2(B), 6.2	01(B), 07, 04(B)	Board 1
	02(B), 05(B)	Board 2
	03(B), 06(B)	Board 3
5.2(B), 5.3(B)	01(B), 02(B), 03(B), 04(B), 05(B), 06(B), 07	Board 1

Each specimen size was measured using a digital caliper with a precision of 0.01mm, based on the calculated average height, width, and length. The calculated average height, width, and length were determined by measuring the height at 8 locations, width at 4 locations, and length at 4 locations.

3.2.2 Laboratory Testing

Moisture sorption testing was completed at George Brown College (GBC) building science laboratory between February to July 2018 and was carried out simultaneously with the vapour permeance testing. Moisture sorption testing was conducted using insect growth chambers 6045 series as environmental chambers with both temperature and relative humidity control. The chambers have a manufacturer specified temperature control ±0.1˚C, temperature uniformity ±0.3˚C, and relative humidity control of ±2%. Temperature and relative humidity data were collected at five-minute intervals throughout the duration of the testing. Throughout the duration of the experiment, specimens were weighed using a Mettler Toledo XP1203S scale with a precision of 0.001g.

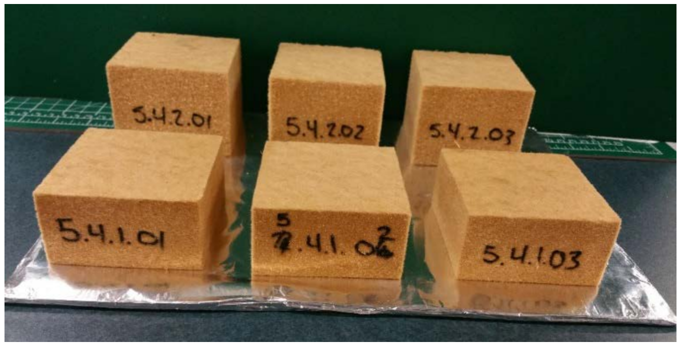
Moisture sorption testing was carried out at several relative humidity conditions for both 25˚C and 10˚C. The relative humidity conditions for moisture sorption testing are outlined in Table 3.4. For materials 1.1, 2.1, 2.2, and 6.2, specimens 01-06 were tested at all RH steps. Due to the scheduling of testing and timing of receiving materials, moisture sorption testing was completed with 2 sets of specimens for materials 3.1, 4.1, and 4.2. For materials 3.1, 4.1, and 4.2, specimens 01B-06B were tested at RH steps 35%, 50%, and 75%, and specimens 01-06 were tested at 85% and 95% (if applicable). For materials 5.2 and 5.3, specimens 01B-06B were tested at all RH steps.

Table 3.4: Moisture Sorption Temperature and Relative Humidity Testing Conditions.

<table>
<tr><td></td><td colspan="5">Relative Humidity Step</td></tr>
<tr><td></td><td>35%</td><td>50%</td><td>75%</td><td>85%</td><td>95%</td></tr>
<tr><td>Temp. 25˚C
(Test .1)</td><td colspan="5">Products 1.1, 2.1, 2.2, 3.1(B), 4.1(B), 4.2(B), 4.2(B), 5.2(B), 5.3(B), 6.2
Specimens 01(B), 02(B), 03(B), 07
ex. 1.1.01.1
Product # Specimen # Temp. Test #</td></tr>
<tr><td>Temp 10˚C
(Test .2)</td><td colspan="4">Products 1.1, 2.1, 2.2, 3.1(B), 4.1(B), 4.2(B), 4.2(B), 5.2(B), 5.3(B), 6.2
Specimens 04(B), 05(B), 06(B)
ex. 1.1.04.2
Product # Specimen # Temp. Test #</td><td>N/A</td></tr>
</table>

Prior to moisture sorption testing, specimen 07 for all materials was placed in a drying oven at approximately 100˚C. The specimens were weighed daily until a constant dry mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant dry mass were based on a change of mass less than 0.1% during three consecutive daily weighings as per ASTM C1498 standards (ASTM International, 2016a). Specimen 07 for all materials was oven dried prior to moisture sorption testing to determine the impact of oven drying WFIB materials on material moisture sorption. Sorption testing for an oven dried specimen for each product was performed to determine the impact of oven drying on the materials ability store moisture. Oven drying of wood materials has been shown to decrease wood materials ability to store moisture by increasing the cell wall matrix stiffness (Altgen et al., 2016).

All specimens were conditioned to the ambient temperature and relative humidity in the laboratory. After initial weighing, specimens were place in the environmental chamber on a tray that included 3-6 specimens as shown in Photograph 3.1. Specimens were left undisturbed for 2-3 days and then weighed daily. For weighing, the entire tray of 3-6 specimens was removed from the environmental chamber. Care was taken to minimize the amount of time that the chamber door was open between removing and returning each tray. Additionally, each specimen was weighed individually as quickly as possible to avoid moisture gains/losses while outside the environmental chamber. Trays were utilized to remove 3-6 specimens from the chamber to minimize the number of times that the chamber door was opened and closed.



Photograph 3.1: Moisture Sorption Test Specimens on Tray.

The specimens were weighed daily until a constant mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant mass were based on a change of mass less than 0.1% during three consecutive daily weighings as per ASTM C1498 standards (ASTM International, 2016a). Once constant mass was attained, the relative humidity step was deemed completed. However, test scheduling restraints resulted in constant mass assumed to be obtained when the change of mass was greater than 0.1%. If visible mould growth occurred on the test specimen, the test specimen was removed from the chamber, a final weighing was recorded, and the relative humidity step was deemed complete. Once the relative humidity step testing was completed, the chamber relative humidity settings were changed to the subsequent relative humidity test condition and the test procedure was repeated until all relative humidity steps were completed.

Following the completion of the final relative humidity test condition for moisture sorption testing, specimens were removed from the environmental chamber and placed in a drying oven at approximately 100˚C. The specimens were weighed daily until a constant dry mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant dry mass were based on a change of mass less than 0.1% during three consecutive daily weighings as per ASTM C1498 standards (ASTM International, 2016a). The mass of the dry specimens was used to determine the moisture content of each specimen at each relative humidity test condition using the equation (1) as discussed in Section 2.3.1.1.5.

3.3 Moisture and Temperature Dependent Water Vapour Permeance

3.3.1 Material Selection and Specimen Preparation

From the WFIB materials obtained, 6 vapour permeance specimens for each material were cut to approximately 90-100mm diameter discs using a bandsaw. For materials 1.1, 2.1, 2.2, 3.1, 4.1, 4.2 and 6.2, the disc diameter was cut to approximately 92mm to accommodate the test cup used for vapour permeance testing. For materials 5.2 and 5.3, the disc diameter was cut to approximately 100mm to accommodate the test cup used for vapour permeance testing. For materials 1.1, 2.1, 2.2, 3.1, 4.1, 4.2 and 6.2, the 6 specimens were cut from 3 boards, with 2 specimens from each board. Due to limited materials quantities, for materials 5.2 and 5.3, it was required that 6 specimens were cut from a single board.

Table 3.5: Material Selection for Vapour Permeance Specimens

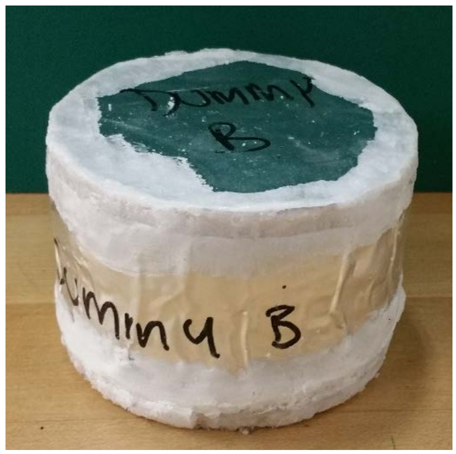
Product	Specimen No.	Product Board No.
1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 6.2	01, 04	Board 1
	02, 05	Board 2
	03, 06	Board 3
5.2, 5.3	01, 02, 03, 04, 05, 06, 07	Board 1

Each specimen size was measured using a digital caliper with a precision of 0.01mm, based on the calculated average height and diameter. The calculated average height and diameter were determined by measuring the height at 4 locations, and diameter at 4 locations.

Edge masking was applied to the specimen edges through several steps. The specimen edges were carefully sealed with a melted paraffin wax. Care was taken to ensure that the wax hardened upon contact with the specimen edge and did not permeate into the specimen, and that the wax did not cover any of the top or bottom surface of the specimens. The wax edge was then allowed time to completely cool to room temperature. The specimen edges were then sealed with aluminum foil tape 2-4mm below and above the top and bottom surface of the specimens, respectively. The aluminum foil tape was smoothed to ensure continuous contact with the wax edging. Lastly, the interface at the edge of the aluminum foil tape and the wax near the top and bottom surfaces were sealed with additional paraffin wax.

Photograph 3.2: Vapour Permeance Specimens with Edge Masking.

Several dummy specimens were prepared to determine any vapour permeance through the edge masking of the vapour permeance specimens. Dummy specimens were cut and measured using a digital caliper, and edge masking applied, through the same process as the vapour permeance specimens. The top surface of the dummy specimens was then sealed with melted paraffin wax and aluminum foil. Lastly, the interface of the aluminum foil and the wax at the top of the specimen was sealed with additional paraffin wax.



Photograph 3.3 - Vapour Permeance Dummy Specimen.

3.3.2 Laboratory Testing

Vapour Permeance testing was completed at GBC building science laboratory between February to July 2018 and was carried out simultaneously with the moisture sorption testing. Vapour permeance testing was conducted using the environmental chambers described in Section 3.2.2. Temperature and relative humidity data were collected at five-minute intervals throughout the duration of the testing. Throughout the duration of the experiment, specimens and assemblies were weighed using the Mettler Toledo XP1203S scale described in Section 3.2.2.

Vapour permeance testing was carried out at several relative humidity gradients for both 25˚C and 10˚C. The cup and chamber relative humidity conditions and gradients for vapour permeance testing are outlined in Table 3.6. Modified vapour permeance testing was conducted for tests .1 through .5, using either desiccant ($CaCl_2$) or saturated salt solutions to control the relative humidity within the cup, and using the environmental chamber to control the relative humidity in the chamber. Saturated salt solutions create an environment of constant relative humidity for a given temperature, so long as the salt solution remains saturated. The relative humidity maintained by the saturated salt solution is specific to the salt. The rationale for the modified vapour permeance test method was to determine the vapour permeance of WFIB at a variety relative humidity conditions. WFIB is nearly entirely comprised of wood and hence is a hygroscopic material, and as such will take on water as relative humidity conditions increase. Additionally, fibrous swelling due to increased water uptake may impact the porosity of the WFIB material. For these reasons, WFIB permeance would be expected to vary with relative humidity.

Dry cup and wet cup testing according to ASTM E96 was conducted for tests .6 and .7, using either desiccant ($CaCl_2$) or distilled water to control the relative humidity within the cup and using the environmental chamber to control the relative humidity in the chamber (ASTM International, 2016b). Materials 1.1, 2.1, 2.2, and 6.2 were completed in test order .1 through .6. Due to the scheduling of testing and timing of receiving materials, vapour permeance testing for materials 3.1, 4.1, and 4.2 were completed in test order .4, .5, .1, .2, .7, .3.

Table 3.6 - Vapour Permeance Test Conditions

Test	.1	.2	.3	.4	.6 Wet Cup	.7 Dry Cup
Chamber RH (%)	35%	50%	75%	85%	50%	50%
Cup RH (%)	2%	33%	54%	76%	100%	2%
Cup Substance	Desiccant	$MgCl_2 \cdot 6H_20$	$MgNO_3 \cdot 6H_20$	NaCl	H_20	Desiccant
RH Gradient	33%	17%	24%	13%	50%	48%
Calc. Avg. RH (%)	19%	42%	66%	82%	75%	26%
Gradient (Pa)	1010	513	723	402	1503	1465
Temp. 25˚C (Test .1)	Products 1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 4.2, 5.2, 5.3, 6.2 Specimens 01, 02, 03 ex. 1.1.01.1 Product # / Specimen # / Temp. Test #					
Temp. 10˚C (Test .2)	Products 1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 4.2, 5.2, 5.3, 6.2 Specimens 04, 05, 06 ex. 1.1.04.2 Product # / Specimen # / Temp. Test #					

The calculated average relative humidity of the specimen for each test condition was calculated based on the arithmetic mean of the chamber and cup relative humidities. The calculated average relative humidity is assumed to be at the mid-point of the material thickness. Therefore, a linear relative humidity throughout a material across a relative humidity gradient is assumed. However, it is expected that the material experiences a non-linear relative humidity throughout the material thickness (ASTM International, 2016b). A comparison of the linear relative humidity and the non-linear relative humidity throughout a specimen across a relative humidity gradient is provided in Figure 3.1. The relative humidity likely experienced at the mid-point of the material is expected to be slightly greater than the calculated average relative humidity, though the difference is likely very small (ASTM International, 2016b).

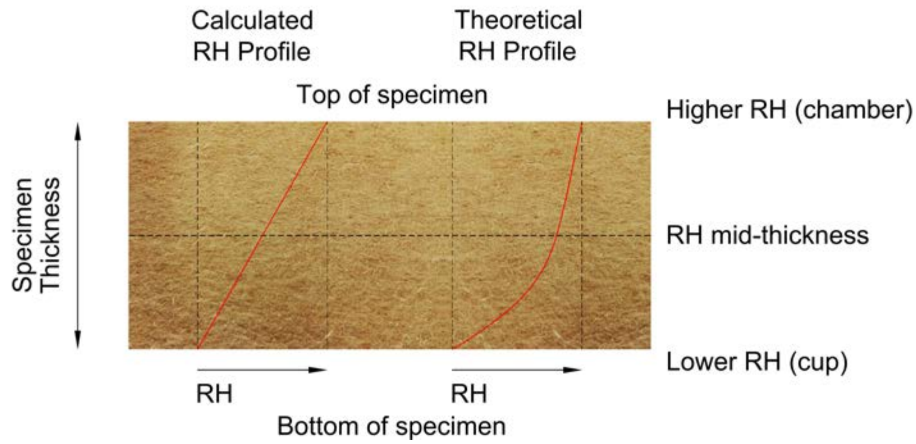
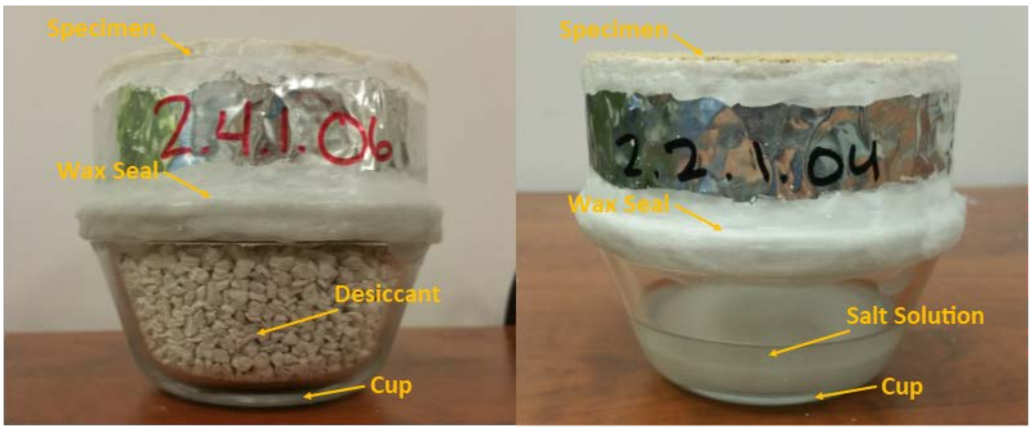


Figure 3.1 - Calculated Relative Humidity Profile vs Theoretical Relative Humidity Profile.

For each vapour permeance test, the cup substance (desiccant, distilled water, or saturated salt solution) used to control the cup relative humidity was placed in the cup. Desiccant was dried at 200C for 90 minutes as per manufacturer's specifications. The vertical distance between the inner lip of the cup and the top of the cup substance was measured using a ruler to the nearest 1mm; this vertical distance is the thickness of the air space between the bottom surface of the test specimen and the cup substance. The air space thickness varied by test type. For dry cup (test .6) testing the air space thickness was approximately 6-10mm. For wet cup (test .7) testing the air space thickness was approximately 15-20mm. For all other vapour permeance tests, the air space thickness was approximately 30-35mm. It was difficult to determine the exact the air space thickness due to the air space being measured prior to actual placement of the specimen on the cup. Paraffin build up on the edge of the specimen occasionally resulted in the specimen sitting slightly above the cup lip, and therefore the air space thickness was greater than the measured air space thickness. However, the inaccuracy of the air space measurement due to placement of the specimen is expected to be minimal.

The edge masked vapour permeance specimen was then placed on the inner lip of the cup and heated wax coated along the cup and specimen interface to seal the specimen to the cup. The sealed cup and specimen assembly is referred to as the test assembly specimen. The test conditions created a relative humidity gradient across the test specimen based on the chamber and the cup relative humidity conditions. The low to negligible vapour permeance of the edge masking, the paraffin wax sealant, and the glass cup, ensures that any vapour entering or leaving the cup passes through the WFIB specimen.

Dummy specimens were assembled to cups through the same process as the vapour permeance specimens. Due to the masking of the top surface of the dummy specimens, the vapour entering or leaving the cup through the edge masking and/or wax sealant at the specimen cup interface may be determined by any mass change of the dummy test assembly specimens.



Photograph 3.4 - Vapour permeance test assembly specimens.

All specimens were conditioned to the ambient temperature and relative humidity in the laboratory. After initial weighing, specimens were placed in the environmental chamber on a tray that included 3-6 specimens. Specimens were left undisturbed for 2-3 days and then weighed 1-2 times per day for at least 4 days. Test objectives for minimum weight change between weighings were 0.1g, such that the scale would be sensitive to 1% of the weight change as per ASTM E96 standards (ASTM International, 2016b). However, test scheduling restraints resulted in weight change between weighings that were less than 0.1g, but typically not less than 0.01g. For weighing, the entire tray of 3-6 specimens was removed from the environmental chamber. Care was taken to minimize the amount of time that the chamber door was open between removing and returning each tray. Additionally, each specimen was weighed individually as quickly as possible to avoid moisture gains/losses while outside the environmental chamber. Trays were utilized to remove 3-6 specimens from the chamber to minimize the number of times that the chamber door was opened and closed.

Once data from 8-10 weighings was collected as per ASTM E96, the chamber and cup relative humidity test condition was deemed completed. After completion of the test condition, the test assembly specimens were disassembled by using a utility knife to cut the wax sealing the WFIB specimen to the cup. The vapour permeance specimen was then removed from the cup, the cup substance was removed, and the cup was cleaned. The vapour permeance specimen was inspected to ensure that the edge masking was intact, and any disrupted edge masking was repaired by applying melted paraffin wax. The test procedure was repeated for preparing and testing the test assembly specimens for the all chamber and cup relative humidity test conditions.

The vapour permeance for each specimen was calculated using a formula for steady-state of Fick's law of fundamental diffusion mass flow relationship, without consideration of the material thickness:

$$\bar{P}_{test} = {W_v}/{\left(A\Delta t(p_1 - p_2)\right)} \quad (5)$$

Where,

$\bar{P}_{test}$ = average permeance of the material from test, over the pressure gradient involved $\left({ng}/{(Pa \cdot s \cdot m^2)}\right)$

W_v = total mass of water vapour transmitted (ng)

A = cross-sectional area of the flow path (m^2)

Δt = time interval (s)

p_1 = vapour pressure on side 1 of the material (Pa)

p_2 = vapour pressure on side 1 of the material (Pa)

The vapour resistance for each specimen was then calculated as the inverse of the vapour permeance:

$$\bar{R}_{wv,test} = {1}/{\bar{P}_{WFIB,test}} \quad (6)$$

Where,

$\bar{R}_{wv,test}$ = average vapour resistance of the material from test, over the pressure gradient involved $\left({(Pa \cdot s \cdot m^2)}/{ng}\right)$

$\bar{P}_{WFIB,test}$ = average permeance of the material from test, over the pressure gradient involved $\left({ng}/{(Pa \cdot s \cdot m^2)}\right)$

Corrections for the resistance due to still air and specimen surface were calculated and applied. Still air provides a vapour resistance within the cup, therefore correction for the resistance due to still air are important to consider for highly permeable materials. As previously discussed, the air space between the specimen and the relative humidity control substance was measured for each test assembly.

$$R_{wv,air} = {}^{1}/_{P_{air}} = {}^{1}/_{\left({}^{\mu_{air}}/_{l_{air}}\right)} = {}^{l_{air}}/_{\left[\frac{2.306\times10^{-5}P_o}{R_vTP}\left(\frac{T}{273.15}\right)^{1.81}\right]} \quad (7)$$

Where,

$R_{wv,air}$ = correction for vapour resistance of still air $\left({}^{(Pa\cdot s\cdot m^2)}/_{ng}\right)$

P_{air} = permeance of still air $\left({}^{ng}/_{(Pa\cdot s\cdot m^2)}\right)$

l_{air} = thickness of still air (m)

μ_{air} = permeability of still air $\left({}^{ng}/_{(Pa\cdot s\cdot m^2)}\right)$

P_o = standard atmospheric pressure $(101325\ Pa)$

R_v = ideal gas constant for water $\left(461.5\ {}^{J}/_{(K\cdot kg)}\right)$

T = temperature (K)

P = ambient pressure (Pa)

In the absence of any measured data, the surface resistances for the inside and outside surface of the specimen were approximated as $R_{wv,surf} = 4\times10^{-5}\left({}^{(Pa\cdot s\cdot m^2)}/_{ng}\right)$.

Therefore, the corrected WFIB water vapour resistance is:

$$\bar{R}_{wv} = \bar{R}_{wv,test} - \left(R_{wv,air} + R_{wv,surf}\right) \quad (8)$$

Where,

$\bar{R}_{wv}$ = corrected vapour resistance of material $\left({}^{(Pa\cdot s\cdot m^2)}/_{ng}\right)$

The final permeability of the WFIB material could then be calculated from the corrected vapour resistance of the WFIB material:

$$\bar{\mu} = {}^{l}/_{\bar{R}_{wv}} \tag{9}$$

Where,

$\bar{\mu}$ = calculated average permeability of the material, over the pressure gradient involved $\left({}^{ng}/_{(Pa \cdot s \cdot m)}\right)$

$\bar{R}_{wv}$ = corrected vapour resistance of material $\left({}^{(Pa \cdot s \cdot m^2)}/_{ng}\right)$

Previous research by Comstock indicated higher values of permeability for steady and un-steady state tests when materials were experiencing desorption, therefore when materials were subjected to at least one relative humidity lower than the specimen relative humidity. Several tests conducted through this research were completed when the material may have been in desorption, therefore permeability results may be greater than if results had been obtained with the material in adsorption.

3.4 Temperature and Moisture Dependent Thermal Conductivity

3.4.1 Material Selection and Specimen Preparation

From the WFIB materials obtained, 3 thermal conductivity specimens for each material were cut to approximately 300mm x 300mm using a bandsaw. For material 6.2, the thermal conductivity specimens were cut to approximately 150mm x 150mm. For materials 1.1, 2.1, 2.2, 3.1, 4.1, 4.2, and 6.2, each specimen was cut from a separate board. Due to limited material quantities, for materials 5.2 and 5.3, it was required that 3 specimens were cut from a single board.

Table 3.7: Material Selection for Thermal Conductivity Specimens

Product	Specimen No.	Product Board No.
1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 4.2, 6.2	01	Board 1
	02	Board 2
	03	Board 3
5.2, 5.3	01, 02, 03	Board 1

Each specimen size was measured using a digital caliper with a precision of 0.01mm, based on the calculated average height, width, and length. The calculated average height, width, and length were determined by measuring the height at 12 locations, width at 4 locations, and length at 4 locations.

3.4.2 Laboratory Testing

Thermal conductivity testing was completed at Ryerson University (RU) building science laboratory between February to July 2018. Thermal conductivity specimens were conditioned using an environmental chamber assembled from extruded polystyrene insulation, programmable temperature and relative humidity controllers, heat lamp, humidifier, and fan. The programmable temperature controller was set to a 25±2˚C. If the temperature within the chamber dropped below 25˚C, the heating control would be activated providing current to the heat lamp until the temperature within the chamber reached 25±2˚C. The programmable relative humidity controller was set according to the specific test conditions with a differential of 5%. If the relative humidity within the chamber dropped below the set relative humidity, the humidification controller would be activated providing current to the humidifier until the relative humidity within the chamber was within 5% of the relative humidity setting. Temperature and relative humidity data for the chamber was collected at 30 second intervals using a HOBO data logger. Throughout the duration of the experiment, specimens were weighed using a scale with a precision of 0.5g.

Photograph 3.5 - Environmental Chamber Used to Condition Thermal Conductivity Specimens.

Conditioning of the thermal conductivity specimens was carried out at 25 ˚C with relative humidity settings of approximately 30%, 60%, 80%, and 95%, as outlined in Table 3.7. For each material, 3 specimens were conditioned in the chamber for each relative humidity setting. The specimens were left undisturbed for 2-3 days and then were weighed daily until a constant mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant mass were based on a change of mass less than 1% over a 24 hour period as per ASTM C518 standard, though lower percentage mass changes were typically obtained (ASTM International, 2017). If visible mould growth occurred on the test specimen, the visible mould was dusted off the specimen using a light brush and the conditioning of the specimen continued as previously outlined. Once constant mass was attained, the specimen was removed from the chamber and wrapped with 1-2 layers of polyethylene wrap. Care was given to ensure that air bubbles were not present in the polyethylene wrap on the thermal conductivity test surface.

The thermal conductivity of the conditioned specimens was measured using a Netzsch Lambda HFM 436 heat flow meter apparatus (HFMA) and following ASTM C518 (ASTM International, 2017). The HFMA test chamber is 300mm x 300mm, with a central metering area of 100mm x 100mm. Specimens that were cut 150mm x 150mm required an insulative frame constructed from extruded polystyrene to fill the outer 75mm between the specimen and the HFM test chamber walls. The specimens were tested at an average specimen temperature of -10 ˚C, 0 ˚C, 10 ˚C, 20˚C, and 30 ˚C, consecutively, with a 10 ˚C temperature gradient between plates. The specimens 01 of all materials were also tested at the 95% relative humidity condition at the same average specimen temperature though in the reversed (30˚C, 20˚C, 10˚C, 0˚C, -10˚C). Specimens were weighed after the completion of the thermal conductivity test to determine whether the specimen mass was maintained throughout the duration of the test.

Table 3.8: Environmental Chamber Conditioning Settings for Thermal Conductivity Specimens.

Average Specimen Temp.	Relative Humidity				
	30%	60%	80%	95%	95%*
-10 ˚C	Products 1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 4.2, 5.2, 5.3, 6.2 Specimens 01, 02, 03 ex. 1.1.01 (Product # . Specimen #)				Products 1.1, 2.1, 2.2, 3.1, 4.1, 4.2, 4.2, 5.2, 5.3, 6.2 Specimens 01
0 ˚C					
10˚C					
20 ˚C					
30 ˚C					

*Thermal conductivity test temperatures reversed order.

Photograph 3.6 - Heat Flow Meter Apparatus with Specimen.

The HFMA equilibrium parameters for rough measurement was set for intervals of 1 minute until 10 successive observations yielded a thermal conductivity which fell within 8-10% of the mean value for these 10 readings. The HFMA equilibrium parameters for fine measurement was set for intervals of 1 minute until 10 successive observations yielded a thermal conductivity which fell within 0.8-1% of the mean value of these 10 readings.

Table 3.9 - HFMA Equilibrium Parameters.

Measurement rate	1/minute
Rough block size	10
Max rough %	8-10%
Fine block size	10
Max fine %	0.8-1%

Following the completion of a thermal conductivity test for a specimen, the specimen was stored in the laboratory until thermal conductivity tests for all specimens for the specific chamber relative humidity condition were completed. The chamber relative humidity setting was then changed to the next test condition and the procedure was repeated until all relative humidity test conditions were completed.

Due to the scheduling of testing and the timing of receiving materials, for materials 3.1, 4.1, 4.2, 5.2, and 5.3, testing at the 30% relative humidity conditions was during June/July 2018, at which time the relative humidity in the laboratory was greater than 30%. The environmental chamber used did not have dehumidification. Therefore, an alternate procedure was required for obtaining the approximate 30% relative humidity chamber conditions. Four small cups of $MgCl_2 \cdot 6H_20$ saturated salt solution were placed along the perimeter of a large plastic container with a locking lid to maintain the container relative humidity at 33%. The specimens for materials 3.1, 4.1, 4.2, 5.2, and 5.3 were placed in a drying oven at approximately 40 ˚C for 2-3 days. Specimens were then placed in the plastic container with the saturated salt solutions. The $MgCl_2 \cdot 6H_20$ saturated salt solution was checked daily and if the solution became too dry, diluted $MgCl_2 \cdot 6H_20$ solution was added to the cups. The specimens were left undisturbed for 2-3 days and then were weighed daily until a constant mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant mass were based on a change of mass less than 1% over a 24-hour period as per ASTM C518 standard, though lower percentage mass changes were typically obtained. Temperature and relative humidity data for the chamber was collected at 30 second intervals using a HOBO data logger. Once constant mass was attained, the specimens were tested as previously outlined.

Photograph 3.7 – Salt Solution Environmental Chamber Used to Condition Thermal Conductivity Specimens.

Following the completion of thermal conductivity tests, specimens were placed in a drying oven at approximately 100˚C. The specimens were weighed daily until a constant dry mass was obtained, indicating that no moisture was being gained or lost. Test objectives for determining constant dry mass were based on a change of mass less than 0.1% during three consecutive daily weighings as per ASTM C1498 standards (ASTM International, 2016a). The mass of the dry specimens was used to determine the moisture content of each specimen at each relative humidity test condition.

4 Results

4.1 Dry Density Results

The dry density of each product was determined using the water vapour sorption specimen dry masses and measurements. A summary of all specimen densities and average product densities is presented in Table 4.1, which includes the standard deviation (SD) and coefficient of variation (CV%) amongst the specimens of a single product. Also included in the percent difference between the declared and calculated densities.

Table 4.1 - Dry Density of Water Vapour Moisture Sorption Specimens

	Density (kg/m³)								
	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2
Declared	140	145	145	110	180	180	140	140	180
.1	135	139	162	96	197	171	134	147	164
.2	137	142	161	95	195	165	138	145	167
.3	129	141	144	95	182	167	140	152	166
.4	134	138	164	95	196	169	140	146	166
.5	138	143	162	93	194	164	139	155	165
.6	128	144	145	95	181	166	138	146	164
Avg	133	141	156	95	191	167	138	149	165
SD	*4.1*	*2.4*	*9.1*	*0.9*	*7.5*	*2.4*	*2.2*	*4.1*	*1.3*
CV%	*3.1%*	*1.7%*	*5.8%*	*0.9%*	*3.9%*	*1.4%*	*1.6%*	*2.8%*	*0.8%*
% Diff.	*-4.7%*	*-2.7%*	*7.7%*	*6.0%*	*-7.2%*	*-13.7%*	*-1.3%*	*6.2%*	*-8.1%*
Board 1 Avg	135	138	163	96	197	170	136	146	165
% Diff.	*-4.1%*	*-4.8%*	*10.8%*	*-15.0%*	*8.5%*	*-6.1%*	-2.7%	4.2%	*-8.8%*
Board 2 Avg	137	142	162	94	194	165	140	149	166
% Diff.	*-2.0%*	*-1.9%*	*10.2%*	*-16.9%*	*7.3%*	*-9.3%*	0.0%	6.1%	*-8.4%*
Board 3 Avg	128	143	144	95	181	167	138	151	165
% Diff.	*-9.1%*	*-1.6%*	*-0.4%*	*-15.9%*	*0.7%*	*-8.1%*	-1.1%	7.0%	*-9.1%*

Figure 4.1 illustrates the calculated density for each specimen for product 1.1, along with the calculated average density and the declared density. The WFIB board which each specimen was cut from is indicated. The calculated density for each specimen for all other products is provided in Appendix B.

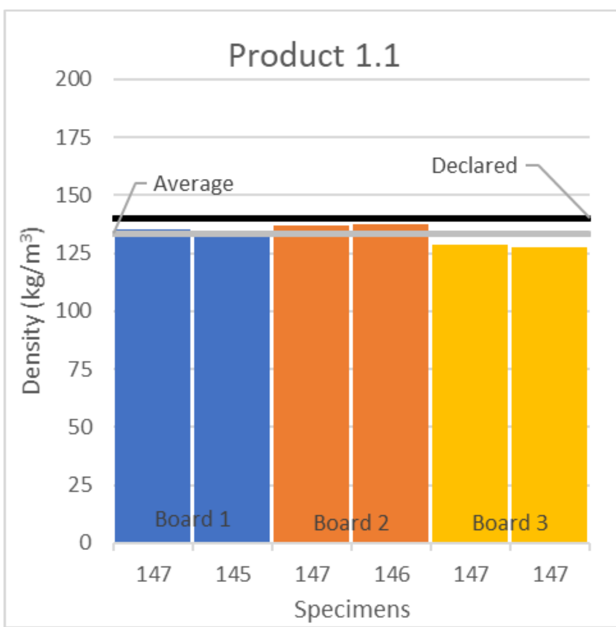


Figure 4.1 - Dry Density of Water Vapour Moisture Sorption Specimens for Product 1.1.

Figure 4.2 presents the calculated average density and declared density for all WFIB products. The products are shown in order of lowest to highest declared density (left to right).

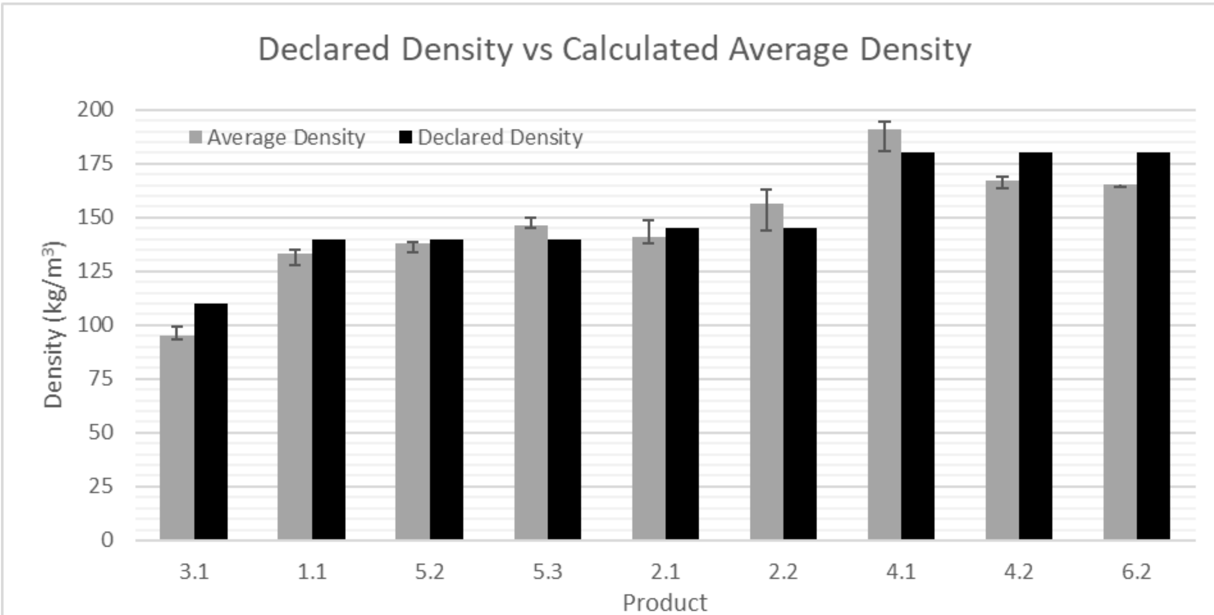


Figure 4.2 – Calculated Average Density and Declared Density for All Products.

4.2 Temperature Dependent Water Vapour Sorption Isotherm Test Results

The temperature dependent water vapour sorption isotherm testing was conducted in accordance to ASTM C1498-04A over the period of approximately 5 months. The water vapour sorption isotherm testing was conducted at temperatures of 10˚C and 25˚C and relative humidities of 35%,50%, 75%, 85%, and 95%. Three specimens for each product were tested at each temperature and relative humidity step. One specimen from each product, which was oven dried prior to testing, was tested at each temperature and relative humidity. The water vapour sorption isotherm test specimens were all approximately 75mm x 75mm x the product thickness.

Parameters investigated included sorption variance of 6 different products, 3 of which included 2 thicknesses (40mm and 60mm, or 60mm and 80mm), the impact of oven drying on sorption, and the variance at temperature conditions of 10˚C and 25˚C.

4.2.1 Mass Gain over Time

For each of the relative humidity steps during the water vapour sorption testing, the specimens were allowed to gain or lose moisture until a state of equilibrium was reached for the set temperature and relative humidity for the testing conditions. Figure 4.3 depicts the 3 specimens for product 1.1 mass versus time for the first relative humidity step of 30% at a temperature of 25˚C. The gain of moisture is evident by the upward sloping curve, and the state of equilibrium is apparent by the constant mass.

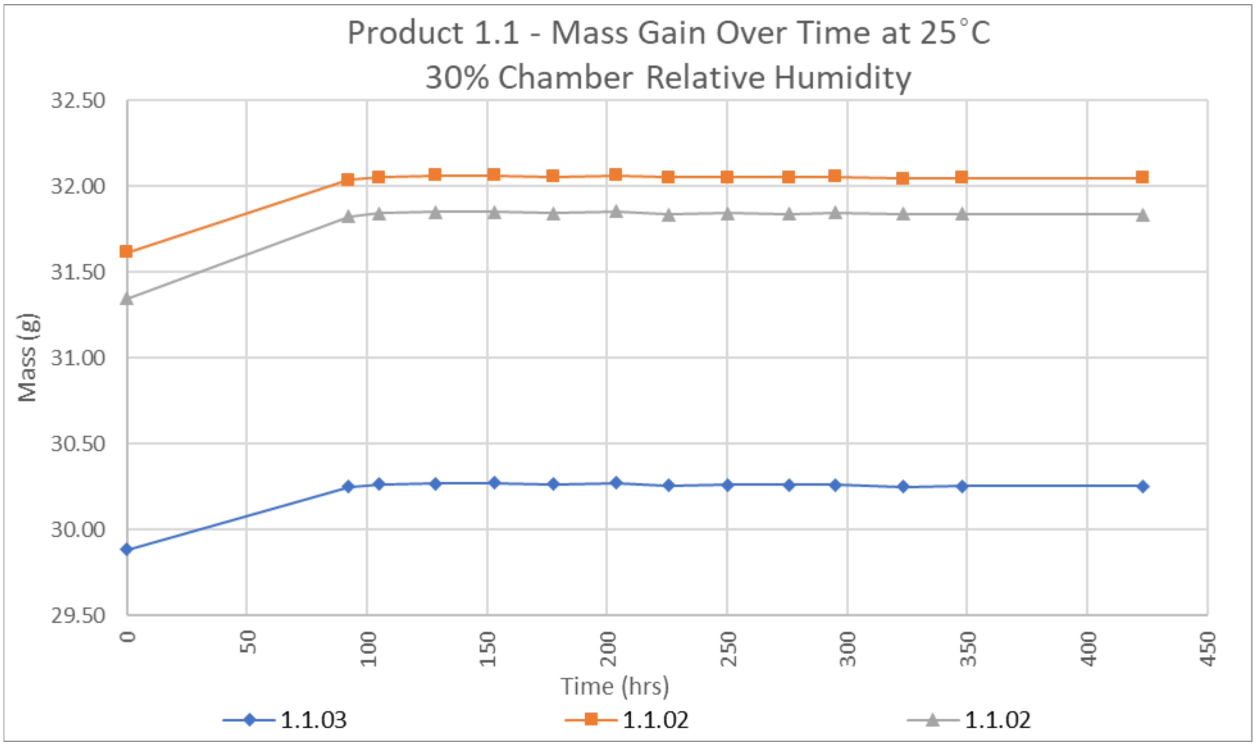


Figure 4.3 – Sorption Test Mass vs Time for Product 1.1 at 25˚C and 30% Relative Humidity.

4.2.2 Sorption Isotherms and Volumetric Moisture Content

For each test condition, the specimens were weighed until a constant mass was obtained, indicating that no moisture was being gained or lost. At the completion of testing at all relative humidity steps, the specimen was dried in an oven to determine the dry mass.

The moisture content for each relative humidity step was calculated as outlined in Section 2.3.1.1.5 using Equation (1). Moisture sorption results are displayed graphically as a sorption isotherm curve, as shown in Figure 4.4, with the x-axis representing the relative humidity percentage and the y-axis representing the moisture content percentage.

4.2.2.1 Sorption Isotherms at Temperature 25˚C

Figure 4.4 depicts the sorption isotherm curves at a temperature of 25˚C for product 1.1, including specimens 1.1.01, 1.1.02, 1.1.03, and the calculated average of the 3 specimens.

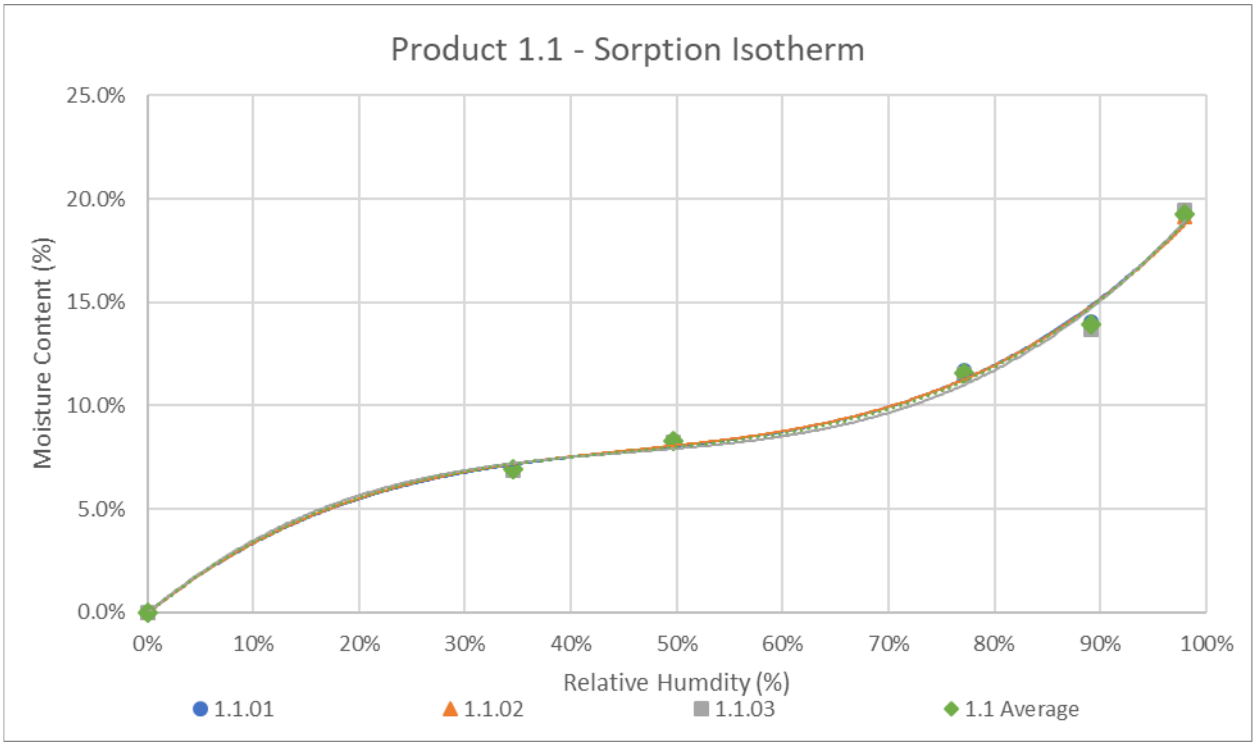


Figure 4.4 - Sorption Isotherms for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C.

Table 4.2 presents the sorption data at a temperature of 25˚C for product 1.1, including specimens 1.1.02, 1.1.02, 1.1.03, and the calculated average of all 3 specimens. The standard deviation (SD) of the calculated moisture contents at each relative humidity step for product 1.1 is included.

Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.2 The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity throughout each test period were calculated and are also included. The relative humidity data for the test conducted at 98% relative humidity (test .5) was higher than the measurement device could detect, therefore the relative humidity was approximated.

Table 4.2 - Moisture Contents for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp		RH		Specimen			1.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	1.1.01	1.1.02	1.1.03			
					MC(%)					
-	-	-	0%	-	0.0%	0.0%	0.0%	0.0%	-	-
.1	24.21	0.03, 0.13%	34.5%	0.19, 0.57%	6.9%	6.9%	6.9%	6.9%	0.00%	0.05%
.2	24.23	0.05, 0.23%	49.6%	1.73, 3.49%	8.3%	8.3%	8.2%	8.3%	0.07%	0.81%
.3	24.40	0.08, 0.34%	77.2%	1.68, 2.18%	11.7%	11.6%	11.5%	11.6%	0.10%	0.82%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	14.0%	14.0%	13.7%	13.9%	0.19%	1.35%
.5	24.44	0.13, 0.54%	98.0%	-	19.2%	19.2%	19.5%	19.3%	0.15%	0.78%

The sorption data and sorption isotherm curves for all specimens and product averages for all other products at a temperature of 25˚C are provided in Appendix C.

Figure 4.5 depicts the average sorption isotherm curves at a temperature of 25˚C for all WFIB products.

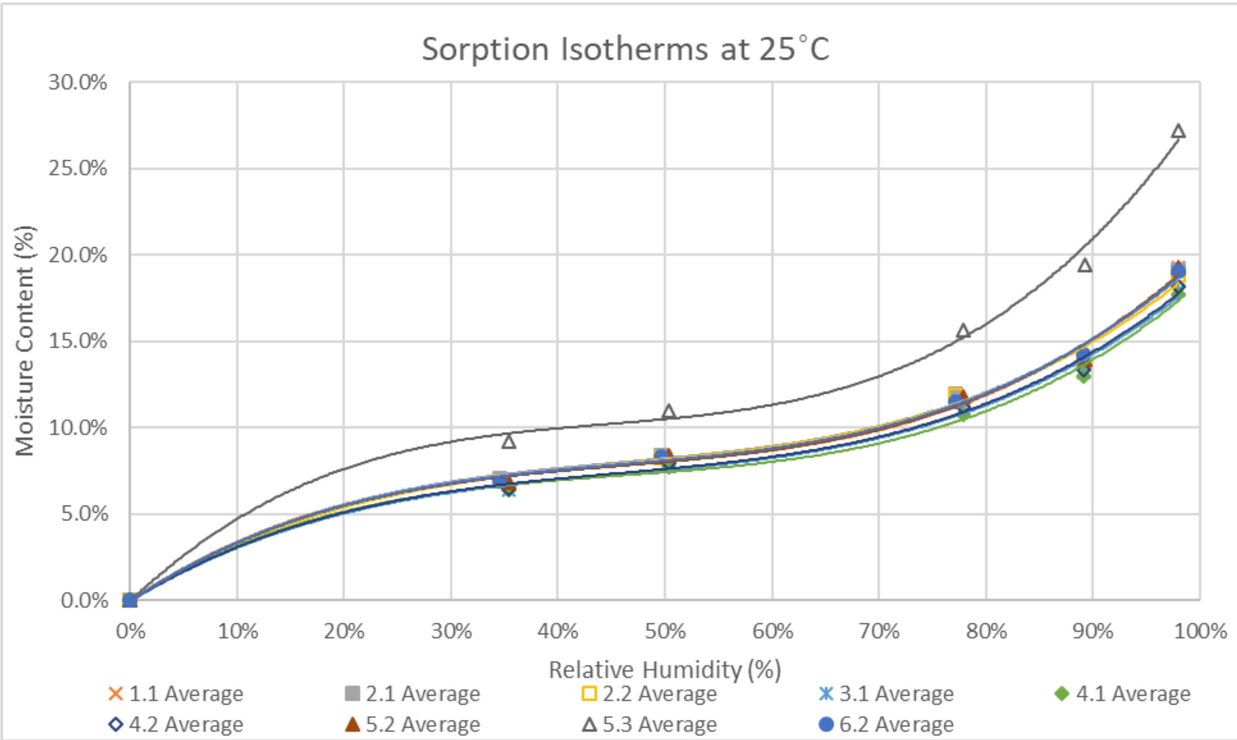


Figure 4.5 – Average Sorption Isotherms for All Products over Full Relative Humidity Range at 25˚C.

4.2.2.2 Volumetric Moisture Content Versus Relative Humidity at Temperature 25˚C

Figure 4.6 depicts the volumetric moisture content versus relative humidity curves at a temperature of 25˚C for product 1.1, including specimens 1.1.01, 1.1.02, 1.1.03, and the calculated average of the 3 specimens.

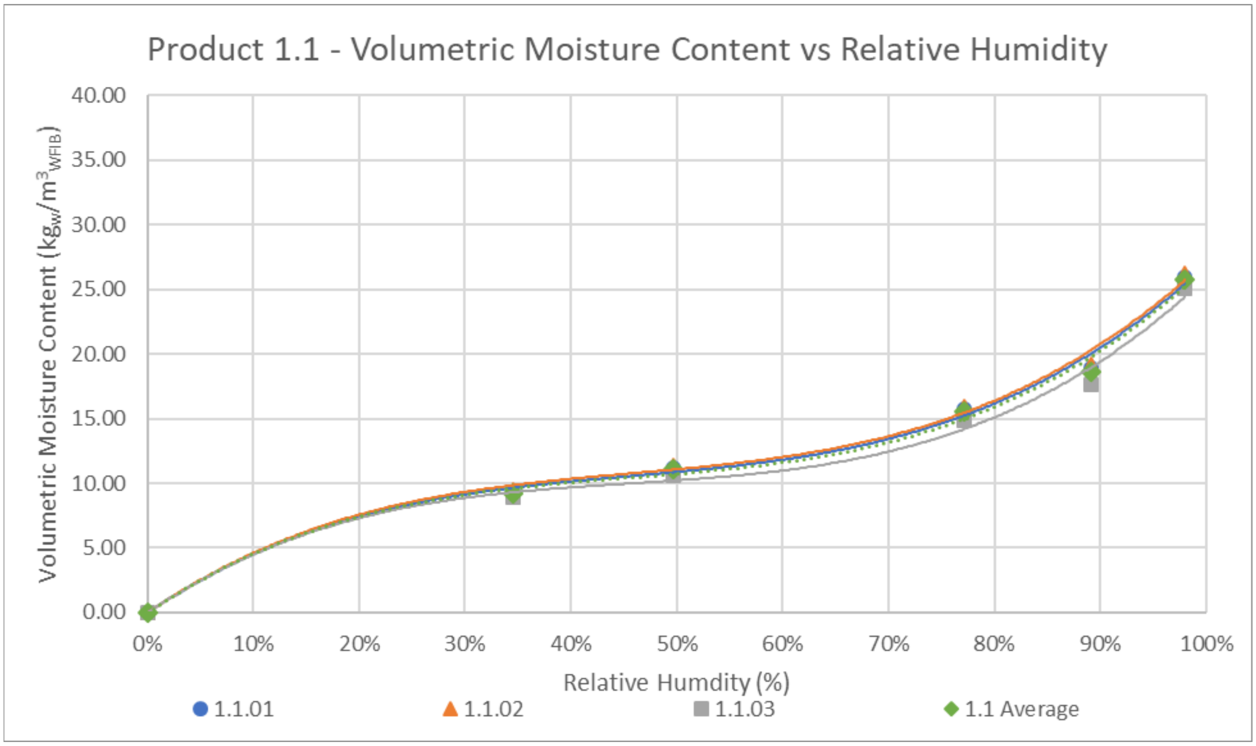


Figure 4.6 – Volumetric Moisture Content vs Relative Humidity for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C.

Table 4.3 presents the volumetric moisture content versus relative humidity data at a temperature of 25˚C for product 1.1, including specimens 1.1.02, 1.1.02, 1.1.03, and the calculated average of all 3 specimens. The standard deviation (SD) of the calculated moisture contents at each relative humidity step for product 1.1 is included.

Environmental chamber data is the same as presented in 7.2.2.1 and therefore is not included in the table.

Table 4.3 – Volumetric Moisture Contents for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 1.1.01	Specimen 1.1.02	Specimen 1.1.03	1.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
-	-	0%	0.00	0.00	0.00	0.00	-	-
.1	24.21	34.5%	9.31	9.46	8.89	9.22	0.30	3.22%
.2	24.23	49.6%	11.15	11.43	10.57	11.05	0.44	3.95%
.3	24.4	77.2%	15.77	15.96	14.82	15.51	0.61	3.93%
.4	24.44	89.1%	18.96	19.18	17.65	18.59	0.83	4.45%
.5	24.44	98.0%	25.98	26.27	25.08	25.78	0.62	2.42%

The volumetric moisture content versus relative humidity data and curves for all specimens and product averages for all other products at a temperature of 25˚C are provided in Appendix C.

Figure 4.7 depicts the average volumetric moisture content versus relative humidity curves at a temperature of 25˚C for all WFIB products.

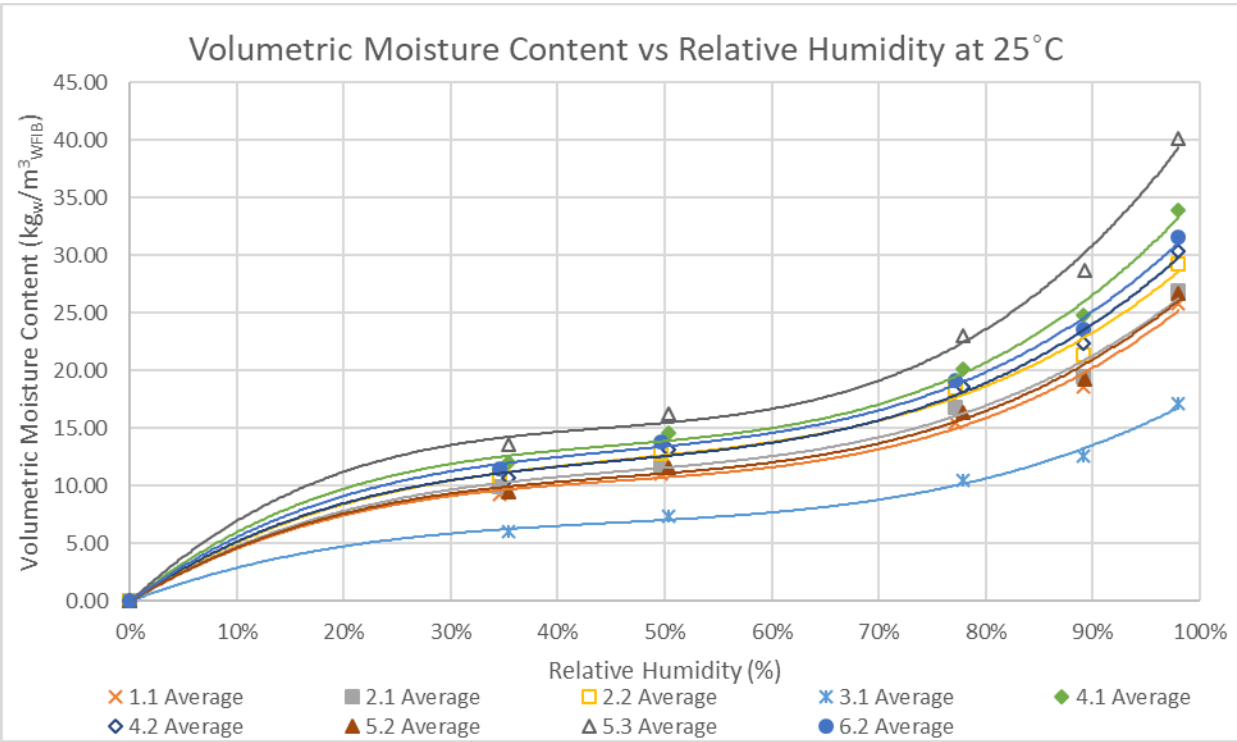


Figure 4.7 – Average Volumetric Moisture Content for All Products over Full Relative Humidity Range at 25˚C.

4.2.2.3 Sorption Isotherms at Temperature 10˚C

Figure 4.8 depicts the sorption isotherm curves at a temperature of 10˚C for product 1.1, including specimens 1.1.04, 1.1.05, 1.1.06, and the calculated average of all 3 specimens.

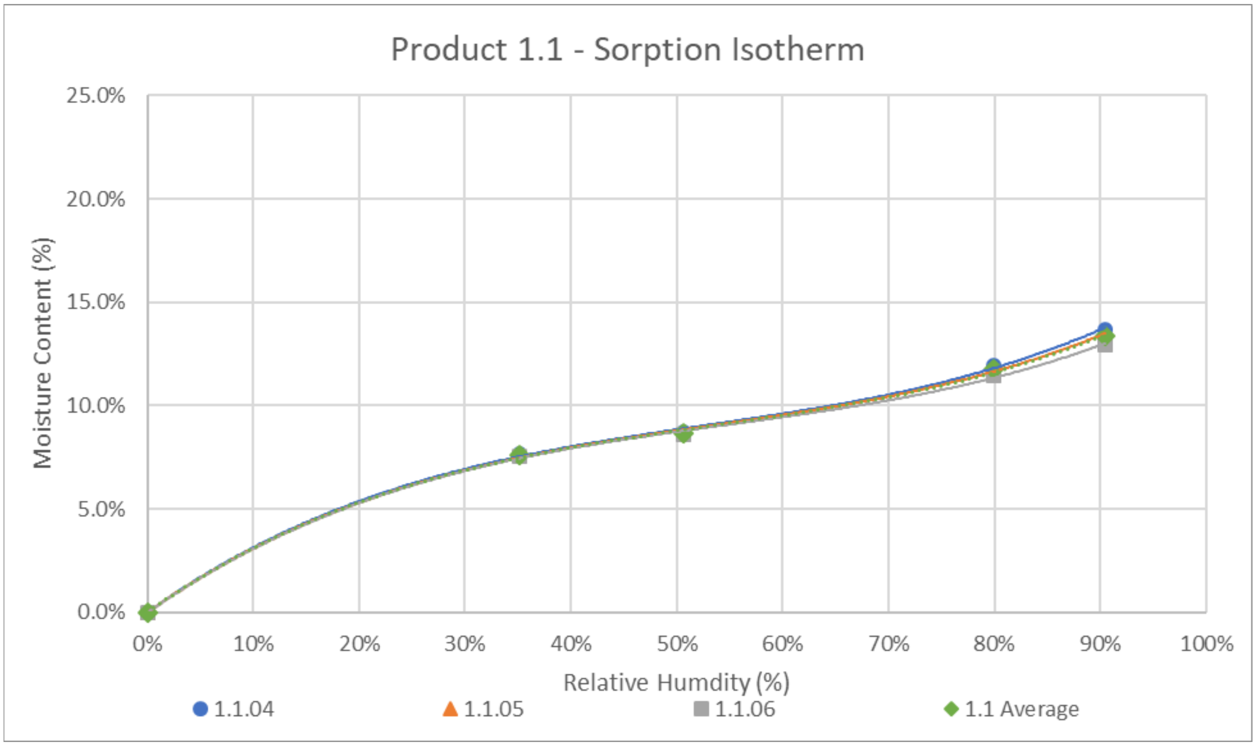


Figure 4.8 - Sorption Isotherms for Specimens 1.1.04, 1.1.05, 1.1.06, and Average over Full Relative Humidity Range at 10˚C.

Table 4.4 summarizes the sorption data at a temperature of 10˚C for product 1.1, including specimens 1.1.04, 1.1.05, 1.1.06, and the calculated average of all 3 specimens. The standard deviation (SD) of the calculated moisture contents at each relative humidity step for product 1.1 is also included.

Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.4. The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity throughout each test period were calculated and are also included.

Table 4.4 - Moisture Contents for Specimens 1.1.04, 1.1.05, 1.1.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp		RH		Specimen			1.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	1.1.01	1.1.02	1.1.03			
					MC(%)					
-	-	-	0%	-	0.0%	0.0%	0.0%	0.0%	-	-
.1	10.07	0.07, 0.70%	35.2%	0.62, 1.76%	7.7%	7.6%	7.6%	7.6%	0.06%	0.82%
.2	10.05	0.12, 1.20%	50.6%	1.16, 2.29%	8.7%	8.7%	8.6%	8.7%	0.04%	0.44%
.3	9.96	0.06, 0.62%	80.0%	0.59, 0.73%	12.0%	11.8%	11.5%	11.7%	0.25%	2.15%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	13.7%	13.4%	13.0%	13.4%	0.38%	2.85%

The sorption data and sorption isotherm curves for all specimens and product averages for all other products at a temperature of 10˚C are provided in Appendix C.

Figure 4.9 depicts the average sorption isotherm curves at a temperature of 10˚C for all WFIB products.

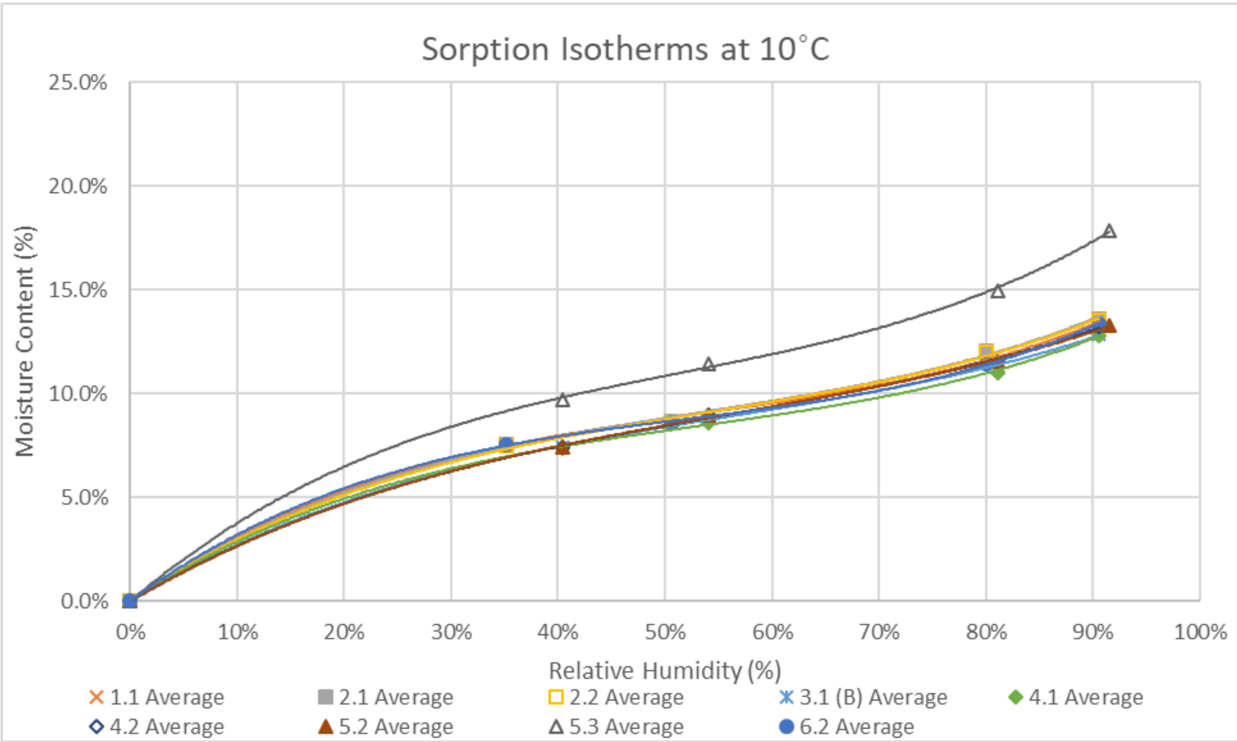


Figure 4.9 – Average Sorption Isotherms for All Products over Full Relative Humidity Range at 10˚C.

4.2.2.4 Volumetric Moisture Content Versus Relative Humidity at Temperature 10˚C

Figure 4.10 depicts the volumetric moisture content versus relative humidity curves at a temperature of 10˚C for product 1.1, including specimens 1.1.01, 1.1.02, 1.1.03, and the calculated average of the 3 specimens.

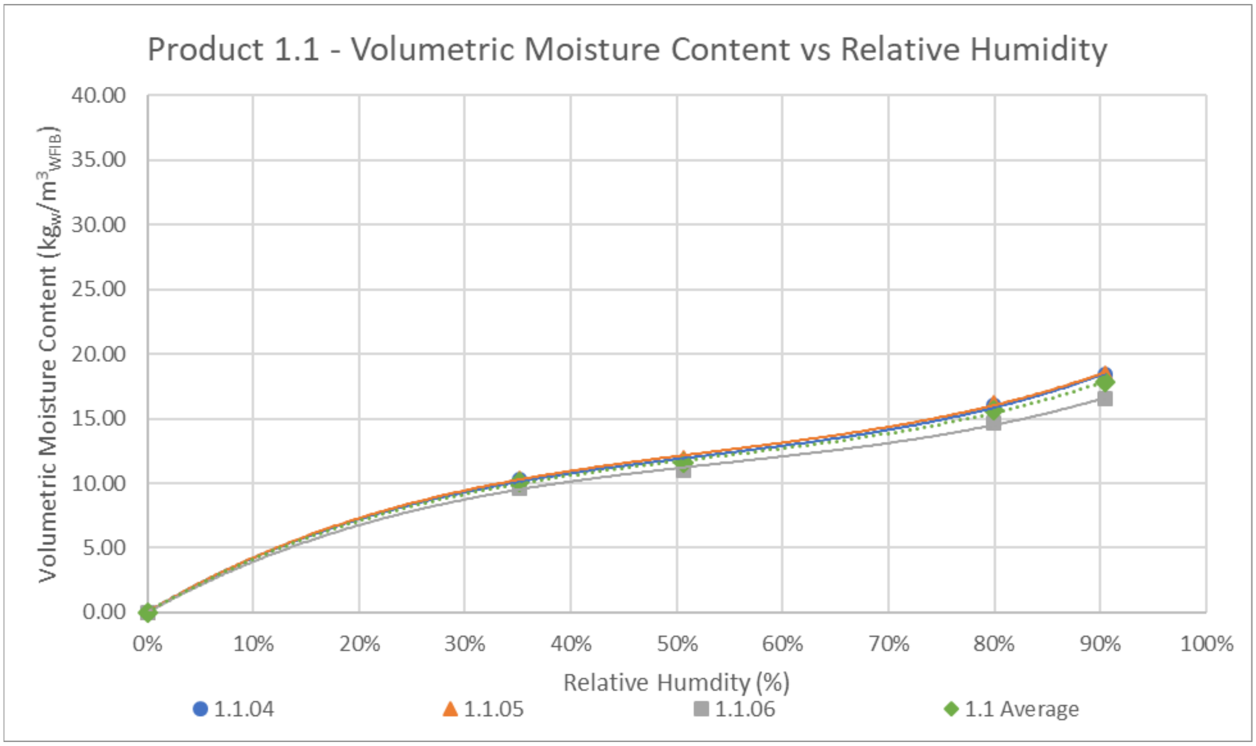


Figure 4.10 – Volumetric Moisture Content vs Relative Humidity for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 10˚C.

Table 4.5 presents the volumetric moisture content versus relative humidity data at a temperature of 10˚C for product 1.1, including specimens 1.1.02, 1.1.02, 1.1.03, and the calculated average of all 3 specimens. The standard deviation (SD) of the calculated moisture contents at each relative humidity step for product 1.1 is included.

Environmental chamber data is the same as presented in 4.2.2.3 and therefore is not included in the table.

Table 4.5 – Volumetric Moisture Contents for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen 1.1.01	Specimen 1.1.02	Specimen 1.1.03	1.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
-	-	0%	0.00	0.00	0.00	0.00	-	-
.1	10.07	35.2%	10.29	10.43	9.65	10.12	0.42	4.13%
.2	10.05	50.6%	11.68	11.93	11.03	11.55	0.47	4.05%
.3	9.96	80.0%	16.05	16.22	14.65	15.64	0.86	5.48%
.4	10.14	90.5%	18.39	18.49	16.56	17.81	1.09	6.11%

The volumetric moisture content versus relative humidity data and curves for all specimens and product averages for all other products at a temperature of 10˚C are provided in Appendix C.

Figure 4.11 depicts the average volumetric moisture content versus relative humidity curves at a temperature of 10˚C for all WFIB products.

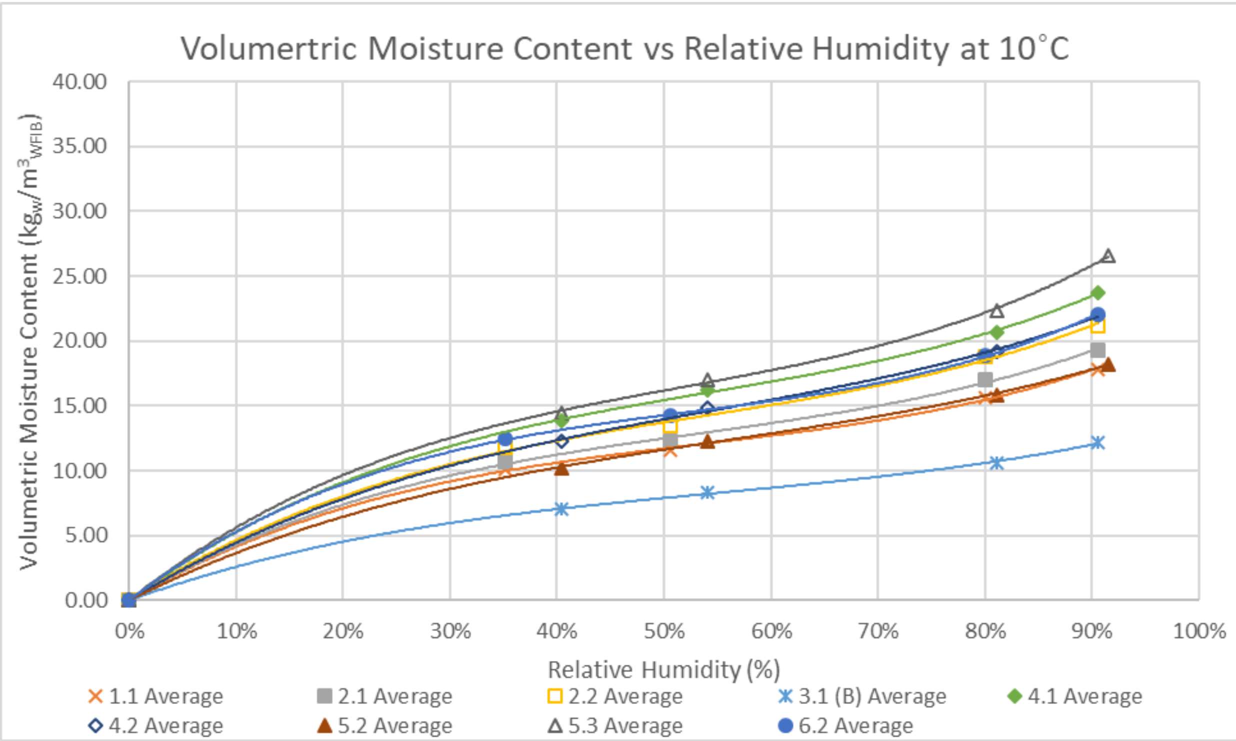


Figure 4.11 – Average Volumetric Moisture Content for All Products over Full Relative Humidity Range at 25˚C.

4.2.3 Sorption Isotherm Variation with Material Thickness

4.2.3.1 Sorption Isotherm Variation with Material Thickness at Temperature 25˚C

Figure 4.12 depicts the average sorption isotherm curves at a temperature of 25˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

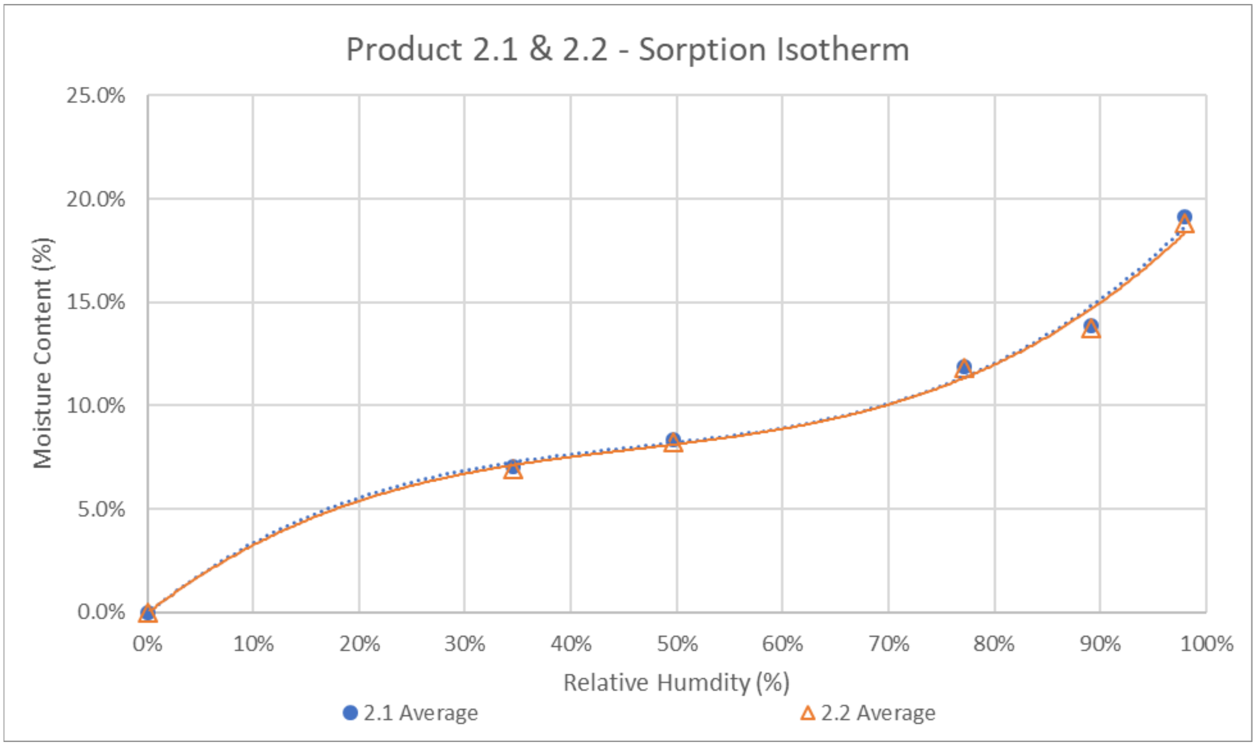


Figure 4.12 – Average Sorption Isotherms for Products 2.1 (40mm) and 2.2 (60mm) over Full Relative Humidity Range at 25˚C.

The average sorption isotherm curves for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3), at a temperature of 25˚C are provided in Appendix C.

Figure 4.13 depicts the volumetric moisture content versus relative humidity curves at a temperature of 25˚C for the average volumetric moisture content for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

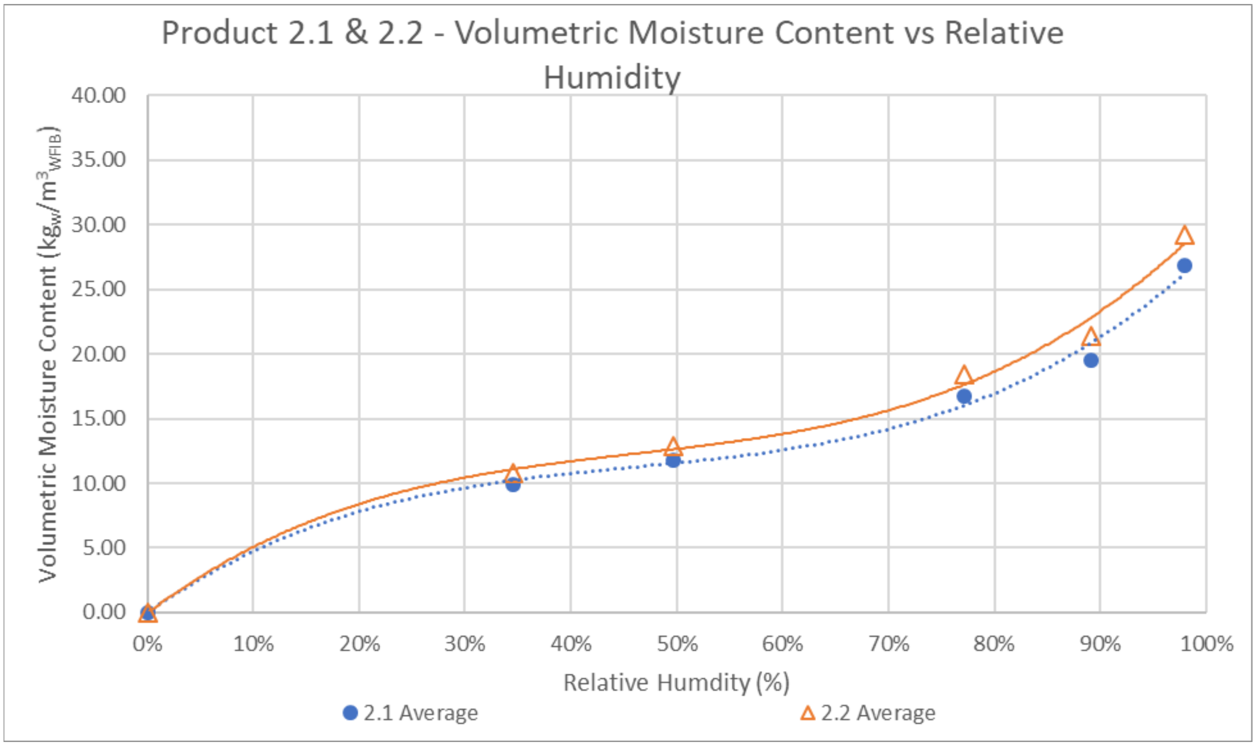


Figure 4.13 – Volumetric Moisture Content vs Relative Humidity for Products 2.1 (40mm) and 2.2 (60mm) over Full Relative Humidity Range at 25˚C.

The volumetric moisture content versus relative humidity curves for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3), at a temperature of 25˚C are provided in Appendix C.

4.2.3.2 Sorption Isotherm Variation with Material Thickness at Temperature 10˚C

Figure 4.14 depicts the average sorption isotherm curves at a temperature of 10˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

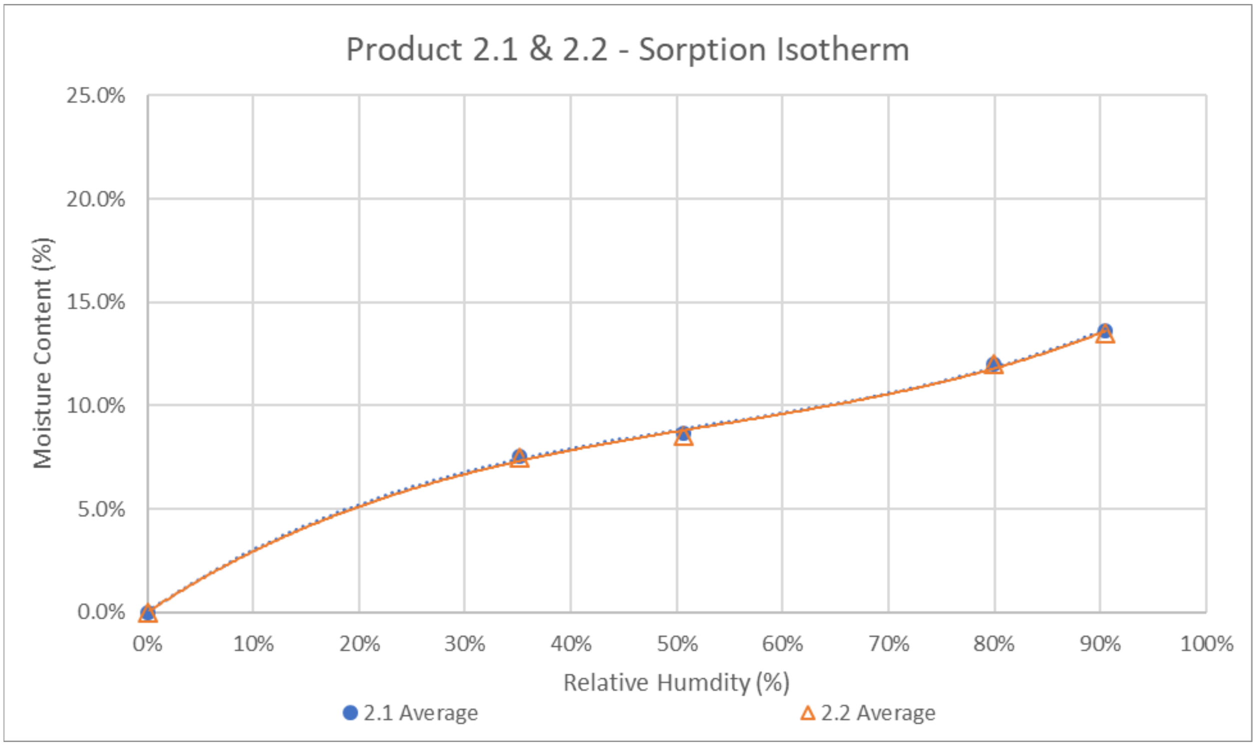


Figure 4.14 – Average Sorption Isotherms for Products 2.1 (40mm) and 2.2 (60mm) over Full Relative Humidity Range at 10˚C.

The average sorption isotherm curves for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3), at a temperature of 10˚C are provided in Appendix C.

Figure 4.15 depicts the volumetric moisture content versus relative humidity curves at a temperature of 10˚C for the average volumetric moisture content for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

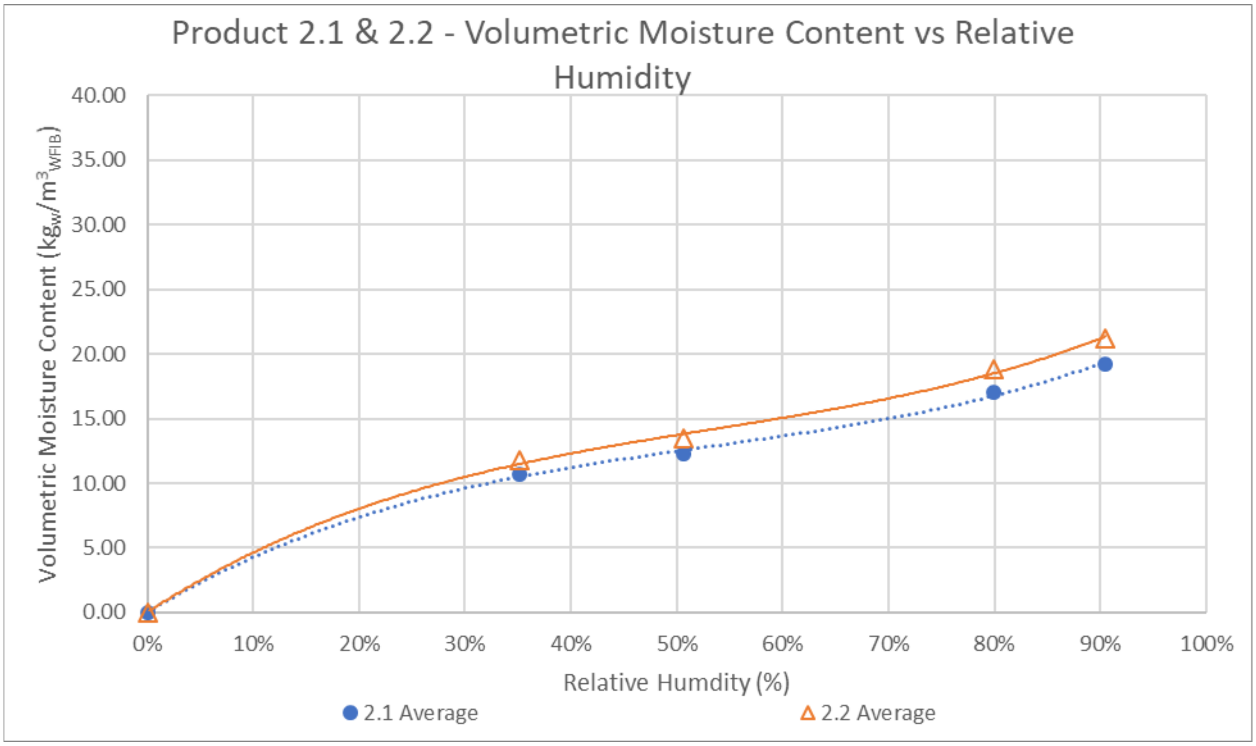


Figure 4.15 – Volumetric Moisture Content vs Relative Humidity for Products 2.1 (40mm) and 2.2 (60mm) over Full Relative Humidity Range at 10˚C.

The volumetric moisture content versus relative humidity curves for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3), at a temperature of 10˚C are provided in Appendix C.

4.2.4 Sorption Isotherm Variation with Temperature

Figure 4.16 depicts the average sorption isotherm curves at a temperature of 25˚C and 10˚C for product 1.1.

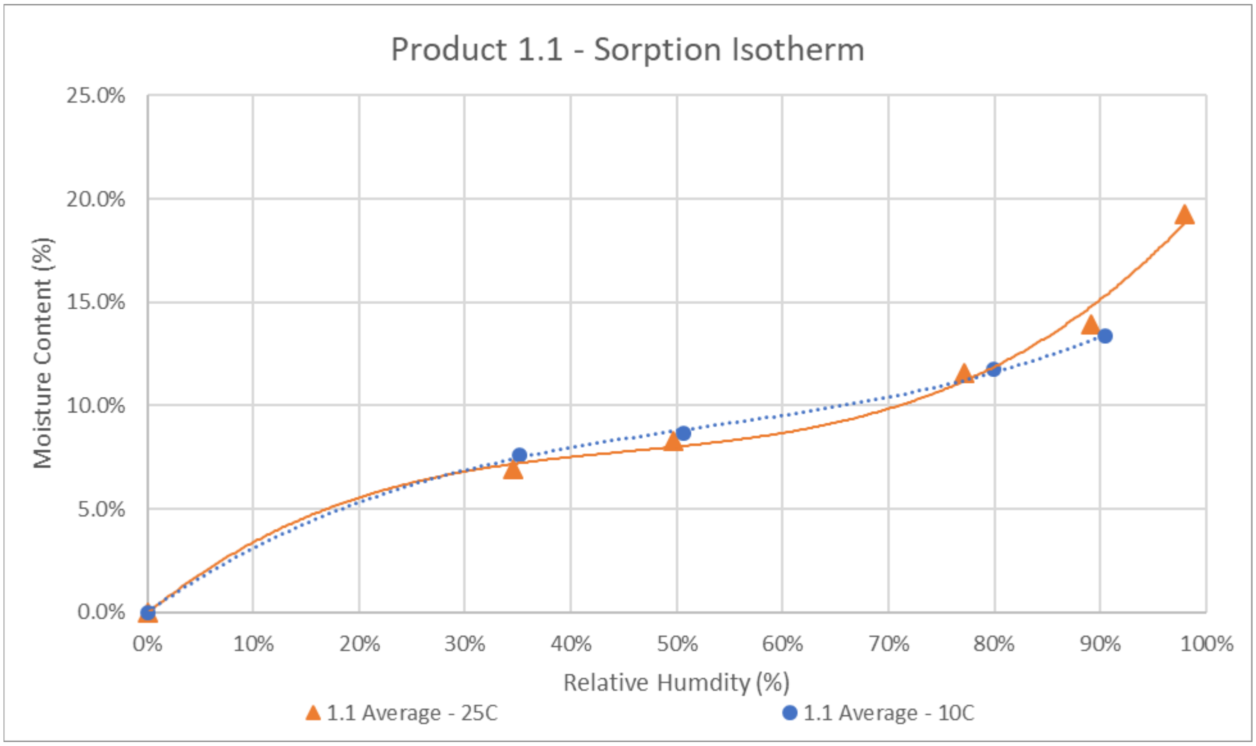


Figure 4.16 – Average Sorption Isotherms for Product 1.1 over Full Relative Humidity Range at 10˚C and 25˚C.

The sorption data and sorption isotherm curves for all product averages for all other products at a temperature of 25˚C and 10˚C are provided in Appendix E.

4.2.5 Impact of Oven drying

Figure 4.17 depicts the sorption isotherm curves at a temperature of 25˚C for the average sorption isotherm for product 1.1 and for specimen 1.1.07, which was oven dried prior to sorption isotherm testing.

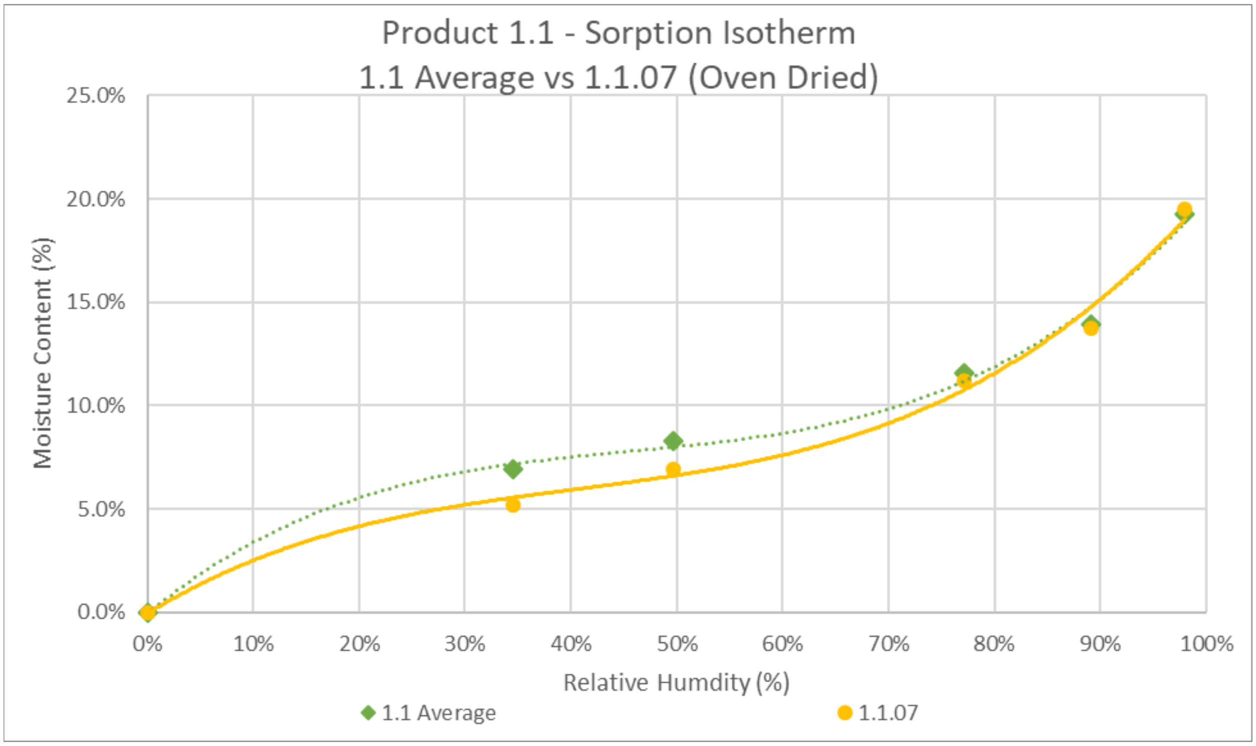


Figure 4.17 –Sorption Isotherms for 1.1.07 and averaged Product 1.1 over Full Relative Humidity Range at 25˚C.

The sorption isotherm curves for all product averages and the corresponding oven dried specimens for all other products at a temperature of 25˚C are provided in Appendix C.

4.3 Moisture and Temperature Dependent Water Vapour Permeance Test Results

Temperature and moisture dependent water vapour permeance testing was conducted in accordance to ASTM E96/E96M-16 over the period of approximately 5 months. Vapour permeance testing was conducted at temperatures 10˚C and 25˚C over a total of six and seven vapour pressure gradients, respectively. Three specimens for each product were tested at each temperature and relative humidity step, with the exception of product 5.3 where only 2 specimens were tested at a temperature of 25˚C. The specimens were all approximately 92mm diameter discs with edge masking comprising paraffin wax and aluminum tape.

Parameters investigated included vapour permeability variance of 6 different products, 3 of which included 2 thicknesses (40mm and 60mm, or 60mm and 80mm), the variance of the vapour permeability at different relative humidities, and the variance of the vapour permeability at temperature conditions of 10˚C and 25˚C.

4.3.1 Mass Gain over Time

For each test condition, the specimens were left undisturbed for 2-3 days and then weighed 1-2 times per day for at least 4 days. The direct results from vapour permeance testing were in the form of mass gain over time measurements for each individual cup test assembly for a given relative humidity test. Figure 4.18 depicts the mass gain over time measurement for product 1.1 at a temperature of 25˚C and relative humidity 35%.

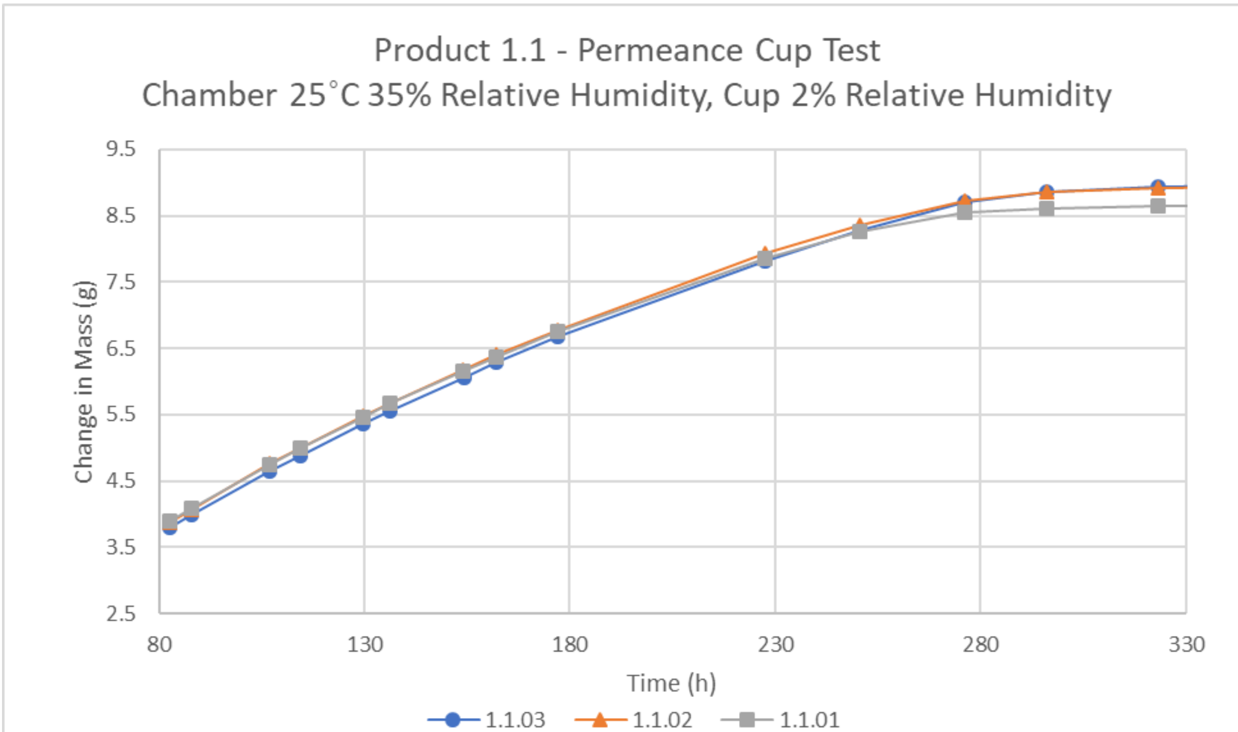


Figure 4.18 – Water Vapour Permeance Mass Gain Over Time, Specimens 1.1.01, 1.1.02, 1.1.03, at Chamber 25˚C and 35% Relative Humidity and Cup 2% Relative Humidity.

The permeability was calculated for each test specimen from the test results, applying corrections for the still air and surface resistances, using Equations (5), (6), (7), (8), and (9) as discussed in Section 3.3.2. Vapour permeability results are displayed graphically as shown in Figure 4.19, with the x-axis representing the calculated average relative humidity (refer to Figure 3.1 for further details of calculated average relative humidity) and the y-axis representing the calculated permeability.

4.3.2 Permeability Variation with Relative Humidity

4.3.2.1 Permeability Variation with Relative Humidity at 25˚C

Figure 4.19 depicts the vapour permeability at a temperature of 25˚C and the calculated average specimen relative humidity for modified cup test conditions for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average permeability of the 3 specimens.

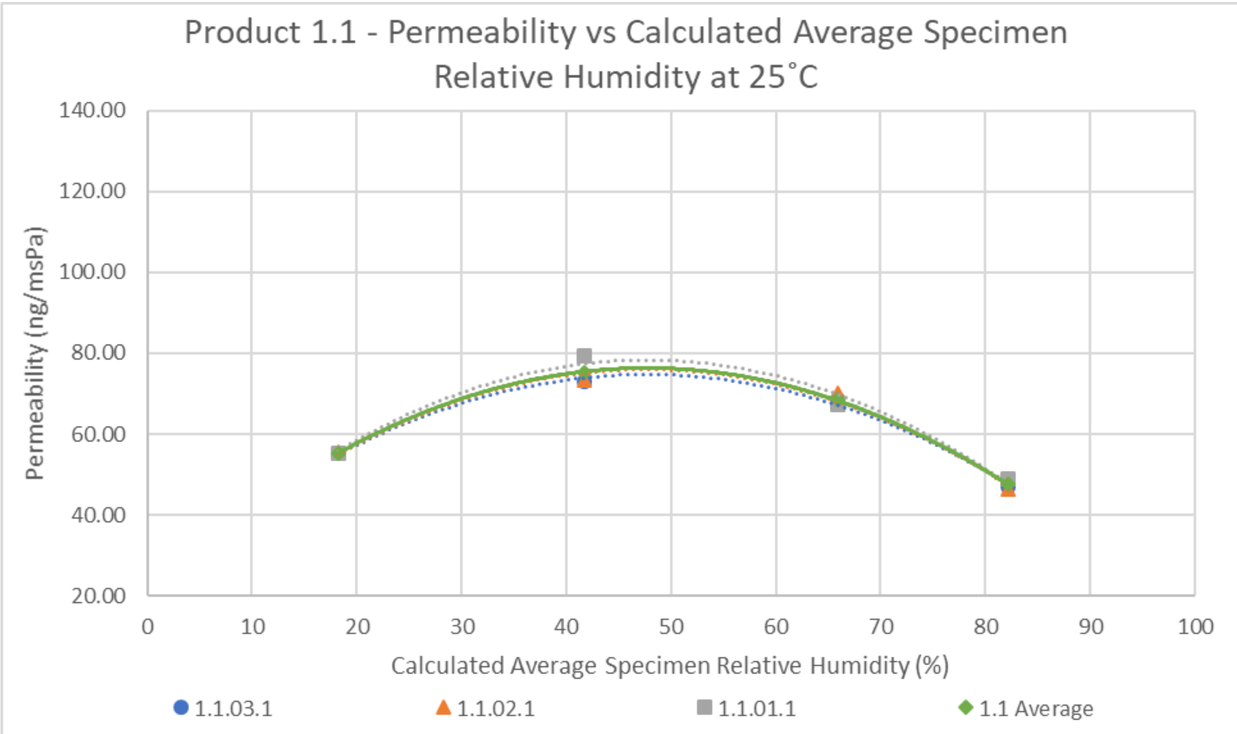


Figure 4.19 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability for Modified Cup Test Conditions at 25˚C.

Table 4.6 presents the permeability data at a temperature of 25˚C for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average of the 3 specimens for the modified cup test conditions. The standard deviation and the coefficient of variation of the specimen permeabilities at each relative humidity for product 1.1 are included. Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.6. The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity conditions during each test period were calculated and are presented.

Table 4.6 - Permeabilities of Specimens 1.1.0.1, 1.1.02.1, 1.1.01.1, and Average Permeability over Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.21	24.23	24.4	24.44
Chamber Temp – SD, CV (%)	0.03, 0.13%	0.05, 0.23%	0.08, 0.34%	0.15, 0.62%
Chamber RH (%)	34.5%	49.6%	77.2%	89.1%
Chamber RH - SD, CV (%)	0.19, 0.57%	1.73, 3.49%	1.68, 2.18%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	18%	42%	66%	82%
Pressure Differential (Pa)	983	514	724	403
1.1.03.1	55.28	72.93	68.52	47.14
1.1.02.1	55.53	73.43	70.11	46.53
1.1.01.1	55.25	79.41	67.45	48.94
1.1 Average	55.35	75.26	68.69	47.54
Standard Deviation	0.15	3.60	1.34	1.25
Coefficient of variation	0.28%	4.79%	1.95%	2.63%

Figure 4.20 depicts the vapour permeability at a temperature of 25˚C and the calculated average specimen relative humidity for dry cup and wet cup test conditions for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average permeability of the 3 specimens.

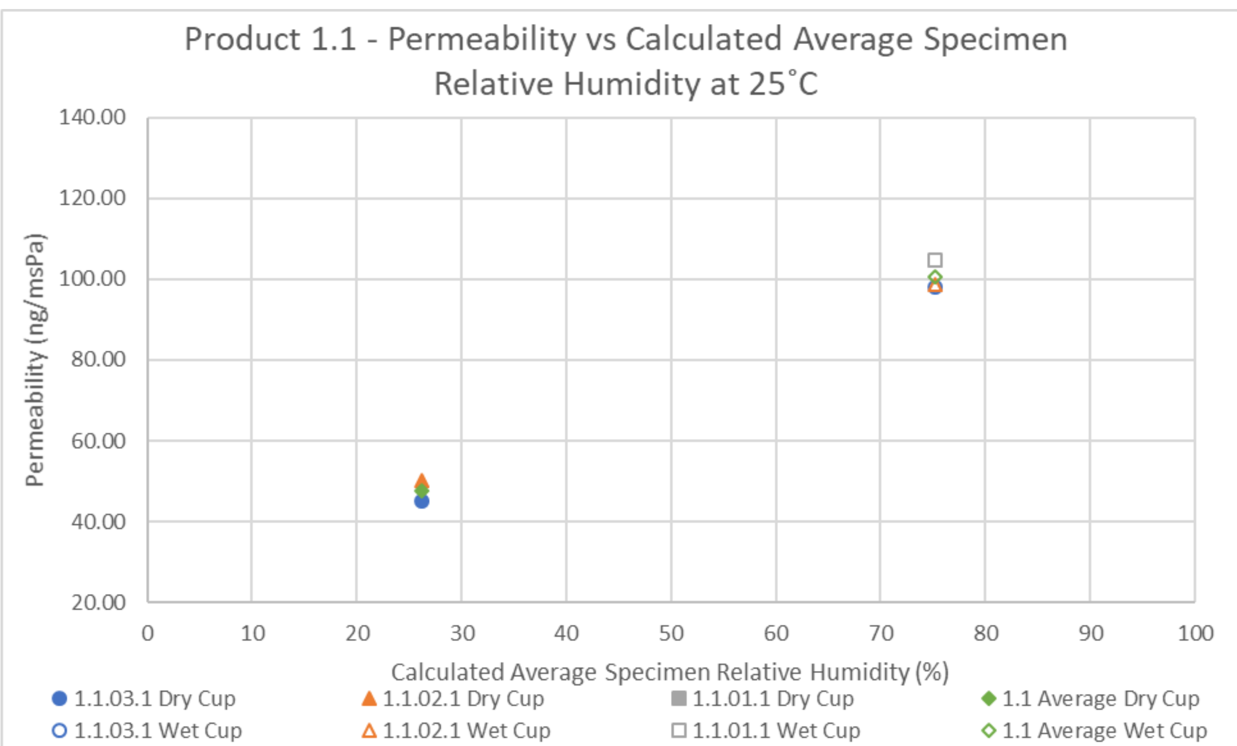


Figure 4.20 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability for Wet Cup and Dry Cup Test Conditions at 25˚C.

Table 4.7 presents the permeability data at a temperature of 25˚C for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average permeability of the 3 specimens for the dry cup and wet cup test conditions. The standard deviation and the coefficient of variation of the specimen permeabilities at each relative humidity for product 1.1 are included. Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.7. The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity conditions during each test period were calculated and are presented.

Table 4.7 - Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
1.1.03.1	98.00	45.28
1.1.02.1	98.61	50.08
1.1.01.1	104.84	38.64
1.1 Average	100.48	44.67
Standard Deviation	3.78	5.74
Coefficient of variation	3.76%	12.86%

The vapour permeability data and graphs depicting the vapour permeability at a temperature of 25˚C and the calculated average specimen relative humidity for modified cup, dry cup, and wet cup test conditions for all other products are provided in Appendix F.

Figure 4.21 illustrates the average vapour permeability at a temperature of 25˚C and the calculated average specimen relative humidity for modified cup test conditions for all WFIB products.

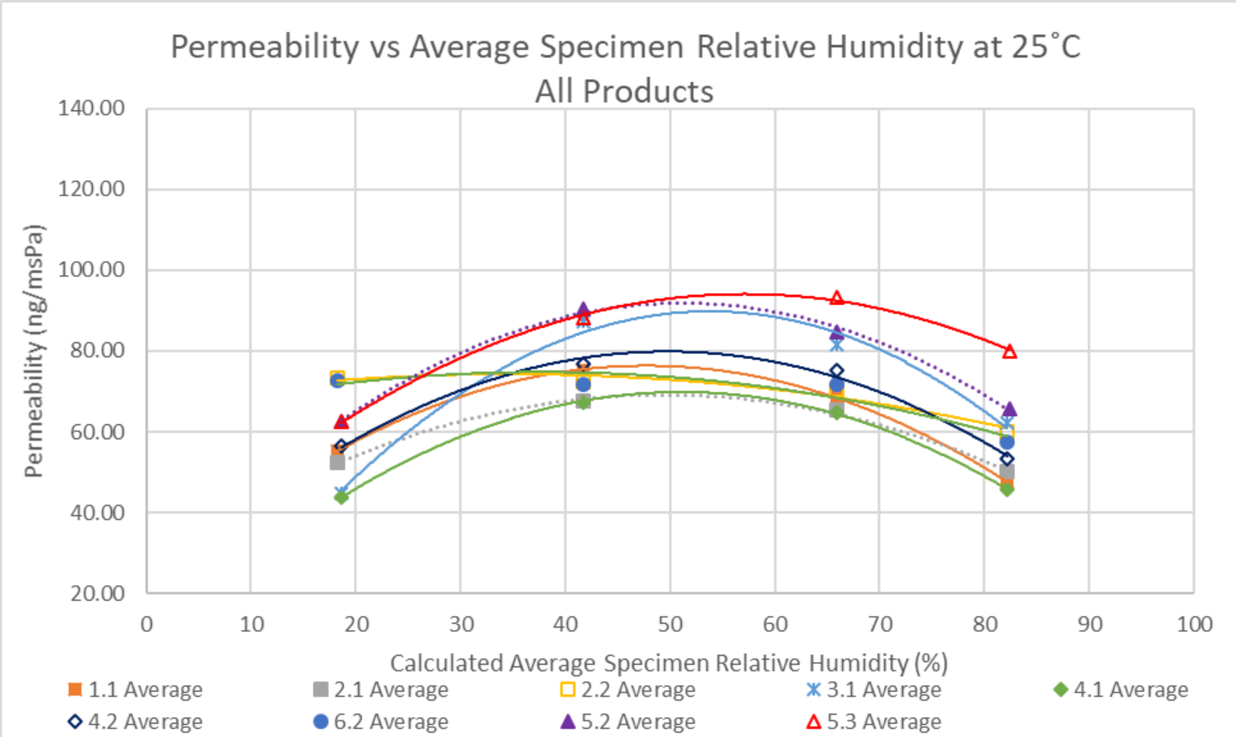


Figure 4.21 – Average Permeabilities for All Products for Modified Cup Test Conditions at 25˚C.

Figure 4.22 depicts the average vapour permeability at a temperature of 25˚C and the calculated average specimen relative humidity for dry cup and wet cup test conditions for all WFIB products.

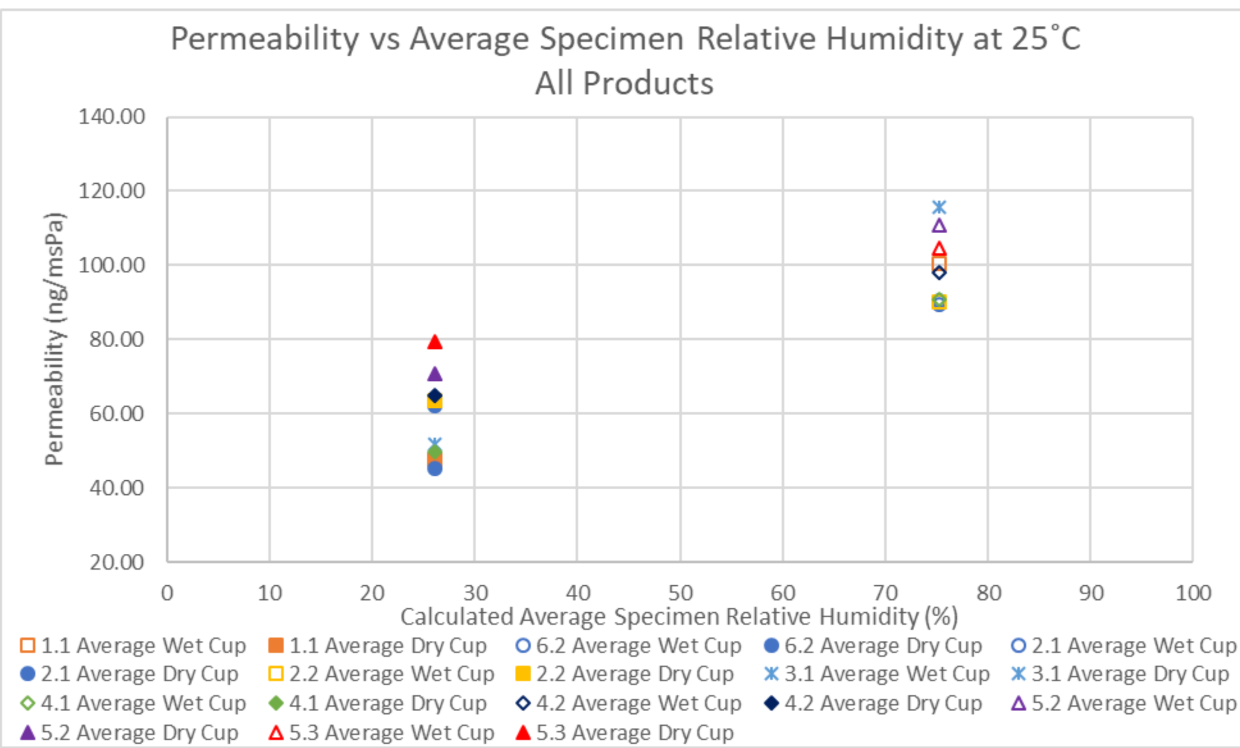


Figure 4.22 - Average Permeability for All Products for Dry Cup and Wet Cup Test Conditions at 25˚C.

4.3.2.2 Permeability Variation with Relative Humidity at 10˚C

Figure 4.23 depicts the vapour permeability at a temperature of 10˚C and the calculated average specimen relative humidity for modified cup test conditions for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average of the 3 specimens.

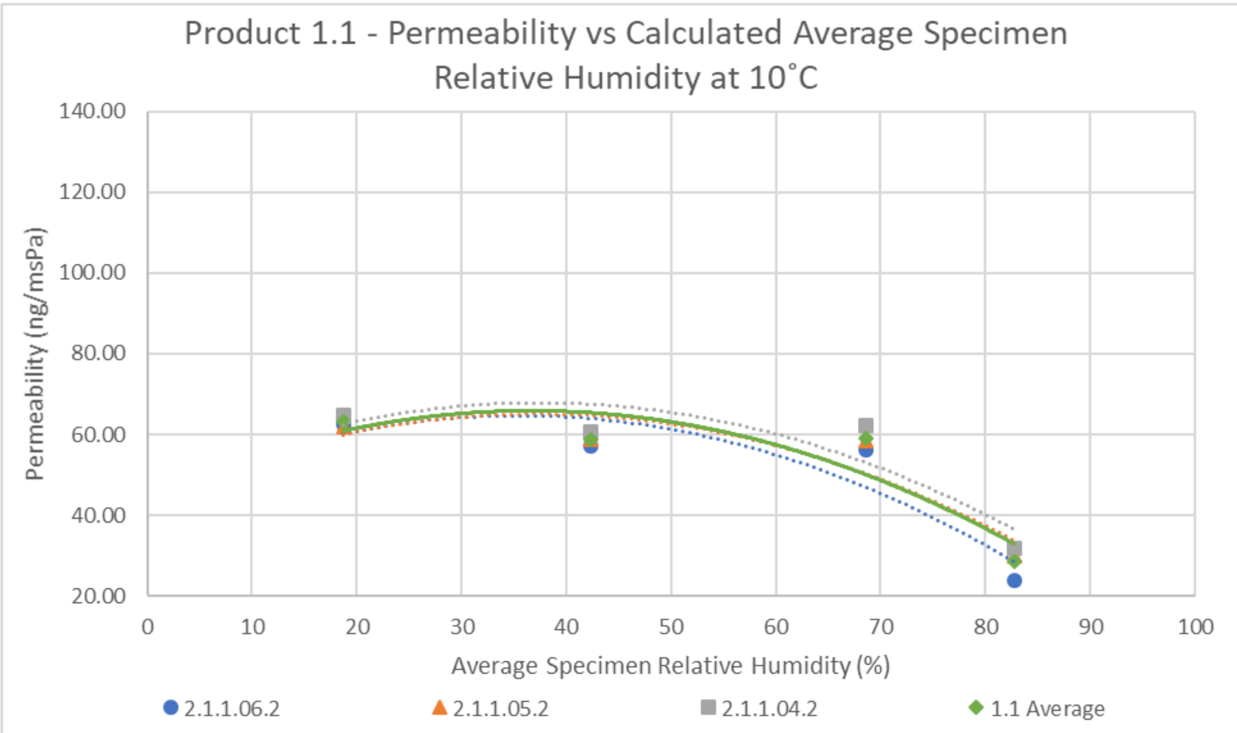


Figure 4.23 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability over Modified Cup Test Relative Humidity Range at 10˚C.

Table 4.8 summarizes the permeability data at a temperature of 10˚C for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average of the three specimens for the modified cup test conditions. The standard deviation and the coefficient of variation of the specimen permeabilities at each relative humidity for product 1.1 are included. Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.8. The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity conditions during each test period were calculated and are presented.

Table 4.8 - Permeabilities of Specimens 1.1.0.1, 1.1.02.1, 1.1.01.1, and Average Permeability for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.1	10.02	9.99	10.14
Chamber Temp – SD, CV (%)	0.10, 1.04%	0.11, 1.13%	0.08, 0.85%	0.09, 0.84%
Chamber RH (%)	35%	51%	81%	90%
Chamber RH - SD, CV (%)	1.03, 2.90%	1.11, 2.19%	0.89, 1.11%	1.54, 1.71%
Cup RH	2%	34%	57%	75%
Calc. Avg. Specimen RH	19%	42%	69%	83%
Pressure Differential (Pa)	413	205	274	185
1.1.06.1	62.46	57.16	56.20	23.96
1.1.05.1	61.93	58.73	58.37	29.76
1.1.04.1	64.83	60.68	62.39	31.88
1.1 Average	63.07	58.86	58.99	28.53
Standard Deviation	1.54	1.76	3.14	4.10
Coefficient of variation	2.45%	3.00%	5.32%	14.38%

Figure 4.24 depicts the vapour permeability at a temperature of 10˚C and the calculated average specimen relative humidity for dry cup and wet cup test conditions for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average of the 3 specimens.

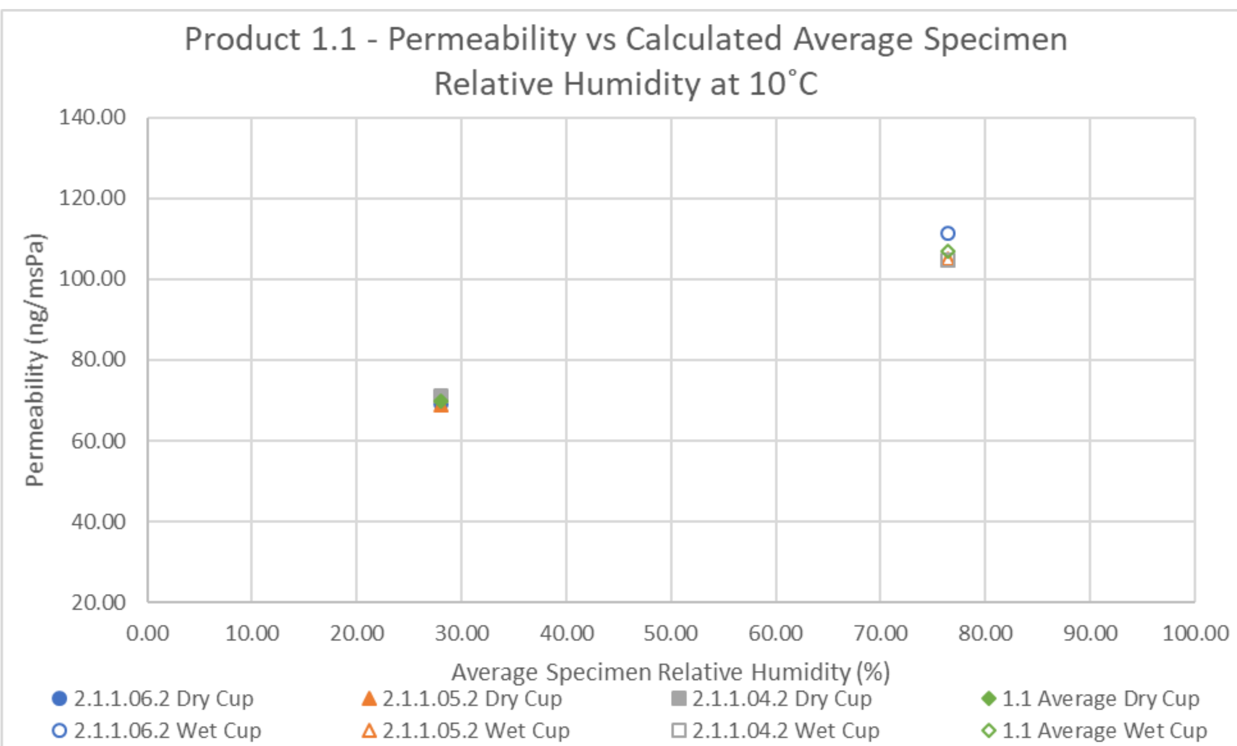


Figure 4.24 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability for Wet Cup and Dry Cup at 10˚C.

Table 4.9 presents the permeability data at a temperature of 10˚C for product 1.1, including specimens 1.1.01.1, 1.1.02.1, 1.1.03.1, and the calculated average of the 3 specimens for the dry cup and wet cup test conditions. The standard deviation and the coefficient of variation of the specimen permeabilities at each relative humidity for product 1.1 are included. Environmental chamber data was collected and the temperature and relative humidity averages for the test period are presented in Table 4.9. The standard deviation (SD) and coefficient of variation (CV%) for the temperature and relative humidity conditions during each test period were calculated and are presented.

Table 4.9 - Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	*.6*	*.7*
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
1.1.06.1	111.22	69.19
1.1.05.1	104.87	68.93
1.1.04.1	104.68	71.02
1.1 Average	106.93	69.71
Standard Deviation	3.72	1.14
Coefficient of variation	3.48%	1.63%

The vapour permeability data and graphs depicting the vapour permeability at a temperature of 10˚C and the calculated average specimen relative humidity for modified cup, dry cup, and wet cup test conditions for all other products are provided in Appendix G.

Figure 4.25 depicts the average vapour permeability at a temperature of 10˚C and the calculated average specimen relative humidity for modified cup test conditions for all WFIB products.

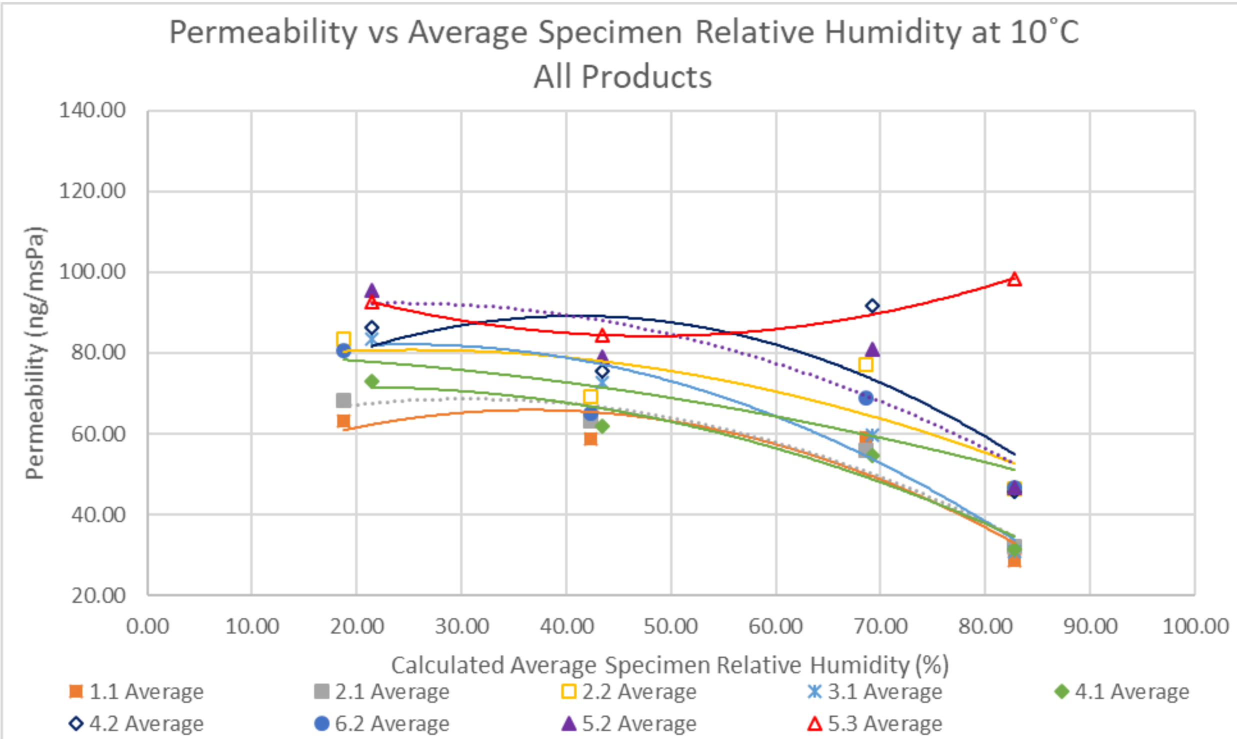


Figure 4.25 – Average Permeabilities for All Products for Modified Cup Test Conditions at 10˚C.

Figure 4.26 depicts the average vapour permeability at a temperature of 10˚C and the calculated average specimen relative humidity for dry cup and wet cup test conditions for all WFIB products.

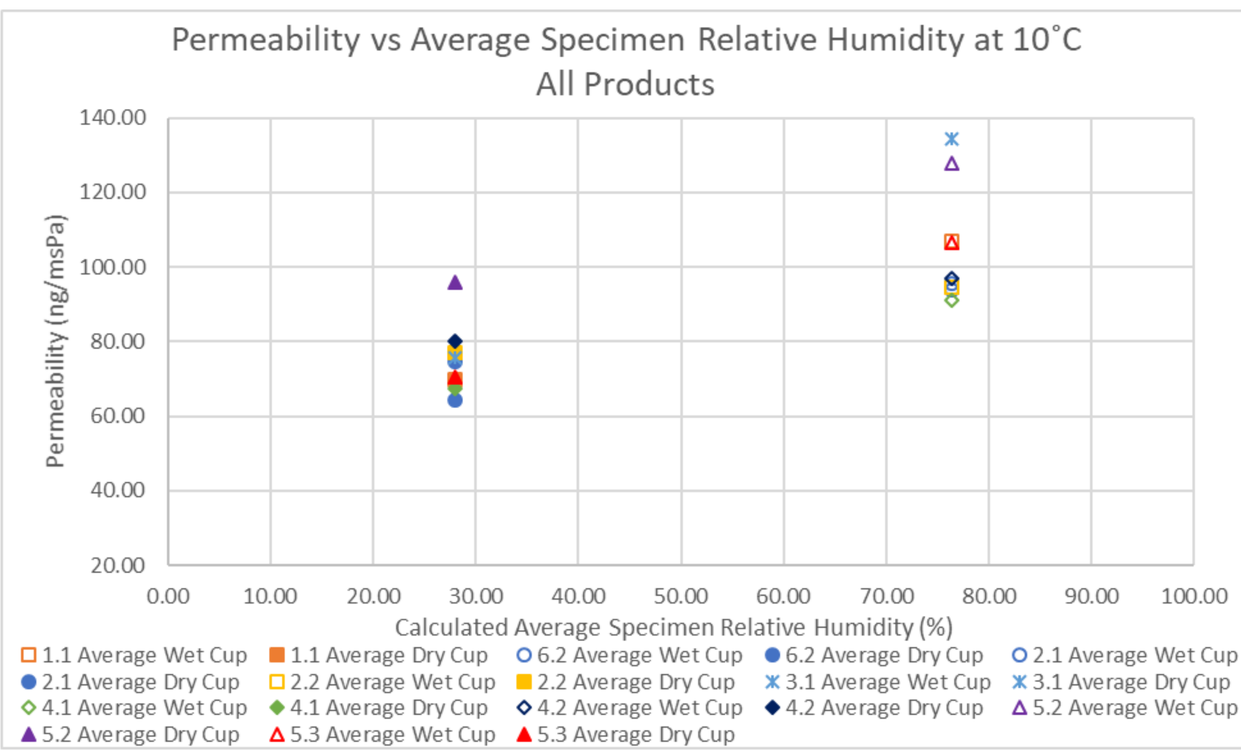


Figure 4.26 - Average Permeability for All Products for Dry Cup and Wet Cup Test Conditions at 10˚C.

4.3.3 Permeability Variation with Temperature

Figure 4.27 illustrates the average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 10˚C and 25˚C for product 1.1

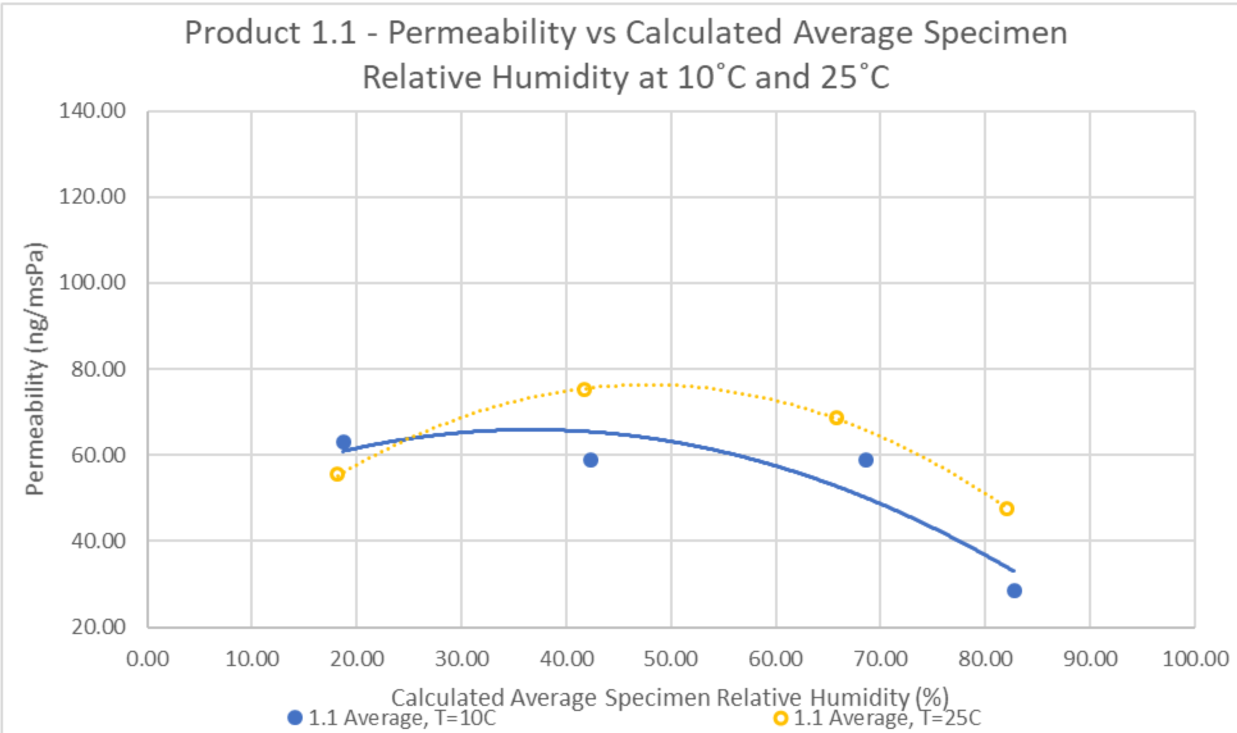


Figure 4.27 - Average Permeabilities for Product 1.1 over Modified Cup Test Relative Humidity Range at 10˚C and 25˚C.

The average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 10˚C and 25˚C for all other products are provided in Appendix H.

Figure 4.28 depicts the average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 10˚C and 25˚C for product 1.1

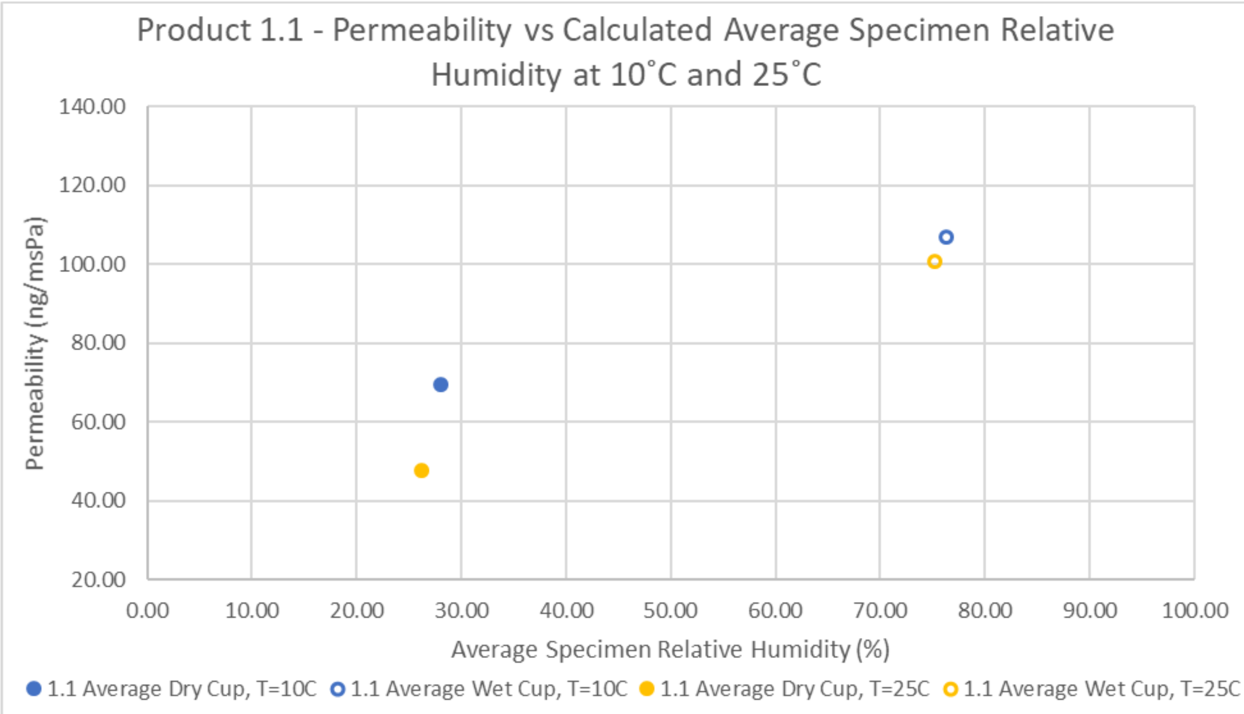


Figure 4.28 – Average Permeabilities for Product 1.1 for Wet Cup and Dry Cup at 10˚C and 25˚C.

The average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 10˚C and 25˚C for all other products are provided in Appendix H.

4.3.4 Permeability Variation with Material Thickness

4.3.4.1 Permeability Variation with Material Thickness at Temperature 25˚C

Figure 4.29 depicts the average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 25˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

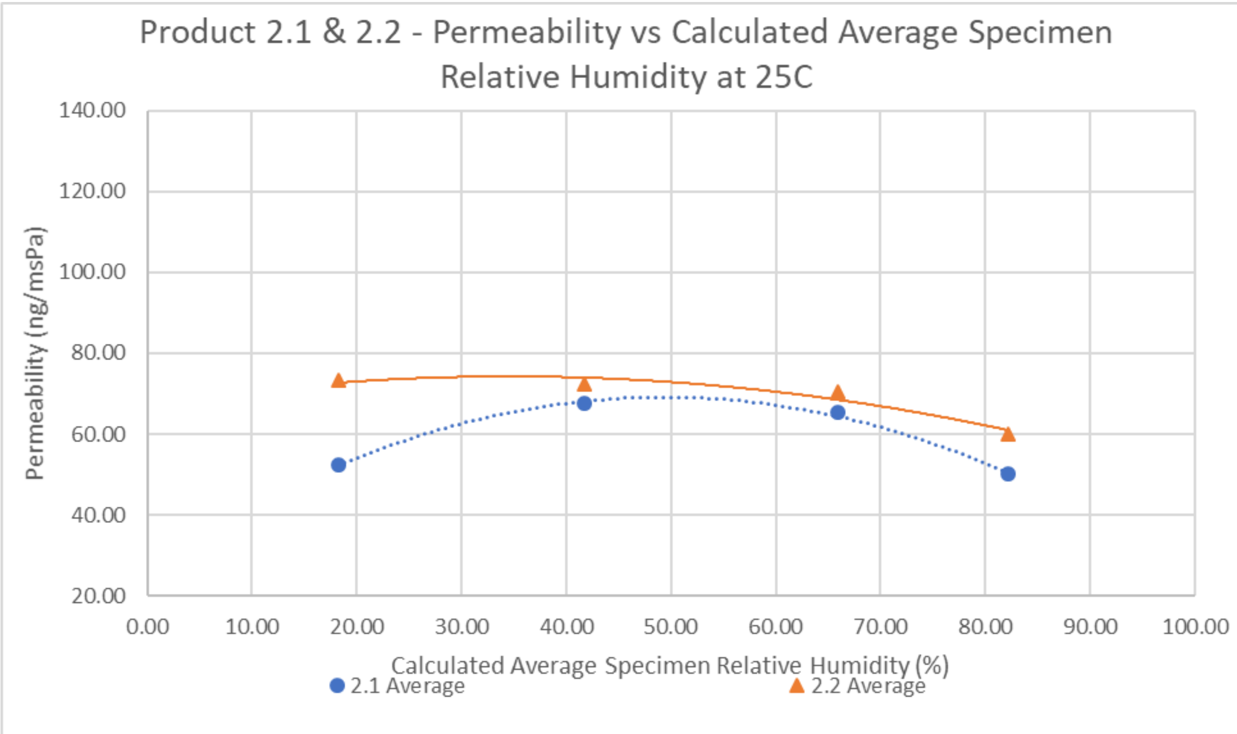


Figure 4.29 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) over Modified Cup Test Relative Humidity Range at 25˚C.

The average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 25˚C for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and for product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3) are provided in Appendix F.

Figure 4.30 depicts the average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 25˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

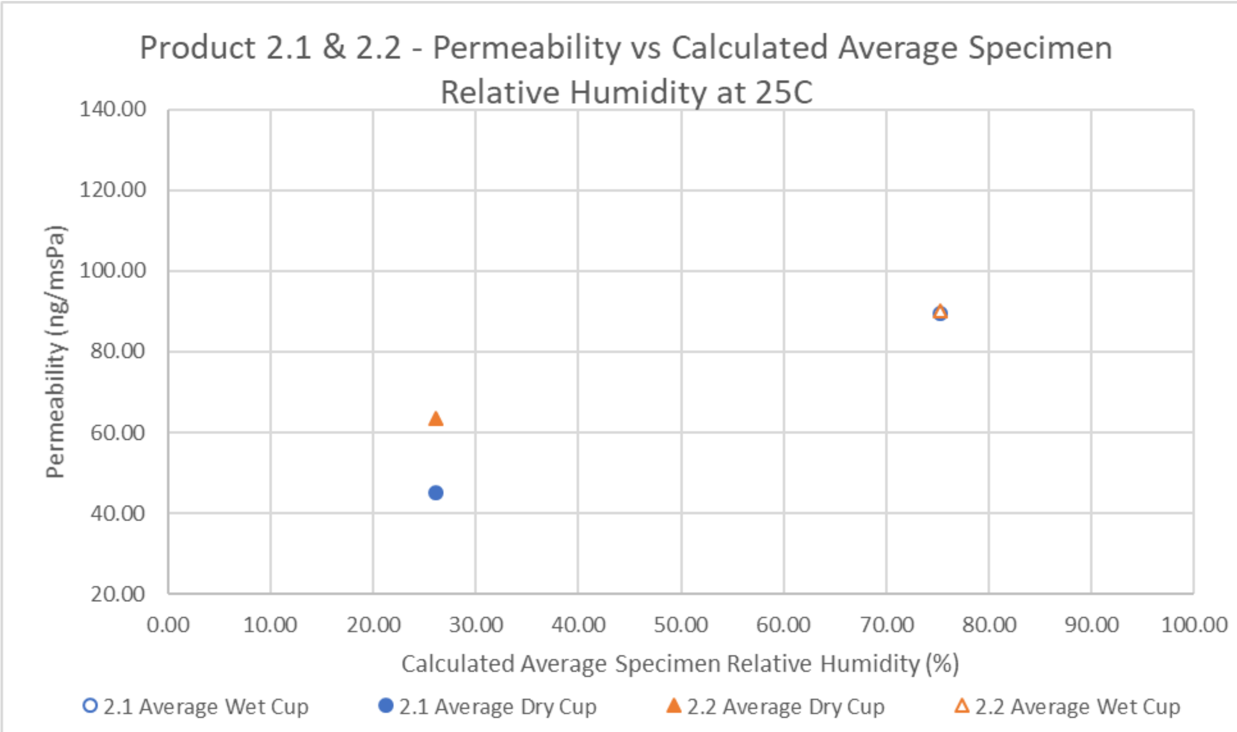


Figure 4.30 – Average Permeabilities for Product 2.1 (40mm) and 2.2 (60mm) for Wet Cup and Dry Cup at 25˚C.

The average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 25˚C for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and for product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3) are provided in Appendix F.

4.3.4.2 Permeability Variation with Material Thickness at Temperature 10˚C

Figure 4.31 depicts the average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 10˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

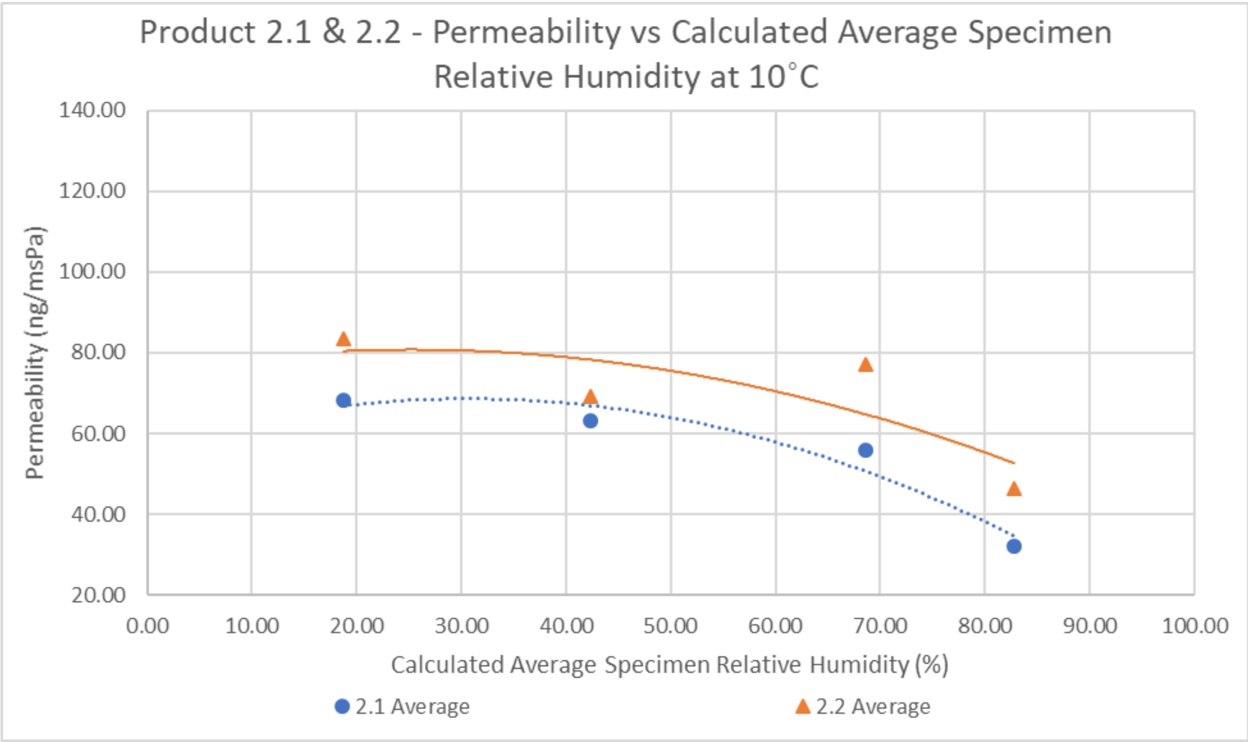


Figure 4.31 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) over Modified Cup Test Relative Humidity Range at 10˚C.

The average vapour permeability and the calculated average specimen relative humidity for modified cup test conditions at a temperature of 10˚C for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and for product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3) are provided in Appendix G.

Figure 4.32 depicts the average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 10˚C for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2).

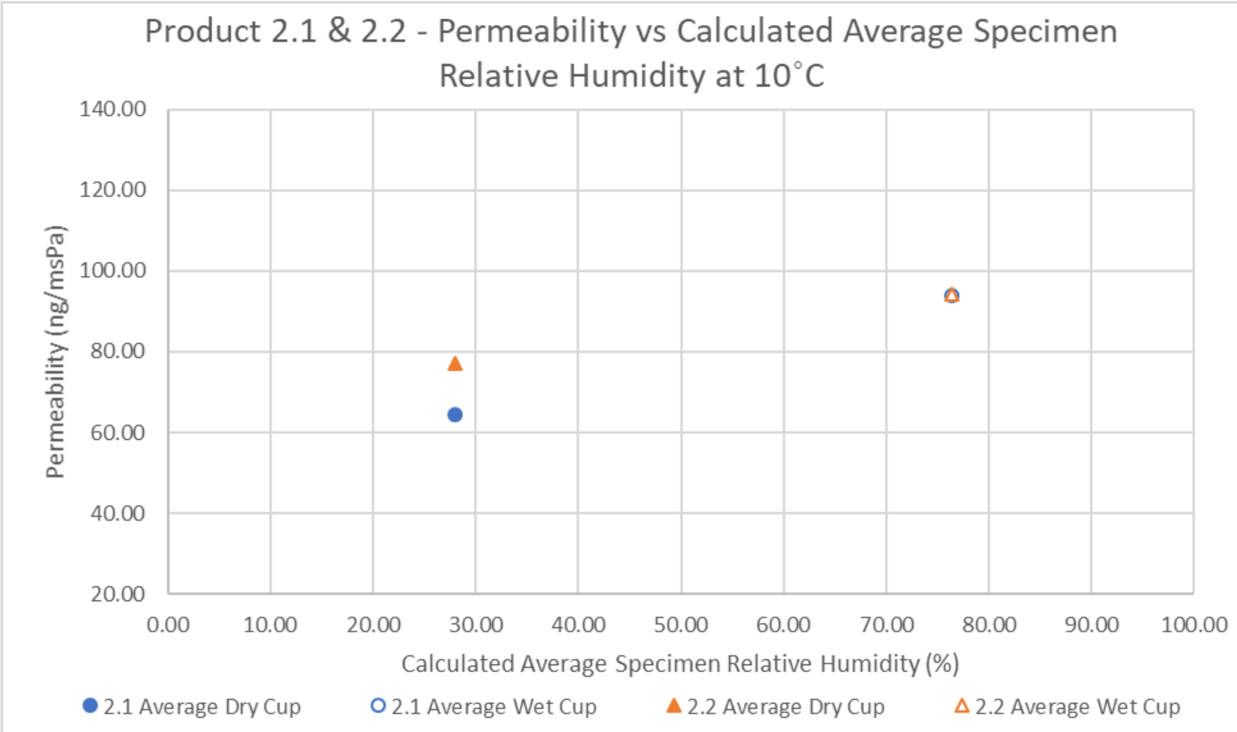


Figure 4.32 – Average Permeabilities for Product 2.1 (40mm) and 2.2 (60mm) for Wet Cup and Dry Cup at 10˚C.

The average vapour permeability and the calculated average specimen relative humidity for dry cup and wet cup test conditions at a temperature of 10˚C for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and for product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3) are provided in Appendix G.

4.4 Temperature and Moisture Dependent Thermal Conductivity Test Results

Temperature and moisture dependent thermal conductivity testing was conducted in accordance to ASTM C518-17 over the period of approximately 6 months. Prior to thermal conductivity testing in the HFM, specimens were preconditioned in an environmental chamber at a temperature of approximately 25˚C and relative humidities of approximately 30%, 60%, 80%, and 95%. Specimens were conditioned in the environmental chamber until a constant mass was obtained. Test objectives for determining constant mass were based on a change of mass less than 1% over a 24-hour period as per ASTM C518 standard, though lower percentage mass changes were typically obtained.

The thermal conductivity tests using the HFM were conducted at approximate temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C, with the test conducted in order from lowest temperature to highest temperature (-10˚C to 30˚C). Three specimens for each product were tested at each temperature and relative humidity step, additionally one specimen from each product was tested at the final relative humidity step (95%) with the thermal conductivity test conducted with temperatures in reverse order (30C to -10˚C). The specimens were all approximately 300mm x 300mm x the product thickness, with the exception of the specimens for product 6.2 which were all approximately 150mm x 150mm x the product thickness.

Parameters investigated included the thermal conductivity of a material at various moisture contents and temperatures for 6 different products, 3 of which included 2 thicknesses (40mm and 50mm, or 60mm and 80mm).

4.4.1 Temperature Dependent Thermal Conductivity

Figure 4.33 depicts the thermal conductivity obtained for specimens 1.1.01, 1.1.02, 1.1.03 preconditioned in an environmental chamber with a relative humidity of 30% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C. Included is the calculated average of all three specimens.

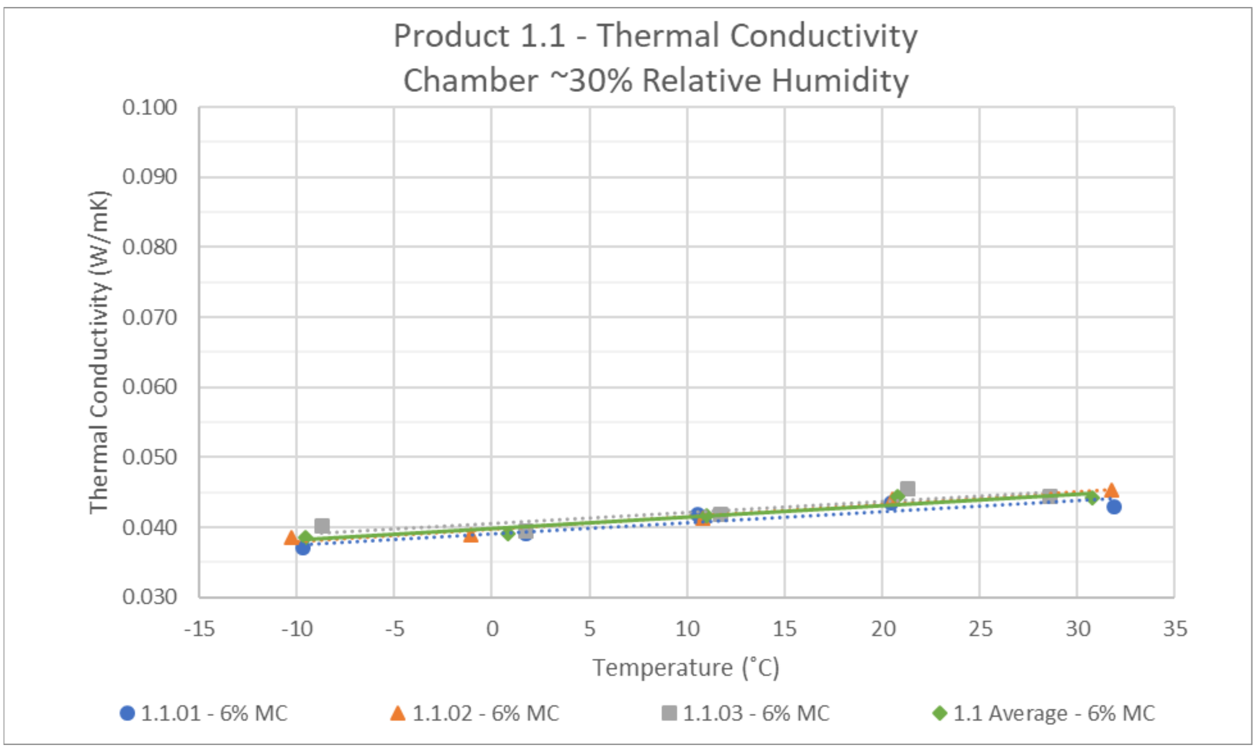


Figure 4.33 – Thermal Conductivities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average Thermal Conductivities over Full Temperature Range.

Table 4.10 summarizes the thermal conductivity data for product 1.1, in which the specimens were precondition at a relative humidity of 30% and tested at -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C. The standard deviation (SD) and coefficient of variation (CV%) of the thermal conductivity at each temperature for the specimens is included.

Table 4.10 - Thermal Conductivities for Specimens 1.1.01, 1.1.02, 1.1.03, and Average for ~30% Relative Humidity and HFM Test Temperatures.

1.1.01 - 6% MC		1.1.02 - 6% MC		1.1.03 - 6% MC		1.1 Average – 6%MC		SD, CV%
Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	
-9.66	0.037033	-10.31	0.038478	-8.71	0.040142	-9.56	0.038551	0.001556, 4.04%
1.77	0.039121	-1.07	0.038867	1.73	0.039459	0.81	0.039149	0.000297, 0.76%
10.54	0.041857	10.79	0.041353	11.74	0.041817	11.02	0.041676	0.000280, 0.67%
20.47	0.043496	20.51	0.044046	21.31	0.045419	20.76	0.044320	0.000990, 2.23%
31.86	0.043005	31.79	0.045233	28.61	0.044487	30.75	0.044242	0.001134, 2.56%

Environmental chamber data was collected and is provided in Appendix I. The calculated average temperature and relative humidity for 72 hours prior to testing specimens 1.1.01, 1.1.02, 1.1.03 is provided in Table 4.11. The standard deviation (SD) and coefficient of variation (CV%) of the temperature and relative humidity for the environmental chamber is included.

Table 4.11 - Chamber Temperature and Relative Humidity Data for Specimens 1.1.01, 1.1.02, 1.1.03, for Chamber ~30% Relative Humidity

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
1.1.01	23.87	0.75, 3.13%	30.66	0.63, 2.06%
1.1.02	23.87	0.74, 3.11%	30.66	0.68, 2.2%
1.1.03	23.77	0.79, 3.32%	29.25	1.45, 4.94%

The data and graphical representation of the thermal conductivities obtained for all specimens and product averages for all other products preconditioned in an environmental chamber with a relative humidity of 30% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Appendix I. The environmental chamber data collected for all specimens for all other products are provided in Appendix I.

Figure 4.34 depicts the average thermal conductivities obtained for all WFIB products preconditioned in an environmental chamber with a relative humidity of 30% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C.

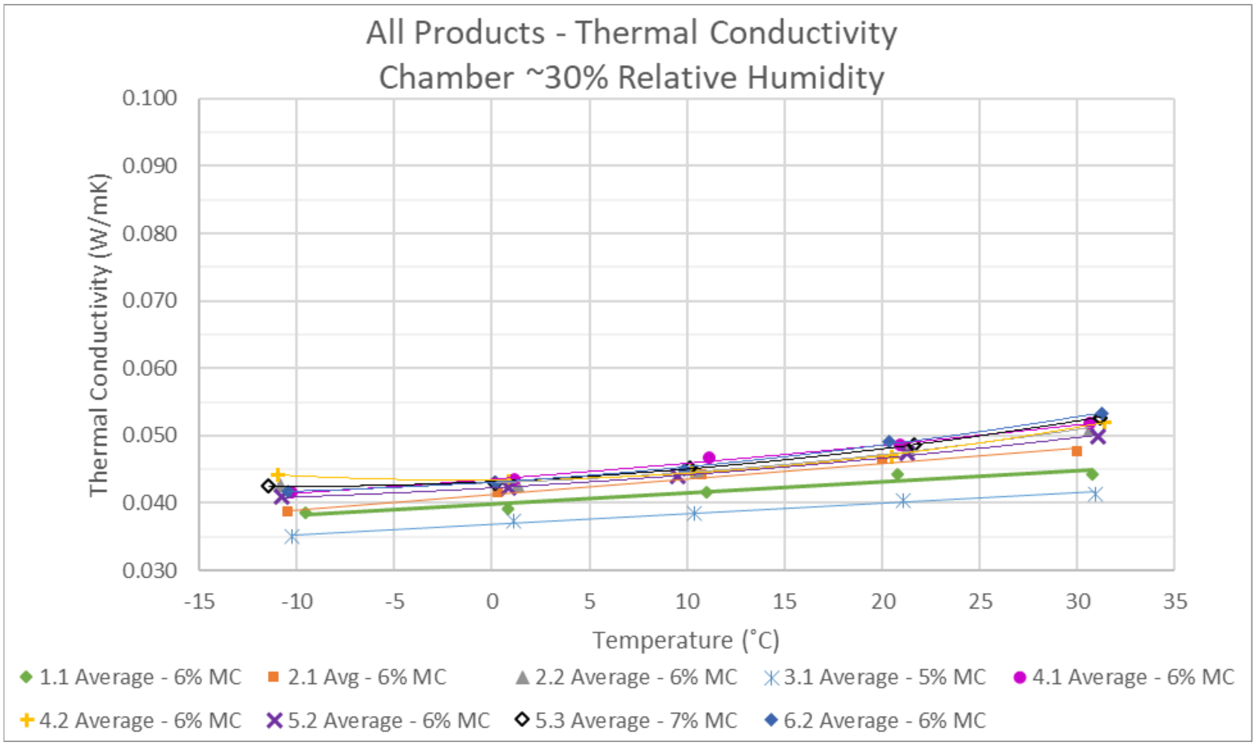


Figure 4.34 – Average Thermal Conductivities of All Products from Chamber at ~30% Relative Humidity over Full Temperature Range.

4.4.2 Temperature Dependent Thermal Conductivity Variation with Material Thickness

Figure 4.35 depicts the average thermal conductivities for product 2, for thickness 40mm (product 2.1) and 60mm (product 2.2), for specimens preconditioned in an environmental chamber with a relative humidity of 30% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C.

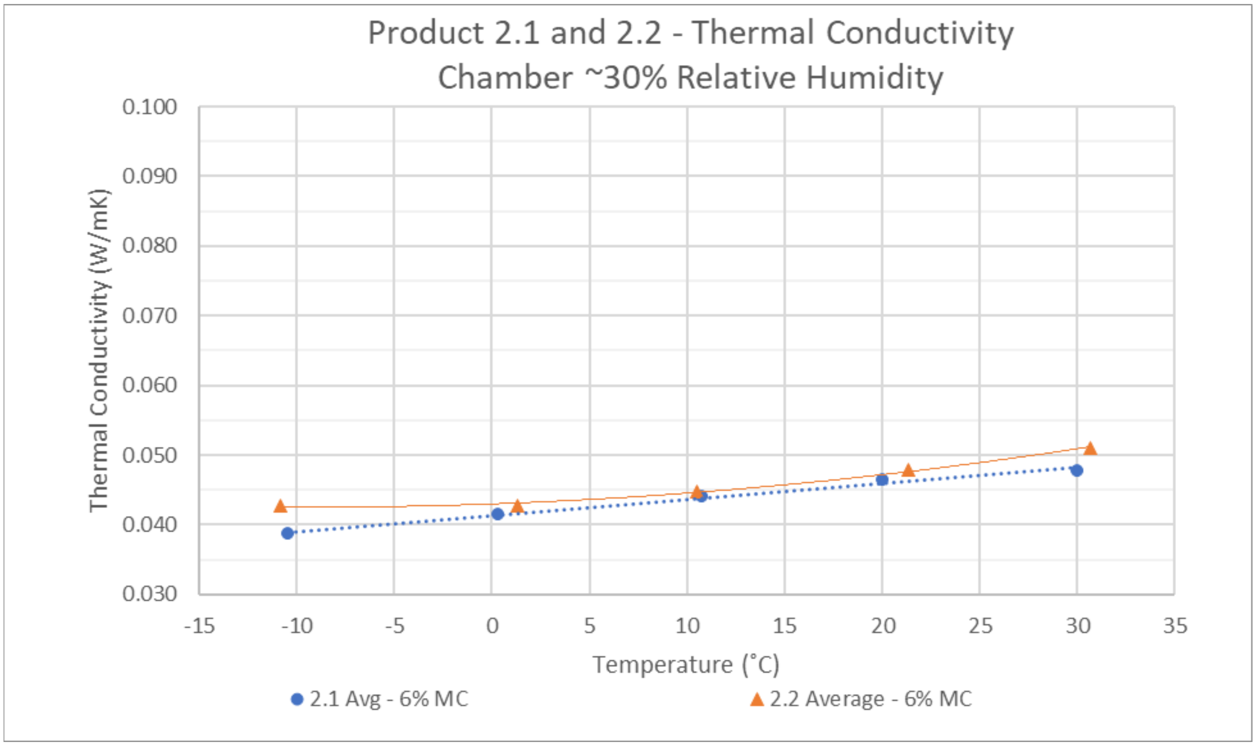


Figure 4.35 – Average Thermal Conductivities for Products 2.1 (40mm) and 2.2 (60mm) from Chamber at ~30% Relative Humidity over Full Temperature Range.

The average thermal conductivities for product 4, for thicknesses 40mm (product 4.1) and 60mm (product 4.2), and product 5, for thicknesses 60mm (product 5.2) and 80mm (product 5.3), for specimens preconditioned in an environmental chamber with a relative humidity of 30% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Appendix I.

4.4.3 Moisture Dependent Thermal Conductivity

Figure 4.36 depicts the average thermal conductivity for product 1.1 specimens preconditioned in an environmental chamber with a relative humidity of approximately 30%, 60%, 80%, and 95%, and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C.

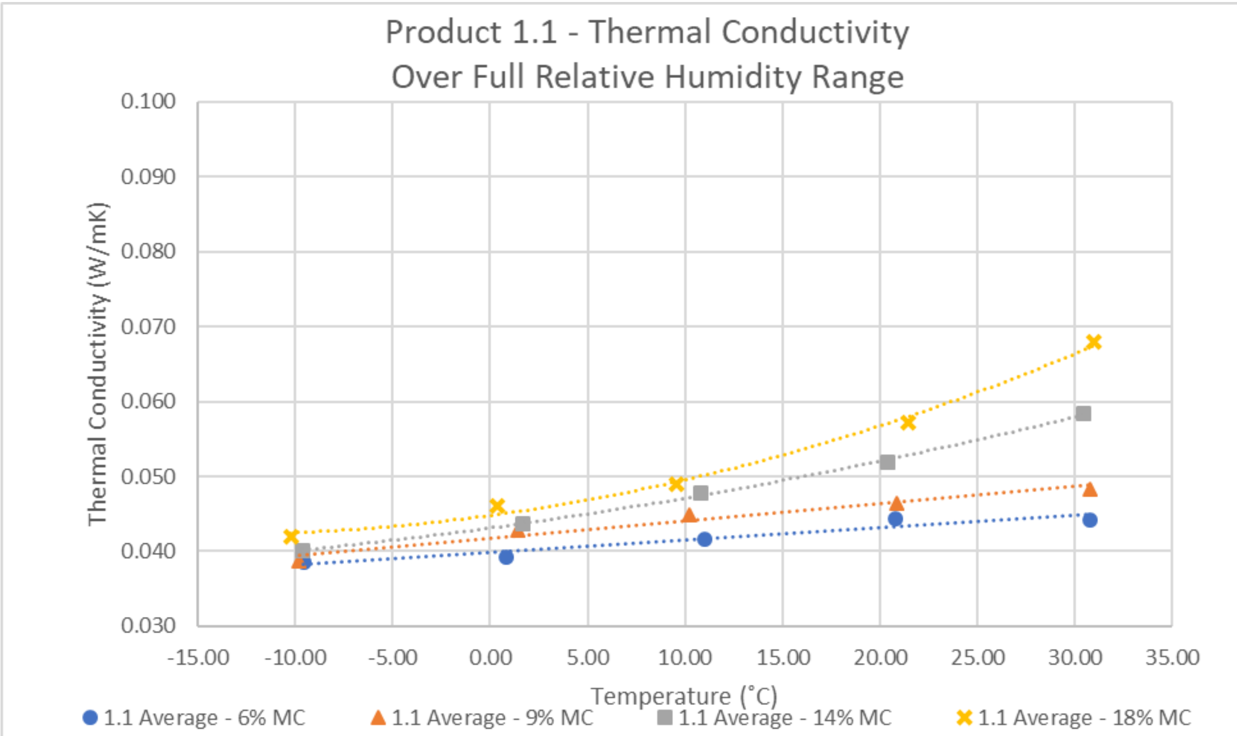


Figure 4.36 – Average Thermal Conductivities for Product 1.1 over Full Temperature and Relative Humidity Range.

The average thermal conductivities obtained for all other products preconditioned in an environmental chamber with a relative humidity of approximately 30%, 60%, 80%, and 95%, and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Appendix I.

4.4.3.1 Effect of Test Order on Thermal Conductivity Results

As previously discussed, thermal conductivity tests using the HFM were conducted in order from lowest temperature to highest temperature (-10˚C to 30˚C) for a majority of specimens. However, one specimen from each product was tested at the final relative humidity step (95%) with the thermal conductivity test conducted with temperatures in reverse order (30˚C to -10˚C).

Figure 4.37 depicts the thermal conductivity obtained for specimen 1.1.01 preconditioned in an environmental chamber with a relative humidity of 95% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C. The figure includes test results from the HFM tests conducted from -10˚C to 30˚C, and from 30˚C to -10˚C.

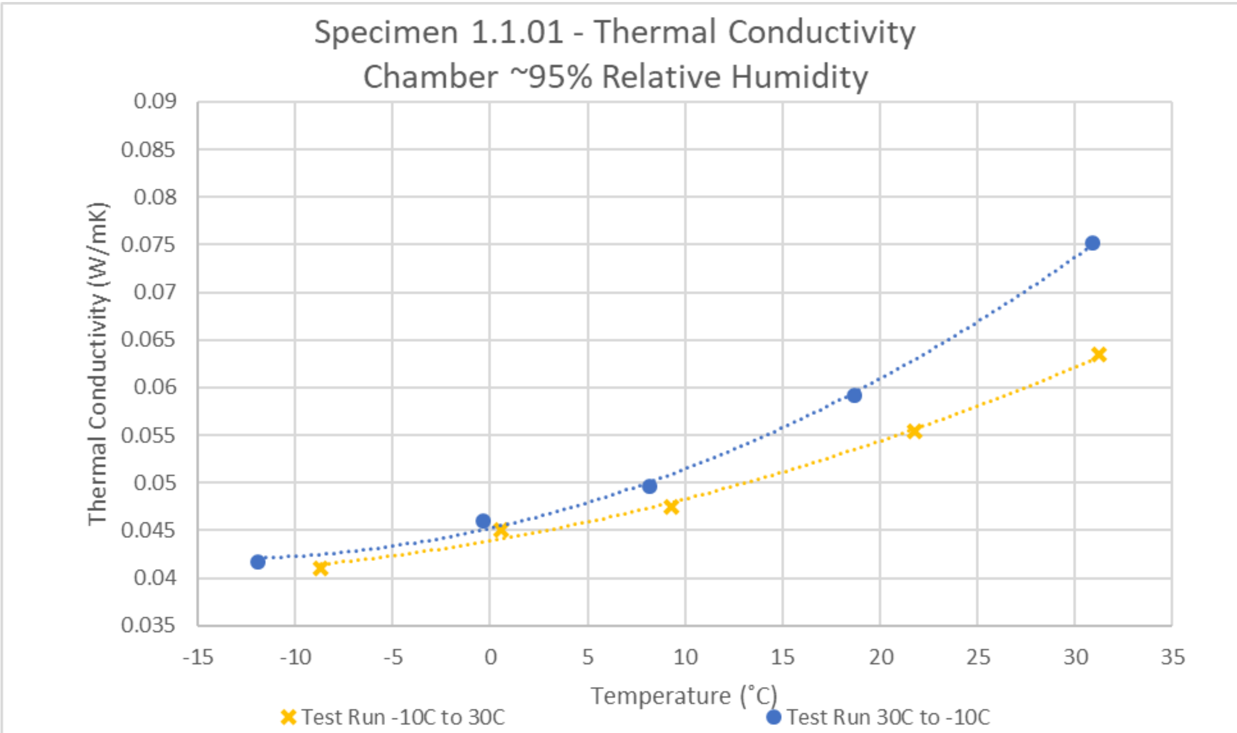


Figure 4.37 – Thermal Conductivities of Specimens 1.1.01 over Full Temperature Range at Chamber 95% Relative Humidity – Order of Heat Flow Meter Test Temperatures Reversed.

The thermal conductivity obtained for a specimen for all other products, preconditioned in an environmental chamber with a relative humidity of 95% and then tested in the HFM at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C, and tested in reverse order of temperatures, are provided in Appendix I.

5 Analysis and Discussions of Results

5.1 Dry Density

The variation in product density as measured from the sorption specimens in this study is presented in Table 4.1, Figure 4.1, and Figure 4.2.

For the sample size provided, the results revealed a variability amongst each manufacturer from board to board. For example, product 2.2 has a declared density of 145 kg/m^3, though comprised an average density for board 3 of 144 kg/m^3, and an average density for board 1 of 163 kg/m^3. These variations indicate a standard deviation of 4.1 kg/m^3 and a coefficient of variation of 7.7%. The range of percent difference of calculated density from the declared density was 0.4-10.8%, and the overall average percent difference of calculated density from the declared density was 7.7%.

On the other hand, product 6.2 has a declared density of 180 kg/m^3, though comprised an average density for board 3 of 165kg/m3, and an average density for board 2 of 166 kg/m3. These variations indicate a relatively smaller standard deviation of 1.3 kg/m^3 and a coefficient of variation of 0.8%. However, the range of percent difference of calculated density relative to the declared density remains high at 8.4%-9.1%, with a percent difference of calculate density from the declared density of 8.1%.

These results indicate that for some products, the variability of density amongst the product is significant (18 kg/m^3), and the percent difference of the product density from the declared density is also notable (7.7%). Whereas for other products, the variability of density amongst the product is less significant (1 kg/m^3), though the percent difference of the product density from the declared density is significant (8.1%). Furthermore, product 5.2 has the lowest percent difference of the product density from the declared density (1.3%), and the variability of density amongst the product is 4 kg/m^3. However, it is worth noting that all specimens from product 5.2 were cut from a single board. The products with a declared density of 140 kg/m^3 have relatively low standard deviations and coefficient of variations, while also obtaining a relatively low percent different of calculated average density from the declared density. Based on the data obtained for the sample size, a correlation of the variation of actual density of products based on declared density cannot be inferred. Based on the data obtained for the sample size, it can be concluded that the largest percent difference between actual density of WFIB and the declared density is 17% with a density difference of 16 kg/m^3 (product 3.1, board 2) and the largest difference between actual density of WFIB and the declared density is 18 kg/m^3 with a percent difference of 11% (product 2.2, board 1).

For product 2, the product with a 40mm material thickness (2.1) has lower density than the product with a 60mm material thickness (2.2). Similarly, for product 5, the product with a 60mm material thickness (5.2) has a lower density than the product with an 80mm material thickness (5.3). Contrarily, for product 4, the product with a 40mm material thickness (4.1) has a higher density than the product with a 60mm material thickness (4.2). Based on the data obtained for the sample size, a correlation of the variation of actual density based on material thickness cannot be inferred.

The variation in density within a product and amongst products does not correlate with a particular density, density range (ex. higher versus lower density), or material thickness.

5.2 Temperature Dependent Water Vapour Sorption Isotherm Testing Analysis and Discussion

The water vapour sorption isotherm testing was conducted at temperatures 10˚C and 25˚C and relative humidities of 35%, 50%, 75%, 85%, and 95%. Three specimens for each product were tested at each temperature and relative humidity step. One specimen from each product was oven dried prior to testing and was also tested at each temperature and relative humidity.

5.2.1 Mass Gain over Time

As discussed and presented in Section 4.2.1, the specimens were allowed to gain or lose moisture until a state of equilibrium was reached for the set temperature and relative humidity for the testing conditions. Several of the specimens experienced occasional mass gains and losses throughout the experiment, even during conditions in which only a mass gain would be expected. For example, when the relative humidity was increased from 30% to 50% from step 1 to step 2, respectively. The mass losses are likely a result of the opening of the environmental doors throughout the weighing process for both the water vapour sorption testing and the water vapour permeance testing. Additionally, the time which the specimens were outside of the environmental chamber for weighing may have impacted the mass of the specimens. Despite these occasional mass losses throughout the testing, the expected overall mass gain occurred. Additionally, most specimens experienced mass equilibrium such that less than 0.1% mass change was measured during the final two or three consecutive weighings.

Products 1, 4, 5, and 6 experienced visible mould during the final relative humidity step at 95% at a temperature of 25˚C, and therefore the test specimens were removed from the chamber and a final weighing was recorded, and the relative humidity step was deemed complete. The mould was brushed off for weighing and appeared to only occur at the surface. Products 2 and 3, and the oven dried specimens from all products, did not experience visible mould throughout testing. When the final relative humidity step at 95% was ended due to mould for products 1, 4, 5, and 6, the test was also ended for products 2 and 3, and the oven dried specimens from all products. Therefore, the final mass for the specimens for the final relative humidity step at 95% typically experienced a mass change greater than 0.1% during the final two consecutive weighings. It is worth noting that prior to experiencing mould, the specimens had been kept in the 25˚C environmental chamber at 85% relative humidity for approximately 11 days, and at 95% relative humidity for approximately 6-12 days.

5.2.2 Interpretation of Sorption Isotherms

As discussed in Section 2.3.1.1.5, and illustrated in Figure 2.7, sorption isotherms represent the relationship between the equilibrium moisture content of a material at a specific relative humidity. The shape of the sorption isotherm is unique to different material characteristics and internal structure of the material. The shape of the sorption isotherm is indicative of the different states of water storage within the material at the corresponding relative humidities. The main segments of the sorption isotherm are the adsorption of a single layer, adsorption of multiple layers, internal capillary condensation, and capillary suction. These segments have been approximately located on the average sorption isotherms for all products at a temperature of 25˚C in Figure 5.1. Note that the main segments of the sorption isotherm are approximately located based on the shape of the moisture sorption curves. The average sorption isotherms for all products at temperature of 10˚C is discussed for the temperature effect on sorption (refer to Section 5.2.6).

It is important to note that while the increase in moisture content in each segment is typically dominated by an increase in a specific type of storage, it is common for multiple storage mechanisms to take place concurrently. For example, multi-layer adsorption may occur at some sites whereas other sites may only have single layer adsorption. Likewise, capillary condensation within small pores and lumens may occur simultaneously with adsorption at other sites.

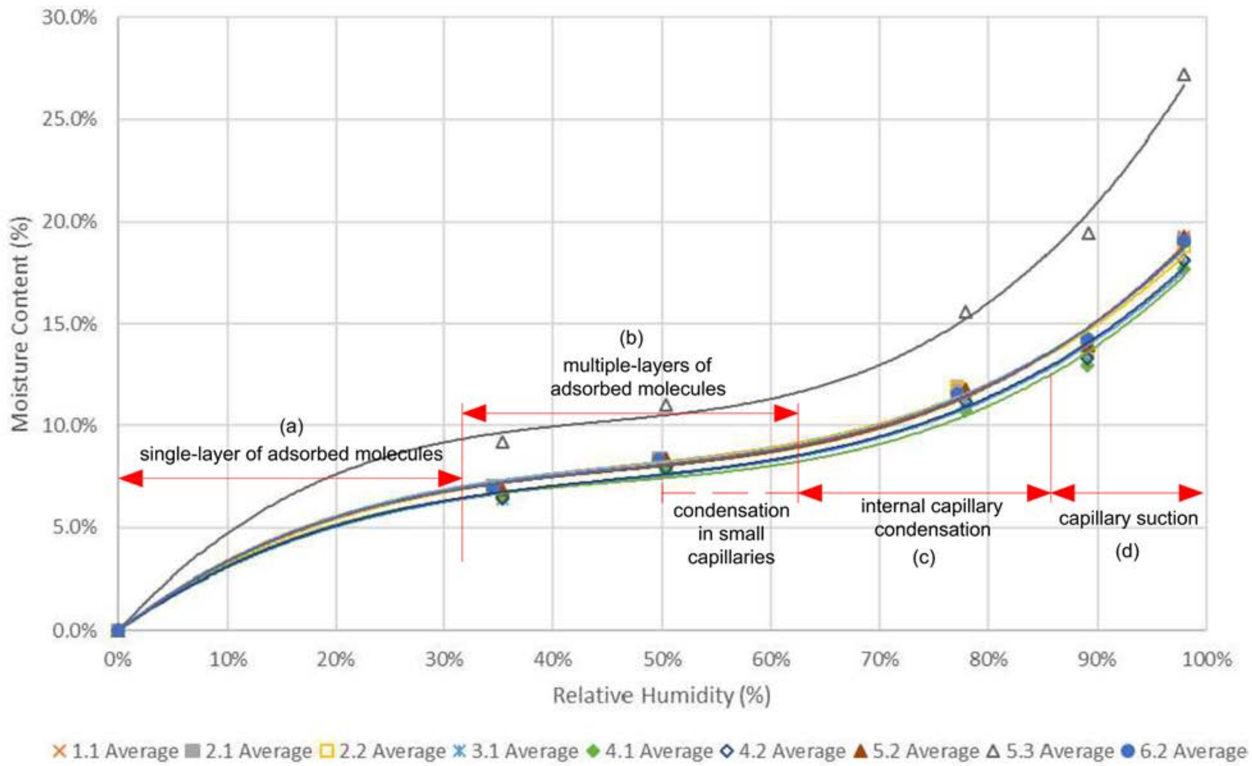


Figure 5.1 - Segments of Average Sorption Isotherms for All Products over Full Relative Humidity at Temperature 25˚C.

5.2.3 Variation within Products

The sorption isotherms and volumetric moisture contents versus relative humidity for product 1.1 specimens at 25˚C are provided in Section 4.2.2.1 (Figure 4.4, Table 4.2) and 4.2.2.2 (Figure 4.6, Table 4.3). The sorption isotherm data and curves for all specimens and product averages for all other products for temperatures at 25˚C are provided in Appendix C. The volumetric moisture content versus relative humidity data and curves for All specimens and product averages for all other products at a temperature of 25˚C are provided in Appendix C.

At a temperature of 25˚C, the standard deviation and coefficient of variation of moisture content was relatively small. The coefficient of variations for moisture content for each relative humidity step for each product are as presented in Table 5.1. The largest coefficient of variation of 2.16% for moisture content was for product 4.1 at a relative humidity of approximately 98% (test step 5). The higher coefficient of variation at a relative humidity of 98% may be associated with the loss of moisture in specimens during weighing. Additionally, the relative humidity sensor was unable to read the relative humidity within the chamber for a majority of the 98% relative humidity test step, therefore the standard deviation and coefficient of variation for the environmental chamber relative humidity is unknown. A large variation in the relative humidity may result in variations in the material moisture contents. The average coefficient of variation of the moisture content for all products and all relative humidity test conditions at 25˚C was 0.69%.

The largest coefficient of variation for moisture content for each relative humidity step does not correlate with a specific product, though it does correlate with the relative humidity conditions of the environmental chamber with the greater standard deviation. Recall that the timing of testing was conducted such that not all products completed the relative humidity steps at the same time, and therefore were subject to slightly different temperature and relative humidity conditions.

At a temperature of 10˚C, the standard deviation and coefficient of variation of moisture content was relatively small, though greater than the standard deviations and coefficient of variants of moisture content at 25˚C. The coefficient of variation for moisture content for each relative humidity step for each product at 10˚C are as presented in Appendix D. Similar to 25˚C, the largest coefficient of variation does not correlate with a specific product, though it does correlate with the relative humidity conditions of the environmental chamber with the greater standard deviation.

Table 5.1 - Moisture Content Coefficient of Variation within Products at 25˚C.

Test No.	RH(%)	MC(%) CV(%)									
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	35%	0.05%	0.95%	0.67%	1.17%	1.30%	0.47%	**1.15%**	0.77%	0.27%	0.76%
.2	50%	0.81%	0.85%	0.17%	1.14%	**1.15%**	0.41%	0.80%	0.58%	0.58%	0.72%
.3	77/78%	0.82%	0.78%	0.12%	**0.94%**	0.55%	0.73%	0.35%	0.47%	0.60%	0.59%
.4	89%	**1.35%**	0.70%	0.08%	0.55%	0.14%	0.36%	0.34%	0.42%	0.46%	0.49%
.5	98%	0.78%	1.04%	0.29%	0.68%	**2.16%**	1.25%	0.60%	0.46%	0.73%	0.89%
									Average		0.69%

At a temperature of 25˚C, the coefficient of variation of volumetric moisture content was larger than that of moisture content. The largest coefficient of variation values of volumetric moisture content for each relative humidity step are as presented in in Table 5.2 The largest coefficient of variation for volumetric moisture content was 6.54% for product 2.2 at a relative humidity of approximately 98% (test step 5). The higher coefficient of variation at a relative humidity of 98% may be associated with the loss of moisture in specimens during weighing. However, it is more likely that the larger coefficient of variation for product 2.2 is associated with the relatively large variation of material density for product 2.2 (coefficient of variation of density 5.8%). The average coefficient of variation for volumetric moisture content for all products and all relative humidity test conditions at 25˚C was 2.18%.

The maximum coefficient of variation for volumetric moisture content for each relative humidity step is consistently associated with product 2.2. As mentioned above, product 2.2 has the largest variation of material density. As discussed in Section 2.3.1.1.5, the density of a material is associated with the quantity of moisture that a material is capable of storing as water vapour, adsorbed water, and capillary water.

Similar to the results at 25˚C, at a temperature of 10˚C the coefficient of variation of volumetric moisture content was larger than that of moisture content. The largest coefficient of variation of volumetric moisture content for each relative humidity step are as presented in Appendix D. Similar to 25˚C, the largest coefficient of variation for volumetric moisture content is consistently associated with product 2.2.

Table 5.2 - Average Volumetric Moisture Content Coefficient of Variation within Products at 25˚C.

Test No.	RH(%)	CV (%) VMC (kg_w/m^3_{WFIB})									
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	35%	3.22%	0.92%	**5.76%**	1.16%	3.35%	0.55%	*0.32%*	2.05%	0.83%	2.02%
.2	50%	3.95%	0.78%	**6.29%**	1.10%	3.28%	0.66%	*0.60%*	1.81%	0.87%	2.15%
.3	77/78%	3.93%	1.09%	**6.22%**	0.96%	2.66%	*0.28%*	1.00%	1.74%	0.82%	2.08%
.4	89%	4.45%	1.10%	**6.32%**	*0.67%*	4.45%	1.45%	1.02%	1.66%	0.81%	2.44%
.5	98%	2.42%	1.14%	**6.54%**	0.87%	4.18%	2.23%	*0.75%*	1.06%	0.95%	2.24%
									Average		2.18%

5.2.4 Variation Amongst Products

The sorption Isotherm and volumetric moisture contents versus relative humidity for all products at 25˚C are provided in Section 4.2.2.1 (Figure 4.5) and Section 4.2.2.2 (Figure 4.7). The sorption isotherm data for all products are for a temperature of 25˚C are provided in Appendix C. The volumetric moisture content versus relative humidity data for all products for a temperature of 25˚C are provided in Appendix C. Table 5.3 presents the moisture contents for all products for each relative humidity step at a temperature of 25˚C. This table includes the maximum and minimum moisture content and the difference at each relative humidity step, excluding product 5.3. As presented, and as depicted in Figure 4.5, the variance in moisture content percentage is relatively small at lower relative humidities. However, the difference in moisture content amongst the products increases as the relative humidity increases. The largest variation in moisture content amongst products is 1.6% at approximately 98% relative humidity (excluding product 5.3).

Excluding product 5.3, the highest moisture contents at lower relative humidities (35%, 50%, 77%) are associated with product 2.1, while the lowest moisture contents at these relative humidities are associated with product 4.1. Excluding product 5.3, the highest moisture contents at higher relative humidities (90%, 98%) are associated with product 6.2 and 1.1, while the lowest moisture contents at these relative humidities are associated with product 4.1.

Note that the moisture sorption curve of product 5.3 behaves differently than all other materials. Product 5.3 consistently obtains much higher moisture contents than all other WFIB materials. Additionally, as the environmental conditions increase beyond approximately 78% relative humidity the moisture content for product 5.3 increases at a greater rate than all other WFIB materials. Furthermore, product 5.3 behaves differently than product 5.2, which is the same product but of different thicknesses. If the sorption properties of product 5.3 are included, the largest variation in moisture content amongst products is 9.5% at approximately 98% relative humidity. The different behaviour of product 5.3 may be due to the additives. Though the additives were not studied, product 5.3 experienced darkening during oven drying, whereas no other products (including product 5.2) experienced similar darkening. The darkening of product 5.3 during oven drying may be indicative of a difference in the additives for product 5.3.

The moisture contents for all products for each relative humidity step at a temperature of 10˚C are presented in Appendix D. Similar to the results at 25˚C, at 10˚C the variance in moisture content amongst products increases with increasing relative humidity. Additionally, the largest and lowest moisture contents are generally associated with similar products. Lastly, product 5.3 exhibits similar behaviour at 10˚C, such that moisture contents are significantly larger than other WFIB products.

The variation in moisture contents for products is somewhat misleading considering the material density is a factor of the moisture content calculation. An alternative method of comparison is using the volumetric moisture content for each product.

Table 5.3 - Moisture Content for all Products at 25˚C for all Relative Humidity Steps with Maximum, Minimum, and Difference in Moisture Content Percentage.

Test No.	RH(%)	MC (%)											
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max*	Min	Diff*
.1	35%	6.9%	**7.0%**	6.9%	6.4%	6.4%	6.5%	6.8%	9.2%	6.9%	7.0%	6.4%	0.6%
.2	50%	8.3%	**8.4%**	8.3%	7.8%	7.8%	7.9%	8.4%	11.0%	8.3%	8.4%	7.8%	0.6%
.3	77/78%	11.6%	**11.9%**	11.9%	11.1%	10.7%	11.2%	11.8%	15.6%	11.5%	11.9%	10.7%	1.2%
.4	89%	13.9%	13.8%	13.7%	13.2%	12.9%	13.3%	13.9%	19.4%	**14.2%**	14.2%	12.9%	1.3%
.5	98%	19.3%	19.1%	18.8%	18.0%	17.7%	18.1%	**19.3%**	27.2%	19.0%	19.3%	17.7%	1.6%

*excluding product 5.3

Table 5.4 presents the volumetric moisture contents for all products for each relative humidity step at a temperature of 25˚C, along with the maximum and minimum volumetric moisture content and the difference at each relative humidity step. As presented, and as depicted in Figure 4.7, the variance in volumetric moisture content is significantly greater than the variance in moisture content. Since the volumetric moisture content is the mass of the sorbed water (kg) per the volume of WFIB (m^3) at a given relative humidity, the density of the WFIB does not influence the data as it does with moisture content. The variation in volumetric moisture content increases with increasing relative humidity conditions. the largest variation in volumetric moisture content amongst all products is 22.99 kg_w/m^3_{WFIB} at approximately 98% relative humidity.

Note that the volumetric moisture content curve for product 5.3 behaves differently than all other materials as the environmental conditions increase beyond approximately 78% relative humidity, with a much steeper curve beyond 78% relative humidity.

The largest variation in volumetric moisture content amongst products is 22.99 kg_w/m^3_{WFIB} at approximately 98% relative humidity, which is for product 5.3. Excluding product 5.3, the largest variation in volumetric moisture content amongst products is 16.77 kg_w/m^3_{WFIB} at 98% relative humidity. Note that though the difference in moisture content due to product 5.3 was quite high, though the difference in volumetric moisture content due to product 5.3 is less significant. This is owing to the fact that denser materials such as product 4.1 also experience high levels of volumetric moisture content, though the moisture contents for product 4.1 is influenced by the higher density.

Excluding product 5.3, The variation in volumetric moisture content is consistently associated with density with increasing differences in volumetric moisture as the relative humidity increases, with the exception of product 2.2 and 6.2. Product 2.2 and 6.2 have lower densities than product 4.2, though product 2.2 and 6.2 obtain higher volumetric moisture contents than product 4.2 at all relative humidity testing conditions. It would be expected that the higher density product would be associated with the higher volumetric moisture content as a result of the greater number of wood cells available for adsorption. However, it would also be expected that the higher density product with a lower pore volume would be associated with a lower volumetric moisture content in the pores. The volumetric moisture content within the pores also depends on pore size, distribution, and connectivity. In comparison, products with similar differences in density, such as comparing product 2.1 to product 3.1, behave such that the volumetric moisture content is consistently greater for the product of greater density. The difference in the hygrothermal behavior of product 2.2 and 6.2 may be associated with the manufacturing processes, including the coating and impregnation of the wood fibres and thermal modification throughout the manufacturing process. Impregnation/coating and thermal modification of the wood cells impacts the wood cells' ability to adsorb water and would be expected to result in lower levels of adsorption. Therefore, product 2.2 and 6.2 may have experienced less thermal modification during manufacturing and board pressing, or comprise less impregnation/coating of the wood cell. Additionally, higher levels of adsorption could result in higher levels of capillary condensation due to higher wood fibre swelling, hence a lower level of porosity being maintained. Analysis on the microscopic level would be required to verify.

The volumetric moisture contents for all products for each relative humidity step at a temperature of 10˚C are presented in Appendix D. Similar to the results at 25˚C, at 10˚C the variance in volumetric moisture content amongst products increases with increasing relative humidity. Additionally, the largest and lowest volumetric moisture contents are generally associated with similar products which is associated with density. Lastly, product 5.3 exhibits similar behaviour at 10˚C, such that volumetric moisture contents are larger than other WFIB products.

Table 5.4 – Volumetric Moisture Content for all Products at 25˚C for all Relative Humidity Steps with Maximum, Minimum, and Difference in Volumetric Moisture Content Percentage.

Test No.	RH(%)	VMC ($kg_w/m^3{}_{WFIB}$)											
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max*	Min	Diff.*
.1	35%	9.22	9.90	10.76	5.98	12.03	10.70	9.47	13.57	11.48	12.03	5.98	6.04
.2	50%	11.05	11.80	12.85	7.33	14.57	13.11	11.58	16.22	13.82	14.57	7.33	7.24
.3	77/78%	15.51	16.76	18.44	10.43	20.16	18.56	16.31	23.02	19.12	20.16	10.43	9.73
.4	89%	18.59	19.47	21.35	12.56	24.78	22.34	19.28	28.66	23.61	24.78	12.56	12.22
.5	98%	25.78	26.90	29.27	17.12	33.89	30.39	26.69	40.11	31.58	33.89	17.12	16.77

*Excluding Product 5.3.

The moisture sorption results obtained through testing for all products differ from results reported in previous research in several ways. Relative to the results obtained by Sonderegger et al. (Sonderegger & Niemz, 2012), the moisture sorption results are similar for relative humidities of 50% or less. At relative humidities of 50% or greater, moisture sorption values obtained in this research are less than Sonderegger et al. results. Furthermore, the results reported in previous research are for WFIB specimens which were oven dried prior to testing, whereas the reported product specimen moisture sorption values for this research were not oven dried prior to testing.

In comparison to the results obtained by Vololonirina et al. (Vololonirina et al., 2014) moisture sorption results for this research are greater at less than approximately 65% relative humidity, indicating greater levels of adsorption. This is consistent with the fact that the WFIB specimens from the previous research were oven dried prior to testing. Moisture sorption results for this research are less than the results from previous research at greater than 65% relative humidity. Furthermore, the sharp rise in moisture content with relative humidity at approximately 98% relative humidity from previous research was not obtained in this research, suggesting that the WFIB capillary regime may exist at higher relative humidities than tested as a part of this research.

5.2.5 Specimen Thickness Effect on Sorption

The sorption isotherm and volumetric moisture contents versus relative humidity for product 2 (2.1, 40mm; 2.2, 60mm) at 25˚C are provided in Section 4.2.3.1 (Figure 4.12, Figure 4.13). The sorption isotherm data for product 4 (4.1, 40mm; 4.2, 60mm) and product 5 (5.2, 60mm; 5.3, 80mm) products for a temperature of 25˚C are provided in Appendix C. The volumetric moisture content versus relative humidity data for products 4 and 5 for a temperature of 25˚C are provided in Appendix C. Table 5.5 presents the moisture contents for products 2, products 4, and products 5, for each relative humidity step at a temperature of 25˚C, along with the difference in moisture content between product thicknesses at each relative humidity step.

As presented, the difference in moisture content percentage between product thicknesses is relatively small for product 2 and 4. For product 2, the moisture content of product 2.1 (40mm) is consistently slightly greater than product 2.2 (60mm), and the difference in moisture content increases slightly with increasing relative humidity. For product 4, the moisture content of product 4.2 (60mm) is consistently slightly greater than product 4.1 (40mm), and the difference in moisture content increases slightly with increasing relative humidity. For product 5, the difference in moisture content percentage between product thickness is relatively large. The moisture content of product 5.3 (80mm) is consistently greater than product 5.2 (60mm), and the difference in moisture content increases significantly with increasing relative humidity. The larger differences in moisture content for product 5 may be associated with differences in additives as discussed in Section 5.2.4.

The moisture contents for products 2, 4, and 5 for each relative humidity step at a temperature of 10˚C are presented in Appendix D. At 10˚C the differences in moisture contents between different thicknesses of t he same products are similar to the results at 25˚C. Additionally, the difference in moisture content percentage been product 5.3 and 5.2 is relatively large.

The variation in moisture contents for different product thicknesses is somewhat misleading considering the material density is a factor of the moisture content calculation. An alternative method of comparison is using the volumetric moisture content.

Table 5.5 - Moisture Content for Products in Various Thicknesses at 25˚C for all Relative Humidity Steps with Difference between Same Product of Different Thickness.

Test No.	RH(%)	MC(%)								
		2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	35%	7.0%	*6.9%*	0.12%	*6.4%*	6.5%	0.06%	*6.8%*	9.2%	2.36%
.2	50%	8.4%	*8.3%*	0.13%	*7.8%*	7.9%	0.16%	*8.4%*	11.0%	2.63%
.3	77/78%	11.9%	*11.9%*	0.06%	*10.7%*	11.2%	0.48%	*11.8%*	15.6%	3.82%
.4	89%	13.8%	*13.7%*	0.12%	*12.9%*	13.3%	0.39%	*13.9%*	19.4%	5.50%
.5	98%	19.1%	*18.8%*	0.31%	*17.7%*	18.1%	0.42%	*19.3%*	27.2%	7.92%

Table 5.6 presents the volumetric moisture contents for products 2 (2.1 & 2.2), product 4 (4.1 & 4.2), and product 5 (5.2 & 5.3), for each relative humidity step at a temperature of 25˚C, along with the difference in volumetric moisture content between product thicknesses at each relative humidity step. As presented, the variance in volumetric moisture content is greater than the variance in moisture content. Since the volumetric moisture content is the mass of the sorbed water (kg) per the volume of WFIB (m3) at a given relative humidity, the density of the WFIB does not influence the data as it does with moisture content. The difference in volumetric moisture content increases with increasing relative humidity conditions. The largest difference in volumetric moisture content s 13.43 kg_w/m^3_{WFIB} between product 5.2 and 5.3 at approximately 98% relative humidity.

For all products, the material with the highest density obtains the largest volumetric moisture content. As discussed in Section 2.3.1.1.5, the density of a material is associated with the quantity of moisture that a material is capable of storing as water vapour, adsorbed water, and capillary water. Additionally, as discussed in Section 5.1, a correlation of the variation of actual density based on material thickness could not be inferred. Therefore, the WFIB density is influencing the volumetric moisture content at each relative humidity step, which was not correlated with the material thickness based on the products tested in this research.

For product 2, the largest increase in difference between product 2.1 and 2.2 occurs at a relative humidity of approximately 35% (step .1). This indicates that the adsorption of single and multiple layers of water in the WFIB accounts for a large difference in volumetric moisture content between product 2.1 and 2.2. This is expected, considering that higher density materials have a greater surface area, hence a greater number of sites for water adsorption. Another large increase in the difference between product 2.1 and 2.2 occurs at a relative humidity of approximately 77% (step .3). This indicates that at the early stages of capillary condensation, the quantity of capillary condensation in product 2.2 is greater than that of 2.1. This may be owing to product 2.2 comprising pore spaces that are smaller in size than those in product 2.1. Additionally, product 2.2 may experience a larger decrease in the porosity due to the larger number of wood fibres experiencing swelling. Particularly, a decrease in pore size of pores that are relatively smaller, thus allowing for capillary condensation at lower relative humidities. Another large increase in the difference of volumetric moisture content between product 2.2 and 2.1 occurs at the approximately 98% relative humidity, possibly for reasons similar to those discussed above. Product 4 experiences similar hygrothermal behaviour as product 2.

Product 5 also experiences similar hygrothermal behaviour as product 2 and 4, though the difference between the volumetric moisture content of product 5.3 and 5.2 is larger. Additionally, at relative humidities greater than approximately 77%, the rate of increase in volumetric moisture content for product 5.3 is greater than that of product 5.2. As discussed in previous sections, product 5.3 exhibits hygrothermal characteristics different than all other WFIB products. Additionally, as discussed in Section 5.2.7, the darkening observed during oven drying for product 5.3 may be indicative of differences of material compositions between product 5.2 and product 5.3. It is difficult to determine the causation of the greater amount of water storage of product 5.3 relative to product 5.2 due to the uncertainties associated with the differences in material compositions.

The volumetric moisture contents for all products for each relative humidity step at a temperature of 10˚C are presented in Appendix D. Similar to the results at 25˚C, at 10˚C the difference in volumetric moisture content amongst the same product of different thicknesses increases with increasing relative humidity. Additionally, the difference in volumetric moisture contents correlates with material density.

Lastly, product 5.3 exhibits similar behaviour at 10˚C, such that volumetric moisture contents are larger than other WFIB products.

Table 5.6 – Volumetric Moisture Content for Products in Various Thicknesses at 25˚C for all Relative Humidity Steps with Difference between Same Product of Different Thickness.

Test No.	RH(%)	VMC (kg_w/m^3_{WFIB})								
		2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	35%	*9.90*	*10.76*	0.86	12.03	*10.70*	1.33	*9.47*	13.57	4.10
.2	50%	*11.80*	*12.85*	1.05	14.57	*13.11*	1.45	*11.58*	16.22	4.65
.3	77/78%	*16.76*	*18.44*	1.68	20.16	*18.56*	1.59	*16.31*	23.02	6.71
.4	89%	*19.47*	*21.35*	1.88	24.78	*22.34*	2.44	*19.28*	28.66	9.38
.5	98%	*26.90*	*29.27*	2.37	33.89	*30.39*	3.50	*26.69*	40.11	13.43

5.2.6 Temperature Effect on Sorption

The sorption isotherms for product 1.1 at 10˚C and 25˚C are provided in Section 4.2.4 (Figure 4.16). The sorption isotherms at 10˚C and 25˚C for all other products are provided in Appendix E Table 5.7 presents the difference between the average moisture content at a temperature of 10˚C and 25˚C for all products at each relative humidity step. Also included is the maximum and minimum difference between the average moisture content at 10˚C and 25˚C for all products at each relative humidity step. As depicted in Figure 4.16 and Appendix E, the sorption curves for the average moisture content at 10˚C and 25˚C follow the same trend for all products. The test specimens at less than or equal to approximately 53% relative humidity experience greater moisture contents at 10˚C than at 25˚C, though the difference in moisture content is always less than 1.0%. The test specimens at greater than or equal to approximately 77% relative humidity experience greater moisture contents at 25˚C than at 10˚C, though the difference in moisture content is always less than 1.6%. The relative humidity at which the material experiences greater levels of moisture content at 25˚C than 10˚C varies slightly, and further testing would be required to accurately determine the exact relative humidity.

At less than or equal to 53% relative humidity, the WFIB at 10˚C experiences a greater amount of adsorption than the WFIB at 25˚C. As discussed in Section 2.3.1.1.2 and 2.3.1.1.5, The number of adsorbed layers at a specific relative humidity is related to the temperature, which is related to energy. Higher temperature water vapour has higher energy levels and therefore has a greater ability to stay in the gas phase. The temperature impact on a materials sorption isotherm is depicted in Figure 2.9, illustrating the decrease in moisture content with increasing temperatures at a specific relative humidity. The results obtained through testing reveal similar trends for WFIB at relative humidities less than 53%.

However, at greater than or equal to 77% relative humidity, the WFIB at 25˚C experiences greater moisture contents than at 10˚C. The swelling of the wood fibres likely impacted the materials moisture storage behaviour. The WFIB at 10˚C adsorbed greater quantities of water, though the degree of wood fibre swelling is expected to be greater for the WFIB specimens at 25˚C than at 10˚C for a specific relative humidity. As discussed in Section 2.3.1.1.3, the percent of wood fibre swelling increases with temperature (Shi & Gardner, 2006). A greater amount of fibre swelling in WFIB at 25˚C may result in decreased pore size which may cause capillary condensation at lower relative humidities. Therefore, it would be expected that WFIB at 25˚C would experience greater amounts of capillary condensation at lower relative humidities than WFIB at 10˚C. The lesser swelling at 10˚C would maintain pore spaces, therefore capillary condensation within the pores may occur at higher relative humidities or not at all.

It is important to note it is expected that a final data point for testing conditions at 10˚C and 98% relative humidity would modify the trendline for the 10˚C data, particularly between approximately 50-80% relative humidity. Therefore, the difference in moisture content between 10˚C and 25˚C should only be considered at the specific relative humidities tested rather than as shown by the trendlines.

Table 5.7 –Difference in Moisture Content for all Products at 10˚C and 25˚C for all Relative Humidity Steps with Maximum and Minimum Difference in Moisture Content.

Test No.	RH(%)		Difference in Average Moisture Content at 10˚C and at 25˚C										
	10˚C	25˚C	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min
.1	35/40%	35%	0.7%	0.5%	0.6%	1.0%	1.0%	1.0%	0.6%	0.5%	0.6%	1.0%	0.5%
.2	51/54%	50%	0.4%	0.3%	0.3%	1.0%	0.9%	1.0%	0.6%	0.4%	0.3%	1.0%	0.3%
.3	80/81%	77/78%	0.1%	0.1%	0.1%	0.1%	0.3%	0.4%	*0.2%*	*0.6%*	*0.1%*	0.6%	0.1%
.4	91/92%	89%	*0.5%*	*0.2%*	*0.2%*	*0.3%*	*0.1%*	*0.1%*	*0.7%*	*1.6%*	*0.9%*	1.6%	0.1%

Italicized text indicates where the moisture content at 25˚C was greater than the moisture content at 10˚C.

5.2.7 Impact of Oven Drying

The sorption isotherm and volumetric moisture contents versus relative humidity of the calculated average and the oven dried specimen for product 1.1 at 25˚C are provided in Section 4.2.5 (Figure 4.17 and Figure 4.13). The sorption isotherm and volumetric moisture contents versus relative humidity of the calculated average and the oven dried specimen at 25˚C for all other products are provided in Appendix C. Table 5.8 presents the difference between the average moisture content and the oven dried specimen moisture content for all products at each relative humidity step at a temperature of 25˚C. Also included in the maximum and minimum difference between the average moisture content and the oven dried specimen moisture content. As depicted in Figure 4.17 and Appendix C, the sorption curves for the average moisture content and the oven dried moisture content follow the same trend, with the exception of product 5.3.

For a majority of the products, the moisture content of the oven dried specimen is consistently lower than the average moisture content. Additionally, the difference in moisture content percentage is the largest at lower relative humidities. As the relative humidity increases, the moisture content of the oven dried specimen approaches the average moisture content. The oven dried specimen's lower moisture content at lower relative humidities is indicative of the materials reduced ability to adsorb water in the wood cell structure. The materials decreased ability to adsorb water in the wood cell structure may be due to the thermal modification of the wood cell during oven drying. As discussed in Section 2.1, thermal modification has been shown to alter the chemical composition and structure of the wood cell for processed wood products (Altgen et al., 2016). Chemical impacts includes decreased accessibility of water bonding sites. Structural impacts include increased stiffness of the wood cell wall structure resulting in a reduction in swelling of the cell structure and leading to a reduction in adsorption. At higher relative humidities the average moisture content and the oven dried specimen moisture content become nearly equal. This indicates that the WFIBs ability to store water through capillary condensation likely was not altered due to thermal modification of the wood cell.

For product 5.2, though the difference between the average moisture content and the oven dried moisture content decreases with increasing relative humidity, there remains a difference of 1.1% at the highest relative humidity step of approximately 98%. Capillary condensation would continue up to 100% relative humidity, and therefore the difference in moisture content may have decreased or eliminated if testing continued at relative humidities up to 100%. Additionally, the capillary condensation may be impacted by decreased swelling due to thermal modification of the wood cell structure. The decreased swelling of the wood cell would maintain larger pore spaces, therefore capillary condensation within the pores would occur at higher relative humidities or not at all. Alternatively, the thermal modification of the WFIB may have resulted in chemical impacts such that less sites for adsorption were available even prior to swelling of the wood cell structure. This would ultimately result in adsorption sites that were previously available within the wood cell structure which are no longer capable of adsorption due to chemical impacts, resulting in an overall lower moisture content.

As previously noted, the typical sorption isotherm behaviour of the average moisture content and oven dried moisture content for each product was similar for all products except for product 5.3. At relative humidities of approximately 50% and less, the difference between the average moisture content and the oven dried specimen moisture content was approximately 3.6-3.8%. This is much greater than for all other products. Furthermore, as the relative humidity increases the difference in moisture content increases, reaching a maximum difference of 6.84% at approximately 98% relative humidity. Similar to the discussion for product 5.2, the WFIB material for product 5.3 may have experienced both structural and chemical impacts during oven drying, impacting the materials hygrothermal behaviour. Additionally, oven drying of product 5.3 resulted in visible darkening of the WFIB material, indicating that the wood fibres and/or additives (PMDI, paraffin) may have experienced a chemical alteration. Considering that product 5.3 and product 5.2 are the same product in different thicknesses, it was unexpected that product 5.3 experienced visible darkening during oven drying while product 5.2 did not. The difference in response to oven drying between product 5.2 and product 5.3 may be indicative of differences of material compositions, though microscopic examination would be required to confirm this.

Table 5.8 – Difference Between Average Moisture Content and Oven Dried Specimen Moisture Content for all Products at 25˚C for all Relative Humidity Steps with Maximum and Minimum Difference in Moisture Content.

Test No.	RH(%)	Average MC vs Oven Dried Specimen MC – Difference										
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min
.1	35%	1.68%	1.67%	1.73%	1.36%	1.58%	0.97%	1.93%	3.63%	1.83%	3.63%	0.97%
.2	50%	1.35%	1.26%	1.32%	1.28%	1.34%	1.41%	1.87%	3.86%	1.55%	3.86%	1.28%
.3	77/78%	0.37%	0.55%	0.74%	0.55%	0.40%	0.54%	1.26%	4.33%	0.43%	4.33%	0.37%
.4	89%	0.15%	0.03%	0.16%	0.19%	0.22%	0.23%	0.96%	5.42%	0.61%	5.42%	0.03%
.5	98%	-0.24%	-0.25%	-0.03%	-0.04%	0.04%	0.17%	1.10%	6.84%	0.42%	6.84%	-0.25%

The moisture sorption testing conducted by Sonderegger et al. (Sonderegger & Niemz, 2012) was completed using wood fibre specimens that were oven dried prior to testing. The results obtained through this research for oven dried moisture contents is consistently less than the moisture contents obtained by Sonderegger et al. The difference in moisture contents may due to an averaged moisture content of wood fibre insulation materials tested with a higher density range by Sonderegger et al. (120-240 kg/m3).

Similarily, the moisture sorption testing conducted by Vololonirina et al. (Vololonirina et al., 2014) was also completed using wood fibre specimens that were oven dried prior to testing. Relative to the results obtained by Vololonirina et al., the moisture sorption results for oven dried specimens are up to several percentages higher for relative humidities less than 50% or less. At relative humidities between approximately 50-80%, the moisture sorption results obtained by Vololonirina et al. are similar to the results obtained in this research. However, at relative humidities greater than 80%, the results obtained in this research increase a greater amount until the capillary free water regime (approximately 98%

relative humidity) at which point the results obtained by Vololonirina et al. are much greater. A sharp rise in moisture content with relative humidity at approximately 98% relative humidity was not obtained in this research.

5.3 Moisture and Temperature Dependent Water Vapour Permeance Testing Analysis and Discussion

The water vapour permeance testing was conducted at temperatures 10˚C and 25˚C. Testing was conducted at various cup and chamber relative humidities as discussed in Section 3.3. Modified cup test average specimen relative humidity conditions at 25˚C were approximately 19%, 42%, 66%, and 82%. Dry cup and wet cup test average specimen relative humidity conditions at 25˚C were approximately 26% and 75%, respectively. Modified cup test average specimen relative humidity conditions at 10˚C were approximately 20%, 43%, 69%, and 84%. Dry cup and wet cup test average specimen relative humidity conditions at 10˚C were approximately 26% and 75%, respectively. Three specimens for each product were tested at each temperature and relative humidity test condition, with the exception of product 5.3. Two specimens for product 5.3 were tested at 25˚C for each relative humidity test condition.

5.3.1 Mass Gain over Time

As discussed in Section 4.3.1, the direct results from vapour permeance testing were in the form of mass gain over time measurements for each individual cup test assembly for a given relative humidity test. The steady state mass gain over time measurements were utilized for calculating the water vapour transmission rate and for determining the material permeability. The majority of the specimens included 9 mass measurements throughout the steady state mass gain, with some samples having 7 mass measurements. For testing at 25˚C, the average coefficient of determination for the linear regression of mass gain over time measurements was 99.8%, and 95.5% was the lowest. For testing at 10˚C, the average coefficient of determination for the linear regression of mass gain over time measurements was 99.8%, and 98.5% was the lowest.

5.3.2 Interpretation of Permeability Variation with Relative Humidity

As discussed in Section 2.3.1.2.5, the in-service moisture content of a material effects the materials ability to transport water. Non-linear relationships for the permeability in relation to average specimen relative humidity have been experimentally proven for various building materials. Section 5.3.3.1 and 5.3.3.2 discusses the general permeability variation with relative humidity for modified cup, dry cup, and wet cup test conditions at 25˚C. Further discussion of the permeability test results at 10˚C are discussed for the temperature effect on permeability (refer to Section 5.3.6).

5.3.2.1 Permeability Variation with Relative Humidity for Modified Cup Test Conditions at 25˚C

The permeability of WFIB in relation to average specimen relative humidity for modified cup test conditions at 25˚C is depicted in Figure 4.21. As shown, the permeability of WFIB in relation to average specimen relative humidity at 25˚C is generally a concave second order polynomial curve. The permeability of WFIB increases in permeability until approximately 50-60% average specimen relative humidity, at which point the permeability decreases. The overall decrease in permeability as relative humidity increases follows a similar trend to previous test data discussed in Section 2.5.2 (Figure 2.12). A summary of the calculated permeability for each product at each test step with the calculated change in permeability between each test step is provided in Table 5.9.

Table 5.9 – Permeability Amongst Products for Modified Cup Test Conditions at 25˚C with Change of Permeability Between Test Steps.

Test No.	RH(%)			Permeability, μ (ng/(msPa))								
	Cham.	Cup	Avg	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2
.1	35%	2%	18/19%	55	52	73	45	44	57	63	63	73
Δμ				*20*	*15*	*-1*	*43*	*24*	*20*	*28*	*28*	*-1*
.2	50%	33%	42%	75	67	72	87	67	77	90	90	72
Δμ				*-7*	*-2*	*-2*	*-6*	*-3*	*-2*	*-6*	*3*	*0*
.3	77/78%	54%	66%	69	65	71	81	65	75	85	93	72
Δμ				*-21*	*-15*	*-10*	*-19*	*-19*	*-22*	*-19*	*-14*	*-14*
.4	89%	76%	82%	48	50	60	62	46	53	66	80	57

At the first test step the average specimen relative humidity is approximately 18%/19%, and the relative humidity gradient is 33% (2-35%). The vapour pressure gradient across the WFIB specimen is approximately 983/1010 Pa, which is the largest pressure gradient for modified cup tests at 25˚C. At this test step the moisture transport mechanism is primarily vapour diffusion with a small amount of surface diffusion both in the cell wall and on pore wall surfaces with additives (ex. paraffin). As discussed in Section 3.3.2 (Figure 3.1), the actual relative humidity profile through the test specimen is likely greater than calculated for the material. Therefore, the portion of material experiencing a relative humidity between 18-35% would be greater than the portion of the material experiencing a relative humidity between 2-18%. As discussed in Section 5.2.2 (Figure 5.1), at less than 35% relative humidity WFIB is likely experiencing a single layer of adsorbed water molecules. The adsorption site characteristics vary throughout a material, therefore it is expected that there may be water molecules adsorbing in multiple layers at some sites prior to or in conjunction with first layer sites being occupied (refer to Section 2.3.1.1.2). The permeability for the first step of the modified cup test is generally the lowest permeability, which is associated with the relatively slow transport mechanism of vapour diffusion. The large vapour gradient and relative humidity gradient may also impact the vapour permeability, though the low permeability associated with test step .1 may indicate that the slow transport mechanisms have a greater impact.

At the second test step the average specimen relative humidity is approximately 42%, and the relative humidity gradient is 27% (33-50%). The vapour pressure gradient across the WFIB specimen is approximately 516 Pa. At this test step the moisture transport mechanism is primarily surface diffusion within the cell wall and on the pore surfaces, with some vapour diffusion. Additionally, there is potentially a small amount of capillary flow. The portion of material experiencing a relative humidity between 42-50% would be greater than the portion of material experiencing a relative humidity between 33-42%. As discussed in Section 5.2.2 (Figure 5.1), at relative humidities between 33-50% WFIB is experiencing multiple-layers of adsorbed water molecules and potentially a small amount of condensation within small capillaries. Adsorption of water in the wood cell structure may be causing swelling of the wood cell, resulting in a reduction in porosity. Based on previous experiments conducted on WFIB, it is expected that reductions in porosity at relative humidities between 33-50% are relatively small (Ye, 2015). The permeability for the second test step of the modified cup test is generally higher than the permeability of the first step owing to the increase in surface diffusion in the pores and potentially a small amount of capillary flow (refer to Table 5.9). The vapour gradient and relative humidity gradient may also impact the vapour permeability, though the higher permeability associated with test step .2 may indicate that the relatively faster transport mechanisms have a greater impact.

At the third step the average specimen relative humidity is approximately 66%, and the relative humidity gradient is approximately 24% (54-78%). The vapour pressure gradient across the WFIB specimen is approximately 730 Pa, which is less than that of test step .1 but greater than that of test step .2. At this test step the moisture transport mechanisms are primarily surface diffusion and capillary transport, with a lesser amount of vapour diffusion. The portion of the material experiencing a relative humidity between 66-78% would be greater than the portion of the material between 54-66%. As discussed in Section 5.2.2 (Figure 5.1), at relative humidities between 54-78% WFIB is experiencing multiple layers of adsorbed water molecules and internal capillary condensation. Adsorption of water in the wood cell structure is likely causing swelling of the wood cell, resulting in the reduction in pore sizes (refer to Section 2.3.1.1.3). Wood cell swelling may result in obstruction of capillary paths, particularly in the pits connecting lumens and in relatively small pores. The permeability for the third step of the modified cup test is generally approximately equal to or slightly less than the permeability of test step 2. The decreased permeability in the third test step may be due to the reduction in capillary paths and sizes due to wood cell swelling. The vapour gradient and relative humidity gradient may also impact the vapour permeability, though the lower permeability associated with test step .3 relative to test step .2 may indicate that the wood fibre swelling may have a greater impact.

At the fourth step the average specimen relative humidity is approximately 82%, and the relative humidity gradient is approximately 13% (76-89%). The vapour pressure gradient across the WFIB specimen is approximately 422/451 Pa, which is the lowest pressure gradient of all test steps. At this test step the moisture transport mechanisms are primarily capillary transport with some surface diffusion, with the potential for a small amount of vapour diffusion in larger pores. The portion of the material experiencing a relative humidity between 82-89% is greater than the portion of the material between 76-82%. As discussed in Section 5.2.2 (Figure 5.1), at relative humidities between 76-89% WFIB is experiencing full layers of adsorbed molecules, internal capillary condensation, and capillary suction, though there may be some larger pore spaces with vapour diffusion. Adsorption of water in the wood cell structure is likely causing swelling of the wood cell, resulting in the reduction in pore sizes. Wood cell swelling may result in obstruction of capillary paths. Previous research of WFIB indicated a porosity of approximately 78% at a relative humidity of 60%. The porosity decreased to approximately 70%-50% porosity for relative humidities of 75%-90% (Ye, 2015). The permeability for the fourth step of the modified cup test is generally less than the permeability of test step .2 and .3. The low vapour gradient and relative humidity gradient may impact the vapour permeability in combination with the impact from wood fibre swelling.

The products that behave differently than the above described permeability variation with average specimen relative humidity are product 2.2 and 6.2. Product 2.2 and 6.2 show a small and continuous decrease in permeability with average specimen relative humidity. Interestingly, product 2.2 and 6.2 also show differing behaviour from other products with regards to volumetric moisture content variation with relative humidity, as discussed in Section 5.2.4. The decrease in permeability as average specimen relative humidity increases may be associated with the materials higher volumetric moisture content. The different behaviour of the permeability may be related to a number of material characteristics such as the density distribution throughout the thickness of the material, number of interconnected pore spaces, orientation of the wood fibres (horizontal versus vertical), quantity of additives, and the distribution of additives (ex. paraffin). Research regarding the microscopic material characteristics is required.

5.3.2.2 Permeability Variation with Relative Humidity for Dry Cup and Wet Cup Test Conditions at 25˚C

The permeability of WFIB in relation to average specimen relative humidity for dry cup (step .7) and wet cup (step .6) test conditions at 25˚C is depicted in Figure 4.22. As shown, the permeability of WFIB in relation to average specimen relative humidity at 25˚C is lower at dry cup test conditions than at wet cup test conditions. A summary of the calculated permeability for each product at each test step with the calculated change in permeability between each test step is provided in Table 5.10.

Table 5.10 – Permeability Amongst Products for Dry Cup and Wet Cup Test Conditions at 25˚C with Delta Permeability Between Test Steps.

Test	RH(%)			Permeability, μ (ng/(msPa))								
No.	Cham.	Cup	Avg	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2
.6	50.4%	100%	75.2%	100	89	90	116	91	98	111	104	91
Δμ				*-56*	*-44*	*-26*	*-64*	*-41*	*-33*	*-40*	*-25*	*-28*
.7	50.3%	2%	26.2%	45	45	64	52	50	65	71	79	62

For wet cup test conditions, the average specimen relative humidity is approximately 75%, and the relative humidity gradient is 50% (50-100%). The vapour pressure gradient is approximately 1512 Pa. The moisture transport mechanism is primarily surface diffusion and capillary transport with vapour diffusion in larger pores. The portion of the material experiencing a relative humidity between to 75-100% is greater than the portion of the material experiencing a relative humidity between 50-75%. As discussed in Section 5.2.2 (Figure 5.1), for relative humidities between 50-100% the WFIB is experiencing full layers of adsorbed water molecules, internal capillary condensation, and capillary suction. Additionally, water vapour diffusion will occur in large pores and portions of the material at a lower relative humidity. Adsorption of water in the wood cell structure is likely causing swelling of the wood cell, resulting in the reduction in pore sizes. At high relative humidities, wood cell swelling may result in obstruction of capillary paths. The large vapour pressure gradient and relative humidity gradient may impact the vapour permeability results in combination with the impact of relatively faster water transport mechanisms. The wet cup permeability is consistently much greater than all modified cup permeabilities. This may be associated with the different portions of materials experiencing different relative humidities and how this impacts the interaction of different moisture transport mechanisms, and also the larger vapour gradient and relative humidity gradient.

For dry cup test conditions, the average specimen relative humidity is approximately 25%, and a relative humidity gradient of 48% (2-50%). The vapour pressure gradient is approximately 1474 Pa. The moisture transport mechanism is primarily vapour diffusion and surface diffusion. The portion of material experiencing a relative humidity between 25-50% is greater than the portion of the material experiencing a relative humidity between 2-25%. As discussed in Section 5.2.2 (Figure 5.1), at relative humidities less than approximately 50% WFIB is experiencing single-layer and multiple-layer adsorbed water, with the potential for a small amount of condensation in small pores and lumens. The dry cup permeability is greater than or lower than the step 1 modified cup permeability, varying by product. For product 1.1, 2.1, 2.2, and 6.2, the dry cup permeability is less than the step 1 modified cup permeability. For products 3.1, 4.1, 4.2, 5.2, and 5.3, the dry cup permeability is greater tan the step 1 modified cup permeability. The large vapour pressure gradient and relative humidity gradient may impact the vapour permeability, though the low permeability associated with dry cup test results may indicate that the slow transport mechanisms have a greater impact. Additionally, the different portions of materials experiencing different relative humidities and how this impacts the interaction of different moisture transport mechanisms may also impact the vapour permeability.

The permeability for dry cup and wet cup tests may be associated with a higher permeability due to desorption (refer to 3.3.2).

5.3.3 Permeability Variation with Relative Humidity Within a Product

5.3.3.1 Variation Within a Product at 25˚C

The permeability versus average specimen relative humidity for modified cup test conditions for product 1.1 specimens at 25˚C are provided in Section 4.3.2.1 (Figure 4.19, Table 4.6). The permeability versus average specimen relative humidity for modified cup test conditions for all specimens and product averages for all other products for temperature at 25˚C are provided in Appendix F. At a temperature of 25˚C, the coefficient of variation for permeability for modified cup test conditions was relatively small. The coefficient of variations for permeability for each average specimen relative humidity for modified cup test conditions for each product are as presented in Table 5.11.

The largest coefficient of variation of 6.8% for permeability was for product 2.2 at an average specimen relative humidity of 42% (test step .2). The highest coefficient of variation for each average specimen relative humidity for modified cup test conditions does not correlate with a specific product. Therefore, the variance of specimen density within a product cannot be correlated with the permeability variance. The highest coefficient of variation does correlate with the relative humidity conditions of the environmental chamber with the greater standard deviation and coefficient of variation. The highest coefficient of variation also does not correlate with the product experiencing the lowest coefficient of determination for mass gain over time for the test step. However, this is somewhat misleading considering a product may have three specimens experience a relatively low coefficient of determination for mass gain over time and may still obtain a low coefficient of variation.

Based on the lack of correlation of the coefficient of variation to a specific product and/or specimen density, the variation for each test condition may be influenced by testing procedures. Testing procedures that may influence the coefficient of variation include the opening of the environmental chamber doors during weighing and the removal of specimens from the chamber during weighing. The coefficient of variation would be affected by error associated with the measurement of the vertical distance of air space between the test specimen and the cup substance, though it is expected that this error would be minor. Additionally, unaccounted for air movement within the chamber would impact the permeability of the specimens, especially if the air movement varied throughout the chamber.

Table 5.11 – Permeability Coefficient of Variation within Products for Modified Cup Test Conditions at 25˚C.

Test No.	RH(%)		Permeability CV (%)									
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	2-35%	18%/19%	0.3%	1.4%	2.8%	1.4%	2.2%	2.4%	3.9%	**5.8%**	1.3%	2.4%
.2	33-50%	42%	4.8%	1.7%	**6.8%**	0.8%	2.6%	0.5%	0.8%	3.6%	1.3%	2.2%
.3	54-77/78%	66%	1.9%	2.1%	**4.1%**	1.2%	1.3%	0.7%	2.4%	1.1%	1.2%	1.8%
.4	76-89%	82%	2.6%	1.3%	1.1%	1.0%	1.2%	1.1%	**4.1%**	2.0%	0.3%	1.6%
											Average	2.0%

Bold text indicates the maximum permeability CV (%) for each test step.

The permeability versus average specimen relative humidity for dry cup and wet cup test conditions for product 1.1 specimens at 25˚C are provided in Section 4.3.2.1 (Figure 4.20, Table 4.7). The permeability versus average specimen relative humidity for dry cup and wet cup test conditions for all specimens and product averages for all other products for temperature at 25˚C are provided in Appendix F. At a temperature of 25˚C, the coefficient of variation for permeability for dry cup and wet cup test conditions was larger than for modified cup test conditions. The coefficient of variations for permeability for each average specimen relative humidity for dry cup and wet cup test conditions for each product are as presented in Table 5.12.

For wet cup testing, the largest coefficient of variation of 5.8% was for product 2.2. For dry cup testing, the largest coefficient of variation of 12.9% for permeability was for product 1.1. The highest coefficient of variation for each average specimen relative humidity for dry cup and wet cup test conditions does not correlate with a specific product and therefore does not correlate with density variation within a product. Additionally, the highest coefficient of variation also does not correlate with the product experiencing the lowest coefficient of determination for mass gain over time for the test step. Similar to the discussion for modified cup tests, the larger coefficients of variation for each test condition may be influenced by testing procedures.

Table 5.12 - Permeability Coefficient of Variation within Products for Dry Cup and Wet Cup Test Conditions at 25˚C.

Test No.	RH(%)		Permeability CV(%)									
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.6	50.4-100%	75.2%	3.8%	0.3%	**5.3%**	1.8%	3.1%	1.4%	0.3%	2.5%	1.4%	2.2%
.7	2-50.3%	26.2%	**12.9%**	6.6%	6.0%	3.2%	0.3%	1.4%	2.1%	5.3%	4.2%	4.7%
											Average	3.4%

Bold text indicates the maximum permeability CV (%) for each test step.

5.3.3.2 Variation Within a Product at 10˚C

The permeability versus average specimen relative humidity for modified cup test conditions for product 1.1 specimens at 10˚C are provided in Section 4.3.2.2 (Figure 4.23, Table 4.8). The permeability versus average specimen relative humidity for modified cup test conditions for all specimens and product averages for all other products for temperature at 10˚C are provided in Appendix G. At a temperature of 10˚C, the coefficient of variation for permeability for modified cup test conditions was larger than the coefficient of variation for permeability for modified cup test conditions at 25˚C. The coefficient of variations for permeability for each average specimen relative humidity for modified cup test conditions for each product are as presented in Table 5.13.

The largest coefficient of variation of 21.9% for permeability was for product 4.1 at an average specimen relative humidity of 84% (test step .4). The highest coefficient of variation for each average specimen relative humidity for modified cup test conditions does not correlate with a specific product. Therefore, the variance of specimen density within a product cannot be correlated with the permeability variance. The highest coefficient of variation does correlate with the relative humidity conditions of the environmental chamber with the greater standard deviation and coefficient of variation. For test step .1 and .4, the highest coefficient of variation does not correlate with the product experiencing the lowest coefficient of determination for mass gain over time for the test step. However, this is somewhat misleading considering a product may have three specimens experience a relatively low coefficient of determination for mass gain over time and may still obtain a low coefficient of variation. For test step .2 and .3, the highest coefficient of variation does correlate with the product and specimens experiencing the lowest coefficient of determination for mass gain over time. Similar to the discussion for permeability tests conducted at 25˚C, the larger coefficients of variation for each test condition may be influenced by testing procedures.

Table 5.13 – Permeability Coefficient of Variation within Products for Modified Cup Test Conditions at 10˚C.

Test No.	RH(%)		Permeability CV (%)									
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	2-35/40%	19%/21%	2.4%	2.2%	4.2%	2.6%	5.0%	1.1%	**6.9%**	1.3%	2.0%	3.1%
.2	33-51/54%	42%/43%	3.0%	2.3%	1.0%	1.0%	4.9%	1.5%	3.5%	**5.3%**	1.3%	2.6%
.3	54-80/81%	69%	5.3%	2.7%	6.7%	3.4%	2.0%	2.0%	6.5%	**11.8%**	5.9%	5.2%
.4	76-91/92%	83%/84%	14.4%	6.0%	9.0%	16.2%	**21.9%**	12.0%	9.6%	13.4%	24.3%	14.1%
											Average	6.2%

Bold text indicates the maximum permeability CV (%) for each test step.

The permeability versus average specimen relative humidity for dry cup and wet cup test conditions for product 1.1 specimens at 10˚C are provided in Section 4.3.2.2 (Figure 4.24, Table 4.9). The permeability versus average specimen relative humidity for dry cup and wet cup test conditions for all specimens and product averages for all other products for temperature at 10˚C are provided in Appendix G. At a temperature of 10˚C, the coefficient of variation for permeability for dry cup and wet cup test conditions was generally less than for modified cup test conditions, and similar to the coefficient of variation for permeability for dry cup and wet cup test conditions at 25˚C. The coefficient of variations for permeability for each average specimen relative humidity for dry cup and wet cup test conditions for each product are as presented in Table 5.14.

For wet cup testing, the largest coefficient of variation of 8.5% was for product 2.2 and correlates with the product with the lowest coefficient of determinations for mass gain over time. For dry cup testing, the largest coefficient of variation of 5.7% for permeability was for product 2.2, though this does not correlate with the product with the lowest coefficient of determinations for mass gain over time. The highest coefficient of variation for each average specimen relative humidity for dry cup and wet cup test conditions is associated with product 2.2 which does correlate to the product with the greatest variance in density. Similar to the discussion for permeability tests conducted at 25˚C, the larger coefficients of variation for each test condition may be influenced by testing procedures.

Table 5.14 - Permeability Coefficient of Variation within Products for Dry Cup and Wet Cup Test Conditions at 10˚C.

Test No.	RH(%)		Permeability CV(%)									
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.6	53-100%	76.5%	3.5%	3.5%	**8.5%**	3.4%	7.0%	4.9%	1.2%	2.4%	5.5%	4.4%
.7	2-54%	28%	1.6%	3.2%	**5.7%**	3.7%	1.4%	0.9%	1.7%	1.4%	2.0%	2.4%
											Average	3.4%

Bold text indicates the maximum permeability CV (%) for each test step.

5.3.4 Permeability Variation with Relative Humidity Amongst Products

5.3.4.1 Variation Amongst Products at 25˚C

The average permeability versus average specimen relative humidity for modified cup test conditions for all products at 25˚C are provided in Section 4.3.2.1 (Figure 4.21). The average permeability data for modified cup test conditions for all products for a temperature of 25˚C are provided in Appendix F. Table 5.15 presents the average permeability for all products for each average specimen relative humidity for modified cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, and as depicted in Figure 4.22, the variance in permeability amongst all products is generally consistent for all average specimen relative humidity conditions for modified cup test conditions. Correlation of the variance in permeability amongst specimens is simpler when the products are grouped by thickness (refer to Section 5.3.5.1).

The vapour permeability results obtained through testing for all products differ from results reported in previous research, though reveal some similarity. Results of vapour permeability testing at several average specimen relative humidities conducted by Goto et al. (Goto et al., 2011) indicated a general decrease in vapour permeability of WFIB with increasing relative humidity. The results obtained in this research are similar to the results obtained by Goto et al., as an overall decrease of permeability with increasing relative humidity is also obtained. However, the results from this research also include an increase in permeability with increasing relative humidity for relative humidities less than approximately 50%. Additionally, higher permeabilities appeared to correlate with lower density materials for the results obtained by Goto et al., though this correlation was not discussed in the journal article.

Table 5.15 – Permeability Amongst Products for Modified Cup Test Conditions at 25˚C with Maximum, Minimum, and Difference in Permeability.

Test No.	RH(%)		Permeability (ng/(msPa))												
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min	Diff.	Avg
.1	2-35%	18%/19%	55	52	**73**	45	*44*	57	63	63	73	73	44	29	58
.2	33-50%	42%	75	67	72	87	*67*	77	**90**	**90**	72	90	67	23	77
.3	54-77/78%	66%	69	65	71	81	*65*	75	85	**93**	72	93	65	29	75
.4	76-89%	82%	48	50	60	62	*46*	53	66	**80**	57	80	46	34	58

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

The average permeability versus average specimen relative humidity for dry cup and wet cup test conditions for all products at 25˚C are provided in Section 4.3.2.1 (Figure 4.22). The average permeability data for dry cup and wet cup test conditions for all products for a temperature of 25˚C are provided in Appendix F. Table 5.16 presents the average permeability for all products for each average specimen relative humidity for dry cup and wet cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, and as depicted in Figure 4.22, the variance in permeability amongst all products is generally consistent for both dry cup and wet cup test conditions. Correlation of the variance in permeability amongst specimens is simpler when the products are grouped by thickness (refer to Section 5.3.5.1).

The vapour permeability results obtained through testing for all products are similar to those obtained through previous research. Results of vapour permeability testing for dry cup and wet cup testing conditions (refer to 2.5.2 for testing condition details) conducted by Sonderegger et al. (Sonderegger & Niemz, 2012) indicated a similar trend of higher permeability for wet cup than for dry cup. The range of wet cup permeability and dry cup permeability for the results obtained by Sonderegger et al. was also large, likely as a result of the large range of densities tested for dry process WFIB (50-240 kg/m^3). The dry cup permeability range is less than that obtained in this research, which is surprising considering the larger density range of materials tested by Sonderegger et al.

Additionally, research conducted by Palumbo and al. (Palumbo et al., 2016) correlated lower density wood insulation materials (wood wool) with higher permeabilities for both wet cup and dry cup results, which is similar to the results obtained through this research. The dry cup and wet cup permeability results obtained by Palumbo et al. were lower than obtained in this research, though the wood fibre material tested by Palumbo et al. also had a higher density (212.2 kg/m3) than the materials from this research (95-191 kg/m^3).

Table 5.16 - Permeability Amongst Products for Dry Cup and Wet Cup Test Conditions at 25˚C.

Test No.	RH(%)		Permeability (ng/(msPa))												
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min	Diff.	Avg
.6	50.4-100%	75.2%	100	*89*	90	**116**	91	98	111	104	91	116	89	26	99
.7	2-50.3%	26.2%	45	*45*	64	52	50	65	71	**79**	62	79	45	35	59

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

5.3.4.1.1 Permeability Amongst Products with Thickness of 40mm

The average permeability versus average specimen relative humidity for modified cup, dry cup, and wet cup test conditions at 25˚C for products with thickness of 40mm are provided in Appendix F. Table 5.17 presents the average permeability for products with thickness of 40mm for each average specimen relative humidity for modified cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability amongst all products is smallest at the first relative humidity step and is generally consistent for all other relative humidity steps.

The largest difference in permeability amongst products is 20 ng/(msPa) at an average specimen relative humidity of approximately 42%. The smallest difference in permeability amongst products is 11 ng/(msPa) at an average specimen relative humidity of 18/19%. The lowest permeability is consistently associated with product 4.1. Product 4.1 is the highest density WFIB, and as discussed in Section 5.2.4 (Table 4.3) product 4.1 consistently obtains the highest volumetric moisture content of all WFIB products (excluding product 5.3). As discussed in Section 2.3.1.2, moisture transport mechanisms through the lumens and pores of wood, and the connectivity of lumens and pore spaces, contribute to the overall permeability of WFIB. Higher density WFIB comprises an overall lower volume of pore space, therefore limiting the transport of moisture through the WFIB. Additionally, a higher density of WFIB is associated with a greater number of wood cells providing surface diffusion through the wood cell structure. Furthermore, pore size, distribution, and connectivity may also limit transport of moisture. As discussed in Section 2.3.1.2.2, surface diffusion in the wood cell structure is a slower transport mechanism than vapour diffusion. The lower porosity of a higher density material may be associated with a lower pore surface area, therefore lower amount of surface diffusion along the pore surface. Moisture transport in pore spaces through vapour diffusion, surface diffusion, and capillary flow may be limited by the relatively lower pore space of the higher density WFIB. In contrast, for the average specimen relative humidity of 18/19% (step .1) product 3.1 has a permeability of 45 ng/(msPa) which is only 1 ng/(msPa) greater than product 4.1. Product 3.1 is the lowest density WFIB product and therefore comprises a higher volume of pore space, therefore potentially providing relatively more transport paths for moisture. The size, distribution, and connectivity of the pore spaces for product 3.1 may contribute to the relatively low permeability at lower average specimen relative humidity.

For the average specimen relative humidity of 18/19% (step .1), the highest permeability is associated with product 1.1. For all other relative humidity steps, the highest permeability is associated with product 3.1. The higher volume of pore space associated with product 3.1 likely allows for a greater amount of surface diffusion and capillary flow in the pores.

Table 5.17 - Permeability Amongst Products with Thickness of 40mm for Modified Cup Test Conditions at 25˚C

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	1.1	2.1	3.1	4.1	Max	Min	Diff.	Avg
.1	2-35%	18%/19%	**55**	52	45	*44*	55	44	11	49
.2	33-50%	42%	75	67	**87**	*67*	87	67	20	74
.3	54-77/78%	66%	69	65	**81**	*65*	81	65	17	70
.4	76-89%	82%	48	50	**62**	*46*	62	46	17	51

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

Table 8.18 presents the average permeability for products with thickness of 40mm for each average specimen relative humidity for dry cup and wet cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability is greater for wet cup than for dry cup. The permeability variation for wet cup test conditions is 26 ng/(msPa). The permeability variation for dry cup test conditions is 7 ng/(msPa). The lowest permeability is consistently associated with product 2.1, though the permeability of product 4.1 for wet cup conditions is only 2 ng/(msPa) greater. The highest permeability is consistently associated with product 3.1, similar to the results obtained for modified cup test conditions.

Table 5.18 - Permeability Amongst Products with Thickness of 40mm for Dry Cup and Wet Cup Test Conditions at 25˚C.

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	1.1	2.1	3.1	4.1	Max	Min	Diff.	Avg
.6	50.4-100%	75.2%	100	*89*	**116**	91	116	89	26	99
.7	2-50.3%	26.2%	45	*45*	**52**	50	52	45	7	48

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

5.3.4.1.2 Permeability Amongst Products with Thickness of 60mm

The average permeability versus average specimen relative humidity for modified cup, dry cup, and wet cup test conditions at 25˚C for products with thickness of 60mm are provided in Appendix F. Table 5.19 presents the average permeability for products with thickness of 60mm for each average specimen relative humidity for modified cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability is generally consistent for all relative humidity steps.

The largest variation in permeability amongst products is 19 ng/(msPa) at an average specimen relative humidity of approximately 42% (step .2). The smallest variation in permeability amongst products is 12 ng/(msPa) at an average specimen relative humidity of 82% (step .4). As previously discussed in Section 5.3.2.1, product 2.2 and 6.2 behave differently than all other products with regards to permeability variation with average specimen relative humidity. These differences are not discussed further. Excluding products 2.2 and 6.2, the lowest permeability is consistently associated with product 4.2 and the largest permeability is consistently associated wit product 5.2. Product 4.2 has a higher density than product 5.2, therefore correlation with a lower permeability is expected.

The permeability of 60mm specimens is generally greater than that of 40mm specimens for the same density for modified cup test conditions. This may be associated with the non-linear relative humidity gradient throughout the thickness of the material. Additionally, differing density distributions throughout the materials may impact the permeability , particularly density differences due to board pressing (refer to Section 2.2). WFIB may experience higher density wood fibres at the surfaces relative to the core of the specimen, similar to the OSB. For thinner specimens, the percentage of the material thickness impacted by board pressing may be greater than for thicker specimens. A greater percentage of higher density wood fibres due to board pressing may result in a lower permeability due to the decrease in porosity and pore paths at the surfaces. Additionally, differences in wood fibre orientation (vertical versus horizontal) due to differences in product thickness may also impact the vapour permeability. A greater proportion of vertical wood fibres may be associated with a higher permeability (refer to Section 2.3.1.2). Differences in quality of lumber by-products utilized in manufacturing amongst product differences may also be a factor effecting the permeability amongst product thicknesses.

Table 5.19 - Permeability Amongst Products with Thickness of 60mm for Modified Cup Test Conditions at 25˚C

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	2.2	4.2	5.2	6.2	Max	Min	Diff.	Avg
.1	2-35%	18%/19%	**73**	*57*	63	**73**	73	57	17	66
.2	33-50%	42%	*72*	77	**90**	*72*	90	72	19	78
.3	54-77/78%	66%	*71*	75	**85**	72	85	71	14	76
.4	76-89%	82%	60	*53*	**66**	57	66	53	12	59

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

Table 5.20 presents the average permeability for products with thickness of 60mm for each average specimen relative humidity for dry cup and wet cup test conditions at 25˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability is greater for wet cup than for dry cup. The permeability variation for wet cup test conditions is 21 ng/(msPa). The permeability variation for dry cup test conditions is 9 ng/(msPa). The lowest permeability is consistently associated with product 2.2 and 6.2, though recall the different hygrothermal behaviour for these products discussed above. Excluding product 2.2 and 6.2, the lowest permeability is consistently associated to product 4.2 and the highest permeability is consistently associated with product 5.2, which is similar to the results obtained for modified cup test conditions.

Similar to the modified cup test results, the permeability of 60mm specimens for wet cup and dry cup testing is generally greater than that of 40mm specimens for the same density. As discussed above, the greater permeability may be associated with a variety of material characteristics.

Table 5.20 - Permeability Amongst Products with Thickness of 60mm for Dry Cup and Wet Cup Test Conditions at 25˚C.

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	2.2	4.2	5.2	6.2	Max	Min	Diff.	Avg
.6	50.4-100%	75.2%	*90*	98	**111**	91	111	90	21	97
.7	2-50.3%	26.2%	64	65	**71**	*62*	71	62	9	65

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

5.3.4.2 Variation Amongst Products at 10˚C

The average permeability versus average specimen relative humidity for modified cup test conditions for all products at 10˚C are provided in Section 4.3.2.2 (Figure 4.25). The average permeability data for modified cup test conditions for all products for a temperature of 10˚C are provided in Appendix G. Table 5.21 presents the average permeability for all products for each average specimen relative humidity for modified cup test conditions at 10˚C. This table includes the maximum and minimum permeability and the difference at each test condition step. As presented, and as depicted in Figure

4.25, the variance in permeability amongst all products is generally consistent for all average specimen relative humidity conditions for modified cup test conditions, with the exception of product 5.3 at the average specimen relative humidity of 84% (step .4). Correlation of the variance in permeability amongst products is simpler when the products are grouped by thickness (refer to Section 5.3.5.2).

Table 5.21 – Permeability Amongst Products for Modified Cup Test Conditions at 10˚C with Maximum, Minimum, and Difference in Permeability.

Test No.	RH(%)		Permeability (ng/(msPa))											
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min	Diff.
.1	2-35/40%	19%/21%	63	68	83	83	73	86	**95**	93	81	95	63	32
.2	33-51/54%	42%/43%	59	63	69	73	62	75	79	**84**	65	84	59	26
.3	54-80/81%	69%	59	56	77	60	55	**92**	82	-	69	92	55	37
.4	76-91/92%	83%/84%	29	32	47	31	32	46	47	**98**	47	98	29	70

The average permeability versus average specimen relative humidity for dry cup and wet cup test conditions for all products at 10˚C are provided in Section 4.3.2.2 (Figure 4.26). The average permeability data for dry cup and wet cup test conditions for all products for a temperature of 10˚C are provided in Appendix G. Table 5.22 presents the average permeability for all products for each average specimen relative humidity for dry cup and wet cup test conditions at 10˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, and as depicted in Figure 4.26, the variance in permeability amongst all products is generally consistent for both dry cup and wet cup test conditions. Correlation of the variance in permeability amongst products is simpler when the products are grouped by thickness (refer to Section 5.3.5.2).

Table 5.22 - Permeability Amongst Products for Dry Cup and Wet Cup Test Conditions at 10˚C.

Test No.	RH(%)		Permeability (ng/(msPa))											
	Gradient	Avg.	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min	Diff.
.6	53-100%	76.5%	107	94	94	**134**	91	97	128	107	96	134	91	43
.7	2-54%	28%	70	64	77	76	67	80	**96**	71	75	96	64	31

5.3.4.2.1 Permeability Amongst Products with Thickness of 40mm

The average permeability versus average specimen relative humidity for modified cup, dry cup, and wet cup test conditions at 10˚C for products with thickness of 40mm are provided in Appendix G. Table 5.23 presents the average permeability for products with thickness of 40mm for each average specimen relative humidity for modified cup test conditions at 10˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability amongst all products is largest at the first relative humidity step. The variance in permeability amongst all products decreases with increasing average specimen relative humidity.

The largest variation in permeability amongst products is 20 ng/(msPa) at an average specimen relative humidity of approximately 19/21% (test step .1). The smallest variation in permeability amongst products is 4 ng/(msPa) at an average specimen relative humidity of 83/84% (test step .4). The permeabilities for all products are essentially equal at test step .4. The lowest permeability is generally associated with product 1.1, though for test steps .2, .3, and .4 the variation in permeability between products 1.1, 2.1, and 4.1 is relatively small. The highest permeability is consistently associated with product 3.1. Product 3.1 is the lowest density WFIB product and therefore comprises a higher volume of pore space, therefore potentially providing relatively more transport paths for moisture through the WFIB. At lower relative humidities at lower temperatures, relatively higher amounts of adsorption take place in comparison to higher temperatures (refer to Section 2.3.1.1.2). This is further discussed in Section 5.3.6. The surface diffusion for product 3.1 may be greater than for other products owing to the greater amount of pore space surface area on which surface diffusion takes place.

Table 5.23 - Permeability Amongst Products with Thickness of 40mm for Modified Cup Test Conditions at 10˚C

Test No.	RH(%)		*Permeability (ng/(msPa))*							
	Gradient	Avg.	*1.1*	*2.1*	*3.1*	*4.1*	*Max*	*Min*	*Diff.*	*Avg*
.1	2-35/40%	19%/21%	*63*	68	**83**	73	83	63	20	72
.2	33-51/54%	42%/43%	*59*	63	**73**	62	73	59	14	64
.3	54-80/81%	69%	59	56	**60**	*55*	60	55	5	57
.4	76-91/92%	83%/84%	*29*	**32**	31	32	32	29	4	31

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

Table 5.24 presents the average permeability for products with thickness of 40mm for each average specimen relative humidity for dry cup and wet cup test conditions at 10˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability is greater for wet cup than for dry cup. The permeability variation for wet cup test conditions is 43 ng/(msPa). The permeability variation for dry cup test conditions is 11 ng/(msPa). The lowest permeability is consistently associated with product 2.1 and 4.1. The highest permeability is consistently associated with product 3.1, similar to the results obtained for modified cup test conditions.

Table 5.24 - Permeability Amongst Products with Thickness of 40mm for Dry Cup and Wet Cup Test Conditions at 10˚C.

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	1.1	2.1	3.1	4.1	Max	Min	Diff.	Avg
.6	53-100%	76.5%	107	94	**134**	*91*	134	91	43	107
.7	2-54%	28%	70	*64*	**76**	67	76	64	11	69

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

5.3.4.2.2 Permeability Amongst Products with Thickness of 60mm

The average permeability versus average specimen relative humidity for modified cup, dry cup, and wet cup test conditions at 10˚C for products with thickness of 60mm are provided in Appendix G. Table 5.25 presents the average permeability for products with thickness of 60mm for each average specimen relative humidity for modified cup test conditions at 10˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the permeability of all products generally consistent for all relative humidity steps.

The largest variation in permeability amongst products is 23 ng/(msPa) at an average specimen relative humidity of approximately 69% (step .3). The smallest variation in permeability amongst products is 1 ng/(msPa) at an average specimen relative humidity of 83/84% (step .4). As previously discussed in Section 5.3.2.1, product 2.2 and 6.2 behave differently than all other products with regards to permeability variation with average specimen relative humidity. These differences are not discussed further. Excluding products 2.2 and 6.2, at test steps .1 and .2 the permeability of product 5.2 is consistently greater than product 4.2. Though at test step .3 the permeability of product 5.2 is less product 4.2. At test step .4 the permeability of product 5.2 and 4.2 are similar.

Product 4.2 has a higher density than product 5.2, therefore correlation with a lower permeability is expected. At test step .3, an increase in wood cell swelling may result in capillary flow in small pore spaces. Product 4.2 may comprise a greater number of smaller pore spaces, which would be expected for a higher density material. The decrease in permeability between step .3 and .4 may be associated with additional swelling of the wood cells resulting in obstruction of capillary paths and elimination of some capillary spaces entirely.

The permeability of 60mm specimens is generally greater than that of 40mm specimens for the same density for modified cup test conditions. As discussed in Section 5.3.4.1.2, the greater permeability may be associated with a variety of material characteristics.

Table 5.25 - Permeability Amongst Products with Thickness of 60mm for Modified Cup Test Conditions at 10˚C

Test No.	RH(%)		Permeability (ng/(msPa))							
	Gradient	Avg.	2.2	4.2	5.2	6.2	Max	Min	Diff.	Avg
.1	2-35/40%	19%/21%	83	86	95	81	95	81	15	86
.2	33-51/54%	42%/43%	69	75	79	65	79	65	14	72
.3	54-80/81%	69%	77	92	82	69	92	69	23	80
.4	76-91/92%	83%/84%	47	46	47	47	47	46	1	46

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

Table 5.26 presents the average permeability for products with thickness of 60mm for each average specimen relative humidity for dry cup and wet cup test conditions at 10˚C. This Table includes the maximum and minimum permeability and the difference at each test condition step. As presented, the variance in permeability is greater for wet cup than for dry cup. The permeability variation for wet cup test conditions is 33 ng/(msPa). The permeability variation for dry cup test conditions is 21 ng/(msPa).

The lowest permeability is consistently associated with product 2.2 and 6.2, though recall the different hygrothermal behaviour for these products discussed above. Excluding product 2.2 and 6.2, the lowest permeability is consistently associated to product 4.2 and the highest permeability is consistently associated with product 5.2, which is similar to the results obtained for modified cup test conditions, and dry cup and wet cup tests at 25˚C.

Similar to the modified cup test results, the permeability of 60mm specimens for wet cup and dry cup testing is generally greater than that of 40mm specimens for the same density. As discussed in Section 5.3.4.1.2, the greater permeability may be associated with a variety of material characteristics.

Table 5.26 - Permeability Amongst Products with Thickness of 60mm for Dry Cup and Wet Cup Test Conditions at 10˚C.

Test No.	*RH(%)*		*Permeability (ng/(msPa))*							
	Gradient	Avg.	2.2	4.2	5.2	6.2	Max	Min	Diff.	Avg
.6	53-100%	76.5%	*94*	97	**128**	96	128	94	33	104
.7	2-54%	28%	77	80	**96**	*75*	96	75	21	82

Italicized text indicates the minimum permeability for each test number.
Bold text indicates the maximum permeability for each test number.

5.3.5 Specimen Thickness Effect on Permeability

5.3.5.1 Specimen Thickness Effect at 25˚C

The permeability variation with average specimen relative humidity for product 2 (2.1, 40mm; 2.2, 60mm) at 25˚C are provided in Section 4.3.4.1 (Figure 4.29). The permeability variation with average specimen relative humidity for product 4 (4.1, 40mm; 4.2, 60mm) and product 5 (5.2, 60mm; 5.3, 80mm) for a temperature of 25˚C are provided in Appendix F. Table 5.27 presents the permeabilities for modified cup tests for products 2, products 4, and products 5, for each average specimen relative humidity at a temperature of 25˚C, along with the difference in permeability between product thicknesses at each test step.

As presented and as expected, the difference in permeability between product thicknesses is relatively small for product 2 and 4. For product 2, the permeability of product 2.2 (60mm) is consistently greater than product 2.1 (40mm) for all test steps. For product 2, the largest difference in permeability is 21 ng/(msPa) at test step .1. The smallest difference in permeability is 5 ng/(msPa) at test step .2 and .3. For product 4, the permeability of product 4.2 (60mm) is consistently greater than product 4.1 (40mm) for all test steps. For product 4, the largest difference in permeability is 13 ng/(msPa) at test step .1. The smallest difference in permeability is 8 ng/(msPa) at test .4. For product 2 and 4, the variance of permeability with product thickness for modified cup test conditions correlates with the thickness of the product, such that as the product thickness increases the permeability increases. It is worth noting that for product 2, the density of product 2.2 is greater than the density of product 2.1. For product 4, the density of product 4.1 is greater than the density of product 4.2. Based on the results from testing, the product thickness appears to influence the permeability of the material greater than the material density. The product thickness may influence the permeability as a result of the non-linear relative humidity profile experienced throughout the thickness of the material (refer to Section 3.3.2, Figure 3.1). Therefore, it is possible that a larger proportion of the thicker material is experiencing high relative humidities. Surface diffusion and capillary flow in the pore spaces is faster than vapour diffusion and occur at higher relative humidities. Additionally, permeability may be impacted due to material differences between different product thicknesses, such as density distribution and wood fibre orientation as discussed in Section 5.3.4.1.2.

For product 5, the permeability of product 5.2 and product 5.3 are similar for the average specimen relative humidities less than 42% (step .1 and .2). For average specimen relative humidities greater than 42% (step .3 and .4), the permeability of product 5.3 is greater than the permeability of product 5.2. It is difficult to determine the causation for the difference in permeability between product 5.2 and product 5.3. As discussed in Section 5.2, product 5.2 and 5.3 obtain different moisture contents and volumetric moisture contents, which may impact permeability. Additionally, product 5.2 and 5.3 may have differences in coating, impregnation, and thermal modification (refer to Section 5.2.7), which may also impact permeability. For product 5.3 for test steps .3 and .4, the higher moisture content and larger proportion of material experiencing high relative humidities may cause a greater amount of surface diffusion and capillary flow in the pore spaces resulting in higher permeabilities.

Table 5.27 – Permeability for Products in Various Thicknesses at 25˚C for Modified Cup Test Conditions with Difference between Same Product of Different Thickness.

Test No.	RH(%)		Permeability (ng/(msPa))								
	Gradient	Avg.	2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	2-35%	18%/19%	52	73	21	44	57	13	63	63	0
.2	33-50%	42%	67	72	5	67	77	10	90	90	0
.3	54-77/78%	66%	65	71	5	65	75	10	85	93	9
.4	76-89%	82%	50	60	10	46	53	8	66	80	14

Table 5.28 presents the permeabilities for dry cup and wet cup tests for products 2, products 4, and products 5, for each average specimen relative humidity at a temperature of 25˚C, along with the difference in permeability between product thicknesses at each test step.

As presented, the difference in permeability between product thicknesses is relatively small for product 2 and 4. For product 2, the permeability of product 2.2 is only 1 ng/(msPa) greater than product 2.1 for wet cup test conditions. For dry cup test conditions, the permeability of product 2.2 is 18 ng/(msPa) greater than product 2.1. For product 4, the permeability of product 4.2 is 7 ng/(msPa) greater than product 4.1 for wet cup test conditions. For dry cup test conditions, the permeability of product 4.2 is 15 ng/(msPa) greater than product 4.1.

For product 5, for wet cup test conditions the permeability of product 5.2 is greater than the permeability of product 5.3. This is surprising considering that for test steps .3 and .4 for modified cup test conditions the permeability of product 5.2 is less than the permeability of product 5.3. In contrast, for dry cup test conditions the permeability of product 5.3 is greater than the permeability of product 5.2. It is worth noting that the differences in permeability between product 5.2 and 5.3 at both wet cup and dry cup test conditions are relatively small and in the range of 6-8 ng/(msPa).

Table 5.28 – Permeability for Products in Various Thicknesses at 25˚C for all Dry Cup and Wet Cup Test Conditions with Difference between Same Product of Different Thickness.

Test No.	RH(%)		Permeability (ng/(msPa))								
	Gradient	Avg.	2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.6	50.4-100%	75.2%	89	90	1	91	98	7	111	104	6
.7	2-50.3%	26.2%	45	64	18	50	65	15	71	79	8

5.3.5.2 Specimen Thickness Effect at 10˚C

The permeability variation with average specimen relative humidity for product 2 (2.1, 40mm; 2.2, 60mm) at 10˚C are provided in Section 4.3.4.2 (Figure 4.31). The permeability variation with average specimen relative humidity for product 4 (4.1, 40mm; 4.2, 60mm) and product 5 (5.2, 60mm; 5.3, 80mm) for a temperature of 10˚C are provided in Appendix G. Table 5.29 presents the permeabilities for products 2, products 4, and products 5, for each average specimen relative humidity at a temperature of 10˚C, along with the difference in permeability between product thicknesses at each test step.

For product 2, the permeability of product 2.2 (60mm) is consistently greater than product 2.1 (40mm) for all test steps. For product 2, the largest difference in permeability is 21 ng/(msPa) at test step .3. The smallest difference in permeability is 6 ng/(msPa) at test step .2. For product 4, the permeability of product 4.2 (60mm) is consistently greater than product 4.1 (40mm) for all test steps. For product 4, the largest difference in permeability is 37 ng/(msPa) at test step .3. The smallest difference in permeability is 13 ng/(msPa) at test .1. For product 2 and 4, the 40mm thick products (2.1 and 4.1) and the 60mm thick products (2.2 and 4.2) exhibit similar behaviour. However, the 40mm thick products exhibit different behaviour than the 60mm products at the average specimen relative humidity of 69% (test step .3). At test step .3, the relative humidity gradient is 58-81%. For products 2.1 and 4.1, the decrease in permeability between test step .2 and .3 is less than the decrease in permeability between other test steps. For products 2.2 and 4.2, the permeability increases between test step .2 and .3, but the permeability decreases between all other test steps. The permeability at test step .3 for both 40mm and 60mm thick materials may be associated with an increase in surface diffusion and capillary flow. The expected moisture transport mechanisms at 10˚C are discussed in further detail in Section 5.3.6. For product 2 and 4, the variance in permeability with product thickness for modified cup test conditions correlates with the thickness of the product, similar to the results obtained for tests at 25˚C. Refer to Section 5.3.5.1 for additional details

For product 5, the permeability of product 5.2 behaves similar to products 2 and 4 as the calculated average specimen relative humidity increases. However, product 5.3 behaves differently such that the permeability at step .4 is greater than all other permeabilities. The permeability increase with average specimen relative humidity may be related to previously discussed different hygrothermal behaviours of product 5.3, such as the greater moisture content and volumetric moisture content at product 5.3 for all relative humidities at 10˚C.

Table 5.29 – Permeability for Products in Various Thicknesses at 10˚C for Modified Cup Test Conditions with Difference between Same Product of Different Thickness.

Test No.	RH(%)		Permeability (ng/(msPa))								
	Gradient	Avg.	2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	2-35/40%	19%/21%	68	83	15	73	86	13	95	93	3
.2	33-51/54%	42%/43%	63	69	6	62	75	14	79	84	5
.3	54-80/81%	69%	56	77	21	55	92	37	82	-	-
.4	76-91/92%	83%/84%	32	47	14	32	46	14	47	98	52

Table 5.30 presents the permeabilities for dry cup and wet cup tests for products 2, products 4, and products 5, for each average specimen relative humidity at a temperature of 10˚C, along with the difference in permeability between product thicknesses at each test step. As presented, the difference in permeability between product thicknesses is relatively small for product 2 and 4. For product 2, the permeability of product 2.2 and product 2.1 are the same for wet cup test conditions. For dry cup test conditions, the permeability of product 2.2 is 13 ng/(msPa) greater than product 2.1. For product 4, the permeability of product 4.2 is 6 ng/(msPa) greater than product 4.1 for wet cup test conditions. For dry cup test conditions, the permeability of product 4.2 is 13 ng/(msPa) greater than product 4.1.

For product 5, for wet cup test conditions the permeability of product 5.2 is 21 ng/(msPa) greater than the permeability of product 5.3. This is surprising considering that for test step .4 for modified cup test conditions the permeability of product 5.2 is less than the permeability of product 5.3. Similarly, for dry cup test conditions the permeability of product 5.2 is 25 ng/(msPa) greater than the permeability of product 5.3.

Table 5.30 – Permeability for Products in Various Thicknesses at 10˚C for all Dry Cup and Wet Cup Test Conditions with Difference between Same Product of Different Thickness.

Test No.	RH(%)		Permeability (ng/(msPa))								
	Gradient	Avg.	2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.6	53-100%	76.5%	94	94	0	91	97	6	128	107	21
.7	2-54%	28%	64	77	13	67	80	13	96	71	25

5.3.6 Temperature Effect on Permeability

The average permeability versus average specimen relative humidity for modified cup test conditions for product 1.1 at 10˚C and 25˚C are provided in Section 4.3.3 (Figure 4.27). The average permeability versus average specimen relative humidity for modified cup test conditions for all products at 10˚C and 25˚C are provided in Appendix H. Table 5.31 presents the difference in average permeability at 10˚C and 25˚C for all products for each average specimen relative humidity for modified cup test conditions. This

Table includes the maximum and minimum difference in permeability at each test step. As presented, the difference in permeability at 10˚C and 25˚C is generally largest at test steps .1 and .2 and lowest at test steps .2 and .3, except for product 1.1. Correlation of the variance in permeability amongst specimens is simpler when the products are grouped by thickness (refer to Section 5.3.5.1).

Table 5.31 –Difference in Permeability for all Products at 10˚C and 25˚C for Modified Cup Test Conditions with Maximum and Minimum Difference.

Test No.	Average RH(%)		Difference in Average Permeability at 10˚C and at 25˚C										
	10˚C	25˚C	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min
.1	19%/21%	18%/19%	*8*	*16*	*10*	*39*	*29*	*30*	*33*	*30*	*8*	39	8
.2	42%/43%	42%	16	4	*3*	14	6	1	11	4	7	16	1
.3	69%	66%	10	9	6	21	*10*	17	3	-	3	21	3
.4	83%/84%	82%	19	18	14	31	14	8	19	*19*	11	31	8

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

The average permeability versus average specimen relative humidity for dry cup and wet cup test conditions for product 1.1 at 10˚C and 25˚C are provided in Section 4.3.3 (Figure 4.28). The average permeability versus average specimen relative humidity for dry cup and wet cup test conditions for all products at 10˚C and 25˚C are provided in Appendix H. Table 5.32 presents the difference in average permeability at 10˚C and 25˚C for all products for each average specimen relative humidity for dry cup and wet cup test conditions. This table includes the maximum and minimum difference in permeability at each test step. As presented, the difference in permeability at 10˚C and 25˚C for wet cup and dry cup test conditions is greatest for product 3.1. For both wet cup and dry cup test conditions, the permeability at 10˚C is greater than the permeability at 25˚C. Correlation of the variance in permeability amongst specimens is simpler when the products are grouped by thickness (refer to Section 5.3.5.1).

Table 5.32 –Difference in Permeability for all Products at 10˚C and 25˚C for Dry Cup and Wet Cup Test Conditions with Maximum and Minimum Difference.

Test No.	Average RH(%)		Difference in Average Permeability at 10˚C and at 25˚C										
	10˚C	25˚C	1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min
.6	76.5%	75.2%	*6*	*4*	*4*	*19*	*0*	1	*17*	*2*	*5*	*19*	1
.7	28%	26.2%	*14*	*18*	*6*	*21*	*12*	*10*	*8*	*5*	*3*	*21*	*3*

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

5.3.6.1.1 Temperature Effect on Permeability for Products with Thickness of 40mm

Table 5.33 presents the difference in average permeability at 10˚C and 25˚C for products with thickness of 40mm for each average specimen relative humidity for modified cup test conditions. This table includes the maximum and minimum difference in permeability at each test step. At test step .1, the permeability at 10˚C is greater than the permeability at 25˚C. For test steps .2, .3, and .4, the permeability at 10˚C is less than the permeability at 25˚C.

At test step .1 the moisture transport mechanisms are primarily vapour diffusion with some surface diffusion in the pores. The rate of vapour diffusion increases with temperature therefore it is expected that the rate of vapour diffusion at 25˚C is greater than at 10˚C. At relative humidities less than 53%, the WFIB at 10˚C experiences a greater amount of adsorption than the WFIB at 25˚C, as discussed in Section 5.2.6. The higher permeability at 10˚C may be a result of a greater amount of surface diffusion as a result of the greater amount of adsorption.

At test step .2 the moisture transport mechanisms are primarily vapour diffusion and surface diffusion in the pores. Similar to step 1, WFIB at 10˚C experiences a greater amount of adsorption than the WFIB at 25˚C. However, as the adsorption increases the rate of surface diffusion increases, and the rate of surface diffusion increases with temperature. Even though there is less water adsorbed on the pore surfaced for WFIB at 25˚C than at 10˚C, the higher permeability associated with WFIB at 25˚C may be a result of the higher rate of surface diffusion associated with 25˚C. The decrease in permeability at 10˚C is somewhat surprising, as an increase in surface diffusion in the pore spaces is expected to result in an increase in permeability. It is not expected that pore space would be limited due to wood cell swelling as significant swelling is not expected at relative humidities less than 60%.

At test step .3 and .4, the moisture transport mechanisms are primarily capillary flow and surface diffusion, and vapour transport in large pores. At relative humidities greater than 77%, the WFIB at 25˚C experiences a greater amount of capillary condensation than the WFIB at 10˚C, as discussed in Section 5.2.6. The higher permeability at 25˚C may be a result of greater amounts of capillary flow as a result of the greater amount of capillary condensation. Additionally, rate of surface diffusion and capillary flow are greater at higher temperatures. As discussed previously, the decrease in permeability at test step .3 and .4 may be associated with swelling of the wood cells (refer to Section 5.3.2).

The largest difference in permeability between test temperatures is 39 ng/(msPa) at test step .1. The smallest difference in permeability between test temperatures is 4 ng/(msPa) at test step .2. The largest difference in permeability between test temperatures is generally associated with product 3.1. Product 3.1 is the lowest density material, and therefore has the largest porosity volume. The larger porosity volume may have a larger surface area for surface diffusion. Therefore, increases and decreases in the rate of surface diffusion would have a significant impact on the permeability of product 3.1.

Table 5.33 - Difference in Permeability for Products with Thickness of 40mm at 10˚C and 25˚C for Modified Cup Test Conditions.

Test No.	Average RH(%)		Difference in Average Permeability at 10˚C and at 25˚C					
	10˚C	25˚C	1.1	2.1	3.1	4.1	Max	Min
.1	19%/21%	18%/19%	*8*	*16*	*39*	*29*	*39*	*8*
.2	42%/43%	42%	16	4	14	6	16	4
.3	69%	66%	10	9	21	10	21	9
.4	83%/84%	82%	19	18	31	14	31	14

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

Table 5.34 presents the difference in average permeability at 10˚C and 25˚C for products with thickness of 40mm for dry cup and wet cup test conditions. This table includes the maximum and minimum permeability difference at each test condition step. As presented, the permeability at 10˚C is consistently greater than the permeability at 25˚C for both dry cup and wet cup test conditions. This is surprising, considering that the permeability at 10˚C is less than the permeability at 25˚C for steps .2, .3, and .4 for modified cup test conditions. The permeability for dry cup and wet cup testing may be higher for both 10˚C and 25˚C testing due to desorption as a result of testing sequencing (refer to Section 3.3.2). The smallest difference in permeability is consistently associated with product 4.1, which is the highest density product. The largest difference in permeability is consistently associated with product 3.1, which is the lowest density product. The product associated with the largest permeability difference for dry cup and wet cup testing is consistent with modified cup testing results.

Table 5.34 - Difference in Permeability for Products with Thickness of 40mm at 10˚C and 25˚C for Dry Cup and Wet Cup Test Conditions.

Test No.	Average RH(%)		Difference in Average Permeability at 10˚C and at 25˚C					
	10˚C	25˚C	1.1	2.1	3.1	4.1	Max	Min
.6	76.5%	75.2%	*6*	*4*	*19*	*0*	*19*	*0*
.7	28%	26.2%	*14*	*18*	*21*	*12*	*21*	*12*

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

5.3.6.1.2 Temperature Effect on Permeability for Products with Thickness of 60mm

Table 5.35 presents the difference in average permeability at 10˚C and 25˚C for products with thickness of 60mm for each average specimen relative humidity for modified cup test conditions. This table includes the maximum and minimum difference in permeability at each test step. At test step .1 and .3, the permeability at 10˚C is greater than the permeability at 25˚C. For test steps .2 and .4, the permeability at 10˚C is less than the permeability at 25˚C. At test step .1, .2, and .4, the difference in permeability at 10˚C and 25˚C for the 60mm products is similar to the 40mm thick products (refer to Section 5.3.6.1.1). At test step .3, the permeability at 10˚C increases relative to the permeability from the previous test step (step .2). The increase in permeability varies by product, with product 4.2 experiencing the largest increase from 75 ng/(msPa) to 92 ng/(msPa). The increase in permeability at 10˚C is somewhat surprising. It is not expected that surface diffusion would increase within these relative humidity range, and capillary condensation within this range is expected to be limited. It is possible that capillary flow through very small pore spaces could occur at 10˚C in pore spaces that would be obstructed due to swelling of the wood cells at 25˚C.

Table 5.35 - Difference in Permeability for Products with Thickness of 60mm at 10˚C and 25˚C for Modified Cup Test Conditions.

Test No.	Average RH(%)		*Difference in Average Permeability at 10˚C and at 25˚C*					
	10˚C	25˚C	2.2	4.2	5.2	6.2	Max	Min
.1	19%/21%	18%/19%	*10*	*30*	*33*	*8*	*33*	*8*
.2	42%/43%	42%	3	1	11	7	11	1
.3	69%	66%	*6*	*17*	3	3	*17*	3
.4	83%/84%	82%	14	8	19	11	8	19

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

Table 5.36 presents the difference in average permeability at 10˚C and 25˚C for products with thickness of 60mm for dry cup and wet cup test conditions. This table includes the maximum and minimum permeability difference at each test condition step. As presented, the permeability at 10˚C is consistently greater than the permeability at 25˚C for both dry cup and wet cup test conditions, which is similar to the 40mm thick specimens. This is surprising, considering that the permeability at 10˚C is less than the permeability at 25˚C for steps .2 and .4 for modified cup test conditions. The permeability for dry cup and wet cup testing may be higher for both 10˚C and 25˚C testing due to desorption as a result of testing sequencing (refer to 6.3.2). For wet cup testing, the small difference in permeability is associated with product 4.2, and the largest difference in permeability is associated with product 5.2. For dry cup testing, the smallest difference in permeability is associated with product 2.2 and the largest difference in permeability is associated product 4.2

Table 5.36 - Difference in Permeability for Products with Thickness of 60mm at 10˚C and 25˚C for Dry Cup and Wet Cup Test Conditions.

Test No.	*Average RH(%)*		*Difference in Average Permeability at 10˚C and at 25˚C*					
	10˚C	25˚C	2.2	4.2	5.2	6.2	*Max*	*Min*
.6	76.5%	75.2%	*4*	1	*17*	*5*	*17*	1
.7	28%	26.2%	*6*	*10*	*8*	*3*	*10*	*3*

Italicized text indicates where the permeability at 10˚C was greater than the permeability at 25˚C.

5.4 Temperature and Moisture Dependent Thermal Conductivity Testing Analysis and Discussion

The temperature and moisture dependent thermal conductivity testing was conducted in accordance to ASTM C518-17 over the period of approximately 5 months. Pre-conditioning of the thermal conductivity specimens was conducted at a temperature of 25˚C and relative humidities of approximately 30%, 60%, 80%, and 95%. Subsequent thermal conductivity testing was conducted using a HFMA at average specimen temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C, consecutively, with a 10˚C temperature gradient between plates. Additionally, the specimens 01 of all materials were tested at the 95% relative humidity condition at the same average specimen temperatures though in reversed order (30˚C, 20˚C, 10˚C, 0˚C, -10˚C).

5.4.1 Temperature Dependent Thermal Conductivity at 30% Relative Humidity

5.4.1.1 Interpretation of Temperature Dependent Thermal Conductivity Results

The thermal conductivity versus temperature for all WFIB products preconditioned at 30% relative humidity are provided in Section 4.4.1,Figure 4.34. As depicted, the thermal conductivity for WFIB pre-conditioned at 30% relative humidity consistently increases with increasing temperature. As discussed in Section 2.4.1, lower temperature materials have less energy and therefore the molecules are moving slower, resulting in a lower overall thermal conductivity. Higher temperature materials have more energy therefore the molecules are vibrating faster, increasing the rate of heat transfer through conduction. Therefore, the experimental results for thermal conductivity variation with temperature are expected.

For products 1.1, 2.1, 3.1, and 4.1, thermal conductivity increases linearly with increasing temperature. For products 2.2, 4.2, 5.2, 5.3, and 6.2, the thermal conductivity increases polynomially with increasing temperature, such that increases in thermal conductivity at higher temperature are greater than at lower temperatures. These characteristics are further discussed in Section 5.4.1.3.

5.4.1.2 Variation within Products

The thermal conductivities obtained for product 1.1 specimens preconditioned at 30% relative humidity and then tested at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Section 4.4.1 (Figure 4.33, Table 4.10). The average thermal conductivity is also provided. The thermal conductivity data and curves for all other specimens and product averages for all other products are provided in Appendix I.

A summary of the coefficient of variations for products pre-conditioned at 30% relative humidity and then tested at of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C is provided in Table 5.37. The average coefficient of variation of the thermal conductivity for all products pre-conditioned at 30% relative humidity at all temperature test steps was 2.6%.

The largest coefficient of variation of 9.4% for thermal conductivity was for product 6.2 at a test temperature of 30˚C. The higher coefficient of variation at a test temperature of 30˚C may be associated with the redistribution of moisture throughout the material. Since test specimens were tested in the order of -10˚C through 30˚C, the test specimens experienced condensing of moisture throughout the material, with a greater proportion of condensation taking place on the colder surface of the material. For each subsequent test step, the average specimen temperature increased and the moisture throughout the material redistributed with some vapourization of the liquid pore water. Additionally, equilibrium parameters were set to ensure that the final 10 thermal conductivity measurements collected each minute were within 0.8-1% of the mean value of the 10 readings (refer to Section 3.4.2). A lower variation in thermal conductivity results may have been obtained with an increase in the number of measurements within the mean value, and a decrease in the percent variance from the mean value.

The largest coefficient of variation for thermal conductivity for each temperature test step is associated with products 4.1, 4.2, and 6.2, and thus does not correlate with a specific product. Additionally, the largest coefficient of variation for thermal conductivity does not correlate with the products with the largest coefficient of variation for the temperature and relative humidity for 72 hours prior to testing. The largest coefficient of variation for thermal conductivity does consistently associate with the products with the highest density (refer to Section 4.1). The largest coefficient of variation may be associated with the redistribution of moisture throughout denser materials.

The lowest coefficient of variation for each temperature test step is associated with product 2.1 and 3.1, which are products with relatively lower densities and of 40mm thickness. Therefore, the lower coefficient of variation may be a result of the ease of moisture redistribution through less dense products of less thickness.

Based on the lack of correlation of the coefficient of variation to specific product, density, or product thickness, the variation for each test condition may be influenced by testing procedures. Testing procedures that may influence the coefficient of variation include the testing order resulting in moisture redistribution throughout the material, loss of moisture throughout the thermal conductivity testing, and HFMA equilibrium test settings.

Table 5.37 – Thermal Conductivity Coefficient of Variation within Products Pre-Conditioned at 30% Relative Humidity.

Test No.	Test Temp (˚C)	Thermal Conductivity CV (%) at Relative Humidity 30%									
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	-10	4.0%	3.2%	5.2%	0.7%	2.0%	**8.1%**	2.9%	0.8%	2.7%	3.3%
.2	0	0.8%	0.5%	0.9%	0.8%	**6.8%**	1.1%	1.9%	1.1%	1.1%	1.7%
.3	10	0.7%	1.9%	2.0%	0.7%	**3.5%**	1.0%	2.5%	1.8%	1.4%	1.7%
.4	20	2.2%	2.2%	2.0%	1.0%	3.8%	5.3%	2.5%	1.6%	**7.1%**	3.1%
.5	30	2.6%	0.6%	2.6%	2.0%	1.4%	3.6%	4.3%	2.8%	**9.4%**	3.2%
										Average	2.6%

Bold text indicates the maximum thermal conductivity CV (%) for each test step.

5.4.1.3 Variation Amongst Products

The average thermal conductivities obtained for all products preconditioned at 30% relative humidity and then tested at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Section 4.4.1 (Figure 4.34). The thermal conductivity data for all products for these test conditions are provided in Appendix I. Table 5.44 presents the thermal conductivity for all test temperatures for all products pre-conditioned to 30% relative humidity, along with the maximum and minimum thermal conductivity and the difference at each temperature test step. As presented, and as depicted in Figure 4.34, the variance in thermal conductivity is generally consistent for each test temperature, with a slight increase at 30˚C. The largest variation in thermal conductivity amongst the products is 0.012 W/mK at a test temperature of 30˚C.

Table 5.38 – Thermal Conductivity for all Products Pre-Conditioned at 30% Relative Humidity with Maximum, Minimum, and Difference in Thermal Conductivity.

Test No.	Test Temp (˚C)	Thermal Conductivity (W/mK)											
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max	Min	Diff.
.1	-10	0.039	0.039	0.043	0.035	0.041	**0.044**	0.041	0.043	0.042	0.044	0.035	0.009
.2	0	0.039	0.041	0.043	0.037	**0.043**	0.043	0.042	0.043	0.043	0.043	0.037	0.006
.3	10	0.042	0.044	0.045	0.038	**0.047**	0.045	0.044	0.045	0.045	0.047	0.038	0.008
.4	20	0.044	0.046	0.048	0.040	0.049	0.047	0.047	0.049	**0.049**	0.049	0.040	0.009
.5	30	0.044	0.048	0.051	0.041	0.052	0.052	0.050	0.053	**0.053**	0.053	0.041	0.012

Bold text indicates the maximum thermal conductivity for each test step.

Higher thermal conductivities are generally associated with the products with the highest densities. Lower thermal conductivities are associated with the product 3.1, which is the lowest density product. A graphical representation of this relationship for all products pre-conditioned to 30% relative humidity for all test temperatures is depicted in Figure 5.2. Graphical representation of the thermal conductivity versus density for all products pre-conditioned at 30% relative humidity for each individual temperature test step are provided in Appendix I. Note that the trendline for each test temperature excludes product 5.3 due to the generally large thermal conductivity associated with product 5.3, and the greater thickness associated with product 5.3. This will be discussed further below.

As per Figure 5.2, thermal conductivity increases with increasing density. The trendline for the thermal conductivity versus density is second order polynomial, such that the increase in thermal conductivity lessens with increasing density. Table 5.39 presents the equation of the trendline and the coefficient of determination for each temperature test step trendline.

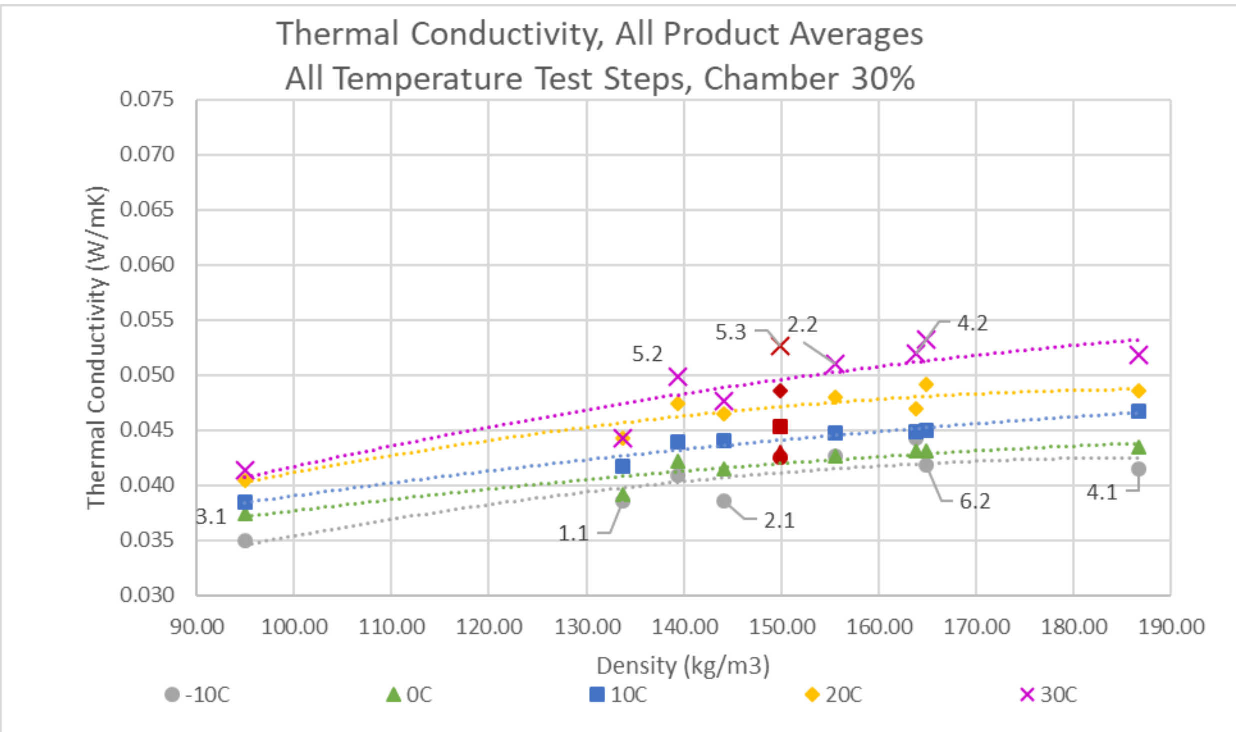


Figure 5.2 - Thermal conductivity vs Density for All Products Pre-Conditioned at 30% Relative Humidity, All Temperature Test Steps.

Table 5.39 – Equation and Coefficient of Determination for Polynomial Trend Lines for Figure 5.2.

Test No.	Test Temp (˚C	Equation	R^2
.1	-10˚C	$y = -9x10^{-7}x^2+0.0003x+0.0108$	0.7593
.2	0˚C	$y = -4x10^{-7}x^2+0.0002x+0.023$	0.8739
.3	10˚C	$y = -4x10^{-7}x^2+0.0002x+0.0231$	0.9563
.4	20˚C	$y = -9x10^{-7}x^2+0.0003x+0.0159$	0.8952
.5	30˚C	$y = -7x10^{-7}x^2+0.0003x+0.0155$	0.8662

The 40mm thick products are generally associated with lower thermal conductivities than the 60mm and 80mm thick products. As depicted in Figure 5.2 the data points for 40mm products are generally below the trendline, whereas the data points for the 60mm and 80mm products are generally above the trendline. Excluding product 5.3 from the trendline analysis allowed for correlation of 40mm products below the trendline and 60mm products above the trendline.

Appendix I includes a graphical representation of thermal conductivity versus density for both 40mm and 60mm products pre-conditioned to 30% relative humidity for all test temperature. The thermal conductivity for 60mm is generally greater than the thermal conductivity for 40mm products. The different behaviour of thermal conductivity may be a result of a number of material characteristics such as the density distribution throughout the thickness of the material, number of interconnected pore spaces, orientation of the wood fibres (vertical versus horizontal), and quantity of water adsorbed within the wood cell rather than within the pore spaces as a result of differences in the quantity of additives and the distribution of additives. Research regarding the microscopic material characteristics is required.

Discussion for correlating the variance of temperature dependent thermal conductivity amongst products is grouped by product thickness.

5.4.1.3.1 Thermal Conductivity Amongst Products with Thickness of 40mm

Table 5.40 presents the thermal conductivity for all test temperatures for all 40mm products pre-conditioned to 30% relative humidity, along with the maximum and minimum thermal conductivity and the difference at each temperature test step. As presented, and as depicted in Figure 5.3, the variance in thermal conductivity increases slightly with increasing temperature. The largest variation in thermal conductivity amongst the products is 0.010 W/mK at a test temperature of 30˚C.

The largest thermal conductivity amongst all products for each temperature test step is consistently associated with product 4.1. The highest thermal conductivity consistently associates with the product with the highest density (refer to Section 4.1). Dense materials comprise less air spaces and therefore a greater amount of continuous wood fibre contact. The greater connectivity of the wood fibres allows for greater amounts of heat transfer within the material. As discussed in Section 4.2, higher volumetric moisture contents are associated with higher density materials. The greater volume of water adsorbed by the denser WFIB materials contributes to the relatively greater thermal conductivity. Sorbed water molecules are in closer contact than water vapour and other air molecules, therefore increasing the rate at which heat transfers through the material. The higher thermal conductivity for product 4.1 may be a result of the higher density and the highest volumetric moisture content associated with product 4.1.

The lowest thermal conductivity for each temperature test step is associated with product 3.1, which is the lowest density product. Lower density materials comprise greater amounts of air spaces and therefore a lesser amount of continuous wood fibre contact. The lesser connectivity of the wood fibres results in a lesser amount of heat transfer within the material. As discussed in Section 4.2, lower volumetric moisture contents are associated with lower density materials. As discussed above, an increase in adsorbed water molecules contributes to an increase in thermal conductivity. The lower thermal conductivity for product 3.1 may be a result of the lower density and the lower volumetric moisture content associated with product 3.1.

Table 5.40 – Thermal Conductivity for all 40mm Products Pre-Conditioned at 30% Relative Humidity with Maximum, Minimum, and Difference in Thermal Conductivity.

Test No.	Test Temp (˚C)	Thermal Conductivity (W/mK)						
		1.1	2.1	3.1	4.1	Max	Min	Diff
.1	-10	0.039	0.039	*0.035*	**0.041**	0.041	0.035	0.006
.2	0	0.039	0.041	*0.037*	**0.043**	0.043	0.037	0.006
.3	10	0.042	0.044	*0.038*	**0.047**	0.047	0.038	0.008
.4	20	0.044	0.046	*0.040*	**0.049**	0.049	0.040	0.008
.5	30	0.044	0.048	*0.041*	**0.052**	0.052	0.041	0.010

Bold text indicates the maximum thermal conductivity for each test step.
Italicized text indicates the minimum thermal conductivity for each test step.

Figure 5.3 depicts the thermal conductivity versus density for all 40mm products pre-conditioned to 30% relative humidity for all test temperatures. As presented, the thermal conductivity increases linearly with increasing density. Additionally, the thermal conductivity increases with increasing temperatures, as shown by the increase in thermal conductivity for each temperature test step.

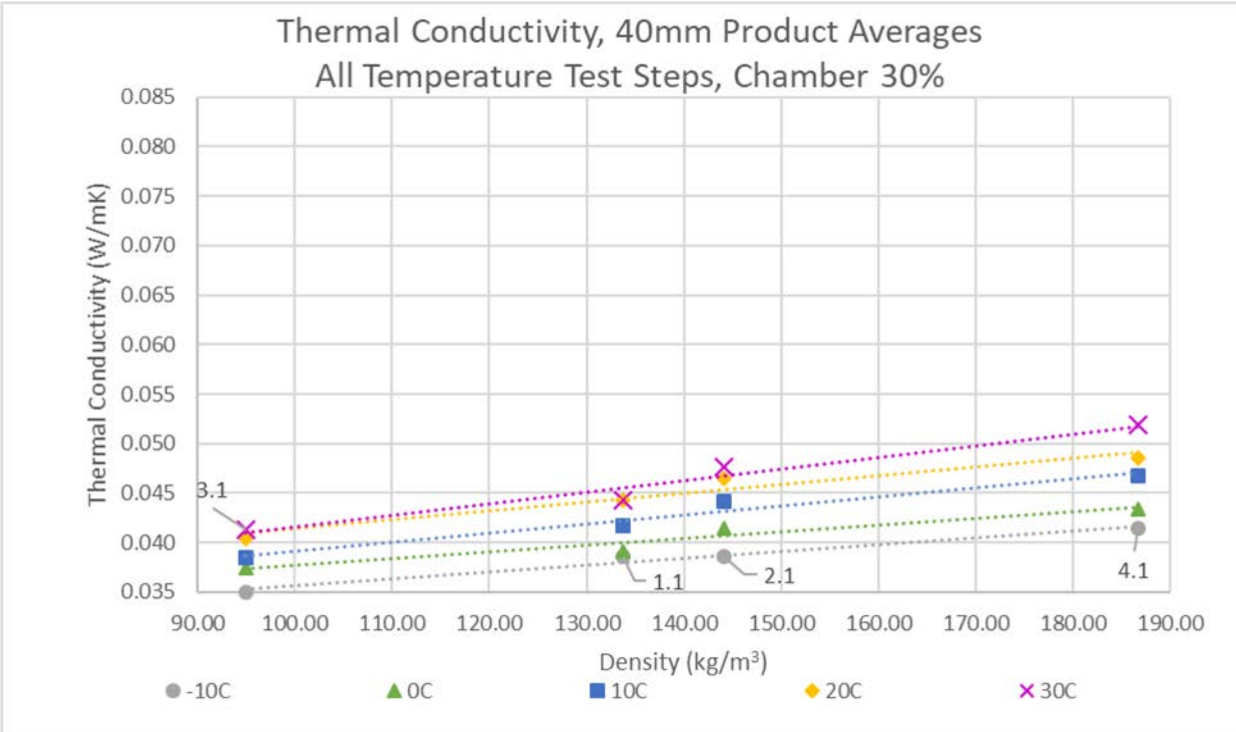


Figure 5.3 - Thermal conductivity vs Density for 40mm Products Pre-Conditioned at 30% Relative Humidity, All Temperature Test Steps.

Table 5.41 presents the linear equation and coefficient of determination for thermal conductivity versus density for each temperature test step trendline at 30% relative humidity for 40mm products. The slope of the linear relationship increases as the temperature increases, indicating that at each temperature test step the thermal conductivity increases are relatively greater with increasing density.

Table 5.41 – Equation and Coefficient of Determination for Linear Trend Lines for Figure 5.3.

Test No.	Test Temp (˚C)	Linear Trendline	
		Equation	R^2
.1	-10˚C	$y = 7x10^{-5}x+0.0287$	0.9792
.2	0˚C	$y = 7x10^{-5}x+0.0309$	0.9375
.3	10˚C	$y = 9x10^{-5}x+0.0300$	0.9651
.4	20˚C	$y = 9x10^{-5}x+0.0324$	0.9480
.5	30˚C	$y = 1x10^{-4}x+0.0299$	0.9581

5.4.1.3.2 Thermal Conductivity Amongst Products with Thickness of 60mm

Table 5.42 presents the thermal conductivity for all test temperatures for all 60mm products pre-conditioned to 30% relative humidity, along with the maximum and minimum thermal conductivity and the difference at each temperature test step. As presented, and as depicted in Figure 5.4, the variance in thermal conductivity does not appear to correlate with temperature. The largest variation in thermal conductivity amongst the products is 0.003357 W/mK at a test temperature of 30˚C, though the thermal conductivity variation at 10˚C is only slightly less at 0.003315 W/mK.

The largest thermal conductivity amongst all 60mm products for -10˚C and 0˚C is associated with product 4.2, which is the highest density product. The highest thermal conductivity for 10˚C, 20˚C, and 30˚C is associated with product 6.2, which is a high-density product that is marginally less dense than product 4.2. As discussed above, dense materials allow for greater amounts of heat transfer within the material. As discussed in Section 4.2, higher volumetric moisture contents are generally associated with higher densities. However, product 6.2 has a lower density than product 4.2, though product 6.2 obtains higher volumetric moisture contents than product 4.2 at all relative humidity testing conditions. As discussed previously, the greater volume of water adsorbed by the WFIB materials contributes to the relatively greater thermal conductivity. Therefore, the higher thermal conductivities for product 6.2 at higher temperature may be associated with the greater volume of adsorbed water by product 6.2 in comparison to product 4.2. Furthermore, the higher amount of volumetric moisture content associated with product 6.2 may be associated with higher wood fibre swelling, further contributing to an increase in thermal conductivity.

The lowest thermal conductivity for each temperature test step is associated with product 5.2, which is the lowest density product. As previously discussed, lower density materials allow for a lesser amount of heat transfer within the material. Additionally, as discussed in Section 4.2, lower volumetric moisture contents are associated with lower density materials. As discussed previously, a lesser amount of adsorbed water molecules is associated with a lesser thermal conductivity. The lower thermal conductivity for product 5.2 may be a result of the lower density and the lower volumetric moisture content associated with product 5.2.

Table 5.42 – Thermal Conductivity for all 60mm Products Pre-Conditioned at 30% Relative Humidity with Maximum, Minimum, and Difference in Thermal Conductivity.

Test No.	Test Temp (˚C)	Thermal Conductivity (W/mK)						
		2.2	4.2	5.2	6.2	Max	Min	Diff
.1	-10	0.043	**0.044**	*0.041*	0.042	0.044	0.041	0.003
.2	0	0.043	**0.043**	*0.042*	0.043	0.043	0.042	0.001
.3	10	0.045	0.045	*0.044*	**0.045**	0.045	0.044	0.001
.4	20	0.048	*0.047*	0.047	**0.049**	0.049	0.047	0.002
.5	30	0.051	0.052	*0.050*	**0.053**	0.053	0.050	0.003

Bold text indicates the maximum thermal conductivity for each test step.
Italicized text indicates the minimum thermal conductivity for each test step.

Figure 5.4 depicts the thermal conductivity versus density for all 60mm products pre-conditioned to 30% relative humidity for all test temperatures. As presented, the thermal conductivity increases linearly with increasing density. Additionally, the thermal conductivity increases with increasing temperatures, as shown by the increase in thermal conductivity for each temperature test step. The density range of the 60mm products is smaller than for the 40mm products. Greater accuracy in correlating thermal conductivity and density for 60mm products could be obtained through testing of additional lower and higher density products.

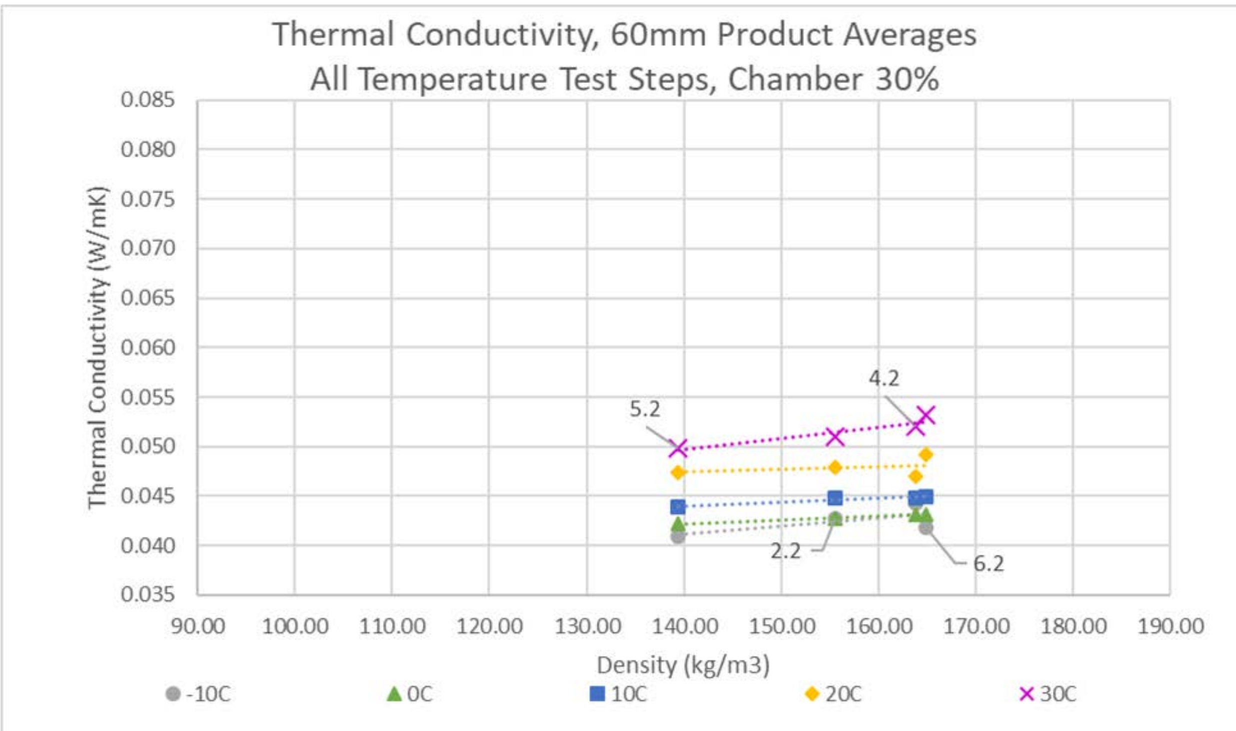


Figure 5.4 - Thermal conductivity vs Density for 60mm Products Pre-Conditioned at 30% Relative Humidity, All Temperature Test Steps.

Table 5.43 presents the linear equation and coefficient of determination for thermal conductivity versus density for each temperature test step trendline at 30% relative humidity for 60mm products. A correlation cannot be made for the change in slope of the linear relationship between each temperature test step.

Table 5.43 – Equation and Coefficient of Determination for Linear Trend Lines for Figure 5.4.

Test No.	Test Temp (˚C)	Linear Trendline	
		Equation	R^2
.1	-10˚C	$y = 8x10^{-5}x+0.0298$	0.4512
.2	0˚C	$y = 4x10^{-5}x+0.0370$	0.9694
.3	10˚C	$y = 4x10^{-5}x+0.0384$	0.9354

.4	20˚C	y = $3x10^{-5}x+0.0434$	0.1182
.5	30˚C	*y = $1x10^{-4}x+0.0341$*	*0.8431*

5.4.1.4 Temperature Dependent Thermal Conductivity Variation with Material Thickness

The average thermal conductivities obtained for product 2 (2.1, 40mm; 2.2, 60mm) preconditioned at 30% relative humidity and then tested at temperatures of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Section 4.4.2 (Figure 4.35). The average thermal conductivities obtained for product 4 (4.1, 40mm; 4.2, 60mm) and product 5 (5.2, 60mm; 5.3, 80mm) preconditioned at 30% relative humidity and then tested at temperatures of 10˚C, 0˚C, 10˚C, 20˚C, and 30˚C are provided in Appendix I. Table 5.44 presents the thermal conductivity for products 2, products 4, and products 5, for each temperature test step for materials pre-conditioned at 30% relative humidity, along with the difference in thermal conductivity between product thicknesses at each temperature test step.

As discussed in Section 5.4.1.3, 40mm products generally have a lower thermal conductivity than 60mm products. This may be due to density distribution differences between products of differing thicknesses, and/or moisture redistribution through thicker specimens. Additionally, 40mm and 60mm products exhibit a linear trend of increasing thermal conductivity with increasing density. If products of different thicknesses comprised the same densities, comparing the same product between 40mm and 60mm thickness should reveal similar results. However, the WFIB products tested have differing densities for differing thickness of the same product, as discussed in Section 5.1. Therefore, comparing a product of differing thicknesses is somewhat misleading.

For product 2, product 2.1 (40mm) has a lower density than product 2.2 (60mm). Similarly, for product 5, product 5.2 (60mm) has a lower density than product 5.3 (80mm). As discussed in Section 5.4.1.3, thermal conductivity increases with increasing density. Additionally, thermal conductivity is greater for products of greater thickness. Therefore, the difference in thermal conductivity due to product thickness for product 2 and 5 is exaggerated due to the higher densities associated with product 2.2 and 5.3, respectively. For product 4, product 4.2 (60mm) has a lower density than product 4.1 (60mm). The difference in thermal conductivity due to product thickness for product 4 is understated due to the lower density associated with product 4.2. As a result, it is best to analyze the WFIB products grouped by product thickness.

Table 5.44 –Thermal Conductivity for Products in various Thicknesses Pre-Conditioned at 30% Relative Humidity with Difference between same product of Different Thicknesses.

Test No.	Test Temp (˚C)	Thermal Conductivity (W/mK)								
		2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	-10	0.039	0.043	0.004	0.041	0.044	-0.003	0.041	0.043	0.002
.2	0	0.041	0.043	0.001	0.043	0.043	0.000	0.042	0.043	0.001
.3	10	0.044	0.045	0.001	0.047	0.045	0.002	0.044	0.045	0.001
.4	20	0.046	0.048	0.001	0.049	0.047	0.002	0.047	0.049	0.001
.5	30	0.048	0.051	0.003	0.052	0.052	0.000	0.050	0.053	0.003

5.4.2 Temperature and Moisture Dependent Thermal Conductivity

5.4.2.1 Interpretation of Temperature and Moisture Dependent Thermal Conductivity

The average thermal conductivity versus test temperature results for all relative humidity conditions (30%, 60%, 80%, 95%) for product 1.1 are provided in Section 4.4.3, Figure 4.36. The average moisture content attained for each precondition relative humidity is included. The average thermal conductivity versus test temperature results for all relative humidity conditions for all other products are provided in Appendix I.

Product 4, 5, and 6 experienced visible mould throughout testing at chamber conditions of 95% relative humidity. The mould was brushed off with each weighing and prior to testing. The mould appeared to only be on the surface of the WFIB specimens.

As previously discussed in Section 5.4.1, the thermal conductivity increases with temperature for all WFIB products. As presented in Section 4.4.3, Figure 4.36, for product 1.1 the thermal conductivity increases with increasing moisture content. As previously discussed in Section 2.4.2, the storage of water vapour, adsorbed water, and liquid water in a material contributes to increased thermal conductivity.

For products 1.1, 2.1, 3.1, and 4.1, thermal conductivity increases linearly with increasing temperature for products pre-conditioned at 30% and 60% relative humidity. However, thermal conductivity increases polynomially with increasing temperature for products preconditioned at 80% and 95% relative humidity. The polynomial increase is such that greater increases in thermal conductivity are obtained at higher temperatures for materials with increasing moisture contents. For products 2.2, 4.2, 5.2, 5.3, and 6.2, thermal conductivity increases polynomially with increasing temperature for all preconditioned relative humidities (30%, 60%, 80%, and 95%). The polynomial increase is such that greater increases in thermal conductivity are obtained at higher temperatures for materials with increasing moisture contents

5.4.2.2 Variation within Products

The average thermal conductivity versus test temperature results for all relative humidity conditions (30%, 60%, 80%, 95%) for product 1.1 are provided in Section 4.4.3, Figure 4.36. The average moisture content attained for each precondition relative humidity is included. The average thermal conductivity versus test temperature results for all relative humidity conditions for all other products are provided in Appendix I. A summary of the coefficient of variations for products pre-conditioned at all relative humidities and then tested at of -10˚C, 0˚C, 10˚C, 20˚C, and 30˚C is provided in Table 5.45.

As discussed in Section 5.4.1.2, the coefficient of variation for specimens preconditioned at 30% relative humidity lacks correlation to properties such as product, density, and product thickness. Similarly, the coefficient of variation for specimens preconditioned to all other relative humidities lacks correlation to properties such as product, density, and product thickness. As discussed in Section 5.4.1.2, the variation for each test condition may be influenced by testing procedures. Testing procedures that may influence the coefficient of variation include the testing order resulting in moisture redistribution throughout the material, loss of moisture throughout the thermal conductivity testing, and HFMA equilibrium test settings.

Table 5.45 – Thermal Conductivity Coefficient of Variation within Products Pre-Conditioned at all Relative Humidities.

RH (%)	Test No.	Test Temp (˚C)	Thermal Conductivity CV (%)										
			1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg	
~30%	.1	-10	4.0%	3.2%	5.2%	*0.7%*	2.0%	**8.1%**	2.9%	0.8%	2.7%	3.3%	2.6%
	.2	0	0.8%	*0.5%*	0.9%	0.8%	**6.8%**	1.1%	1.9%	1.1%	1.1%	1.7%	
	.3	10	*0.7%*	1.9%	2.0%	0.7%	**3.5%**	1.0%	2.5%	1.8%	1.4%	1.7%	
	.4	20	2.2%	2.2%	2.0%	*1.0%*	3.8%	5.3%	2.5%	1.6%	**7.1%**	3.1%	
	.5	30	2.6%	*0.6%*	2.6%	2.0%	1.4%	3.6%	4.3%	2.8%	**9.4%**	3.2%	
~60%	.1	-10	3.2%	2.2%	**8.6%**	4.2%	2.0%	3.3%	*1.0%*	2.1%	3.9%	3.4%	3.8%
	.2	0	*0.3%*	1.9%	6.1%	1.6%	2.7%	3.4%	**7.1%**	5.0%	6.5%	3.8%	
	.3	10	1.3%	1.6%	4.4%	*0.9%*	3.4%	2.9%	2.2%	5.2%	**8.6%**	3.4%	
	.4	20	1.5%	*1.0%*	7.4%	1.5%	3.6%	3.5%	1.2%	2.8%	**8.3%**	3.4%	
	.5	30	3.1%	1.7%	8.3%	1.2%	*0.7%*	3.2%	6.0%	5.0%	**13.6%**	4.7%	
~80%	.1	-10	3.4%	5.3%	6.2%	2.9%	1.7%	4.3%	3.0%	*0.9%*	**10.7%**	4.3%	3.7%
	.2	0	1.9%	2.1%	**5.4%**	3.9%	*0.3%*	2.7%	1.9%	0.7%	3.4%	2.5%	
	.3	10	1.6%	1.0%	5.0%	4.0%	*0.5%*	2.8%	1.7%	**5.4%**	3.2%	2.8%	
	.4	20	4.3%	1.3%	**8.3%**	2.3%	*1.0%*	6.0%	1.5%	2.8%	7.4%	3.9%	
	.5	30	6.5%	1.9%	9.3%	2.3%	*1.3%*	5.4%	5.5%	3.2%	**9.8%**	5.0%	
~95%	.1	-10	1.8%	1.4%	2.2%	1.3%	*0.1%*	2.5%	0.3%	**4.3%**	2.0%	1.8%	2.9%
	.2	0	2.0%	*0.2%*	2.4%	4.2%	**4.4%**	1.7%	2.9%	1.0%	1.3%	2.2%	
	.3	10	2.8%	*1.1%*	2.3%	**5.1%**	2.3%	3.9%	2.4%	3.1%	3.0%	2.9%	
	.4	20	3.3%	*0.3%*	8.3%	2.4%	1.0%	**10.8%**	2.6%	7.5%	1.9%	4.2%	
	.5	30	5.9%	0.4%	**9.2%**	0.4%	1.7%	5.6%	*0.3%*	4.7%	1.2%	3.3%	
												3.2%	

Bold text indicates the maximum thermal conductivity CV (%) for each test step.

Italicized text indicates the minimum thermal conductivity CV (%) for each test step.

5.4.2.3 Variation Amongst Products

Figure 5.5 depicts the maximum and minimum thermal conductivity range of all products for all test temperatures for all relative humidities.

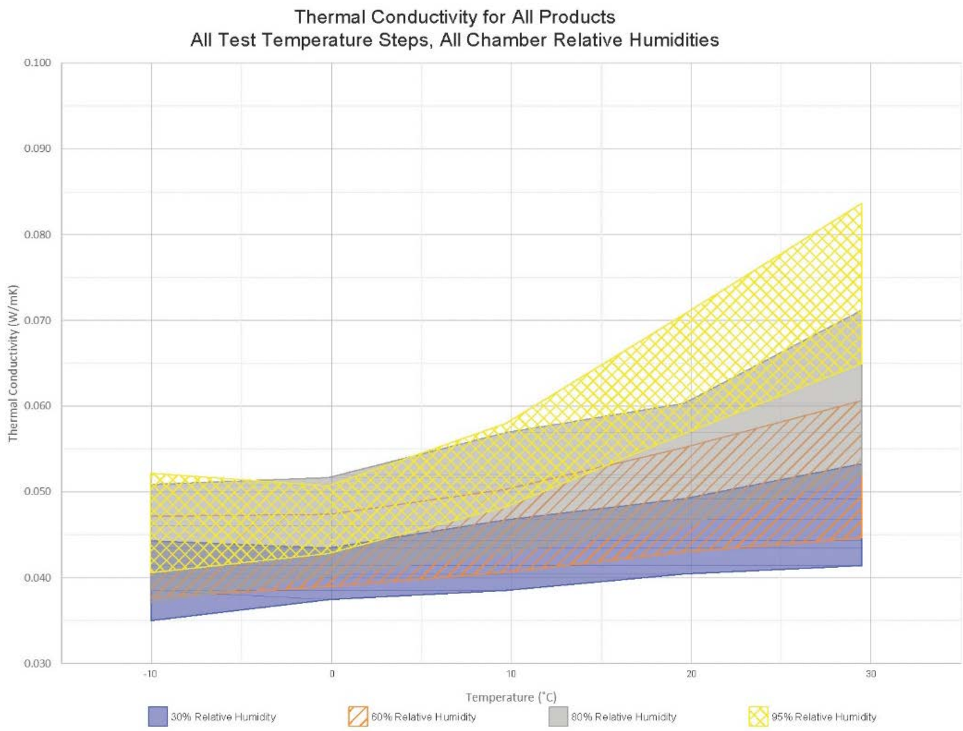


Figure 5.5 – Maximum and Minimum Thermal conductivity Range vs Temperature from All Products for all Relative Humidities, All Temperature Test Steps.

Table 5.46 presents the maximum and minimum thermal conductivity and the difference amongst all products for all test temperatures for all relative humidities. A summary of all average product thermal conductivities for each test temperature and relative humidity is provided in Appendix I.

Table 5.46 – Maximum, Minimum, and Difference in Thermal Conductivity from all Products for all Relative Humidities, All Temperature Test Steps.

RH(%)	Max/ Min/ Diff	Temp (˚C)				
		-10 ˚C	0 ˚C	10 ˚C	20 ˚C	30 ˚C
30%	Max	*0.044*	*0.043*	*0.047*	*0.049*	*0.053*
	Min	*0.035*	*0.037*	*0.038*	*0.040*	*0.041*
	Diff.	*0.009*	*0.006*	*0.008*	*0.009*	*0.012*
60%	Max	0.047	0.047	0.050	0.055	0.061
	Min	0.038	0.039	0.041	0.043	0.045
	Diff.	0.009	0.008	0.010	0.012	0.016
80%	Max	0.051	0.052	0.057	0.060	0.071
	Min	0.037	0.040	0.043	0.046	0.052
	Diff.	**0.014**	**0.011**	**0.014**	**0.014**	**0.019**
95%	Max	**0.052**	**0.051**	**0.058**	**0.071**	**0.084**
	Min	**0.041**	**0.043**	**0.048**	**0.057**	**0.065**
	Diff.	0.012	0.008	0.010	0.014	0.019

As presented, and as depicted in Figure 5.5, the variance in thermal conductivity amongst products increases with increasing moisture content and increasing temperature. Additionally, the variance in thermal conductivities amongst products is largest for WFIB preconditioned at 80% relative humidity. Specifically, the largest variance in thermal conductivities amongst products is at 30˚C for WFIB preconditioned at 80% relative humidity. However, the thermal conductivity values, and thus the variance in thermal conductivities, for all test temperatures for WFIB preconditioned at 95% may be affected by the HFMA testing order (refer to Section 5.4.2.4).

The temperature and moisture dependent thermal conductivity results obtained through testing for all products are similar to previous research, though also differ in several ways. Relative to the results obtained by Palumbo et al. (Palumbo et al., 2016), the thermal conductivity results from this research indicate a similar trend of increasing thermal conductivity with increasing relative humidity. However, the WFIB thermal conductivity results for this research are significantly less than the results obtained by Palumbo et al. which is likely associated with the higher density (212 kg/m3) of the WFIB from the previous research. Similar trends were observed through research conducted by Abdou et al. on wood wool material (348.2 kg/m^3) (Abdou & Budaiwi, 2005), though the results obtained by Abdou are much greater than obtained in this research due to the higher density of the insulation material from previous research.

The results obtained through this research are similar to the results from Sonderegger et al. (Sonderegger & Niemz, 2012) WFIB thermal conductivity research. Both testing results indicate an increase in thermal conductivity with increasing density, an increase in thermal conductivity with increasing moisture content, and an increase in thermal conductivity with increasing temperature. However, the thermal conductivity results for the dry process WFIB materials with similar densities to this research were not included in the results of the previous research, therefore comparison of thermal conductivity values cannot be completed.

The results obtained through this research are similar to the results obtained through research conducted by Ye et al. (Ye, 2015) which simulated heat transfer through WFIB with consideration of porosity changes due to wood fibre swelling with increasing relative humidity. The simulated results from Ye et al. and from this research both indicate an increase in thermal conductivity with increasing relative humidity, with larger increases in thermal conductivity as relative humidity increases.

The results obtained through this research are similar to the results obtained through research conducted by Goto et al. (Goto et al., 2011) such that the thermal conductivity increases with increasing relative humidity. However, for comparable density materials Goto et al. noted an increase from 0.38/0.041 W/mK to 0.040/0.045 W/mK from 0-80% relative humidity. The increase in thermal conductivity with relative humidity determine in this research is larger than that determined by Goto et al.

As discussed in Section 5.4.1.3, 40mm products are generally associated with lower thermal conductivities than 60mm and 80mm products. Discussion for correlating the variance of temperature and moisture dependent thermal conductivity amongst products is grouped by product thickness rather than as an entire group and/or within a single product of different thicknesses.

5.4.2.3.1 Thermal Conductivity Amongst Products with Thickness of 40mm

Table 5.47 presents the maximum and minimum thermal conductivity and the difference amongst all 40mm products for all test temperatures for all relative humidities. As presented, the variance in thermal conductivity amongst products increases with increasing moisture content, with the exception of 95% relative humidity. Additionally, the variance in thermal conductivity increases with increasing temperature. As previously discussed, increased thermal conductivity with increasing temperature is expected for WFIB. Also previously discussed, the storage of water vapour, adsorbed water, and liquid water in WFIB correlates to increased thermal conductivity.

The variance in thermal conductivities amongst products is largest for WFIB preconditioned at 80% relative humidity. Specifically, the largest variance in thermal conductivities amongst products is at 30˚C for WFIB preconditioned at 80% relative humidity. However, the thermal conductivity values, and thus the variance in thermal conductivities, for all test temperatures for WFIB preconditioned at 95% may be affected by the HFMA testing order (refer to Section 5.4.2.4). The largest thermal conductivity amongst all products for each temperature test step for each relative humidity is consistently associated with product 4.1. The highest thermal conductivity consistently correlates with the product with the highest density (refer to Section 4.1). The lowest thermal conductivity for each temperature test step for each relative humidity is consistently associated with product 3.1. The lowest thermal conductivity consistently correlates with the product with the lowest density. As previously discussed, higher density materials correlate with higher thermal conductivities. Additionally, materials comprising higher volumetric moisture contents for a given relative humidity correlate with higher thermal conductivities.

Table 5.47 – Maximum, Minimum, and Difference in Thermal Conductivity for 40mm Products for all Relative Humidities, All Temperature Test Steps.

RH(%)	Max/ Min/ Diff	Temp (˚C)				
		-10 ˚C	0 ˚C	10 ˚C	20 ˚C	30 ˚C
30%	Max	*0.041*	*0.043*	*0.047*	*0.049*	*0.052*
	Min	*0.035*	*0.037*	*0.038*	*0.040*	*0.041*
	Diff.	*0.006*	*0.006*	*0.008*	*0.008*	*0.010*
60%	Max	0.043	0.047	0.050	0.053	0.058
	Min	0.038	0.039	0.041	0.043	0.045
	Diff.	0.006	0.008	0.010	0.010	0.013
80%	Max	0.045	0.050	0.054	0.058	0.064
	Min	0.037	0.040	0.043	0.046	0.052
	Diff.	**0.008**	**0.010**	**0.011**	**0.012**	**0.012**
95%	Max	**0.047**	**0.051**	**0.056**	**0.063**	**0.074**
	Min	**0.041**	**0.043**	**0.048**	**0.057**	**0.065**
	Diff.	0.007	0.008	0.008	0.006	0.009

The thermal conductivity versus density for all 40mm products for all test temperatures for each relative humidity test are provided in Appendix I. As previously discussed, Figure 5.3 depicts the thermal conductivity versus density for all 40mm products for all test temperatures for 30% relative humidity. Each graph depicts tests conducted for each relative humidity, illustrating the thermal conductivity obtained for each density at a specific temperature test. A summary of these graphs is depicted Figure 5.6. The range of thermal conductivities at a specific density for each relative humidity reflects the variation of thermal conductivity as a result of temperature. The lower bound of each relative humidity reflects the lower thermal conductivities obtained for tests conducted at -10˚C. The upper bound of each relative humidity reflects the higher thermal conductivities obtained for tests conducted at 30˚C. As presented, the thermal conductivity increases linearly with increasing density for all relative humidities.

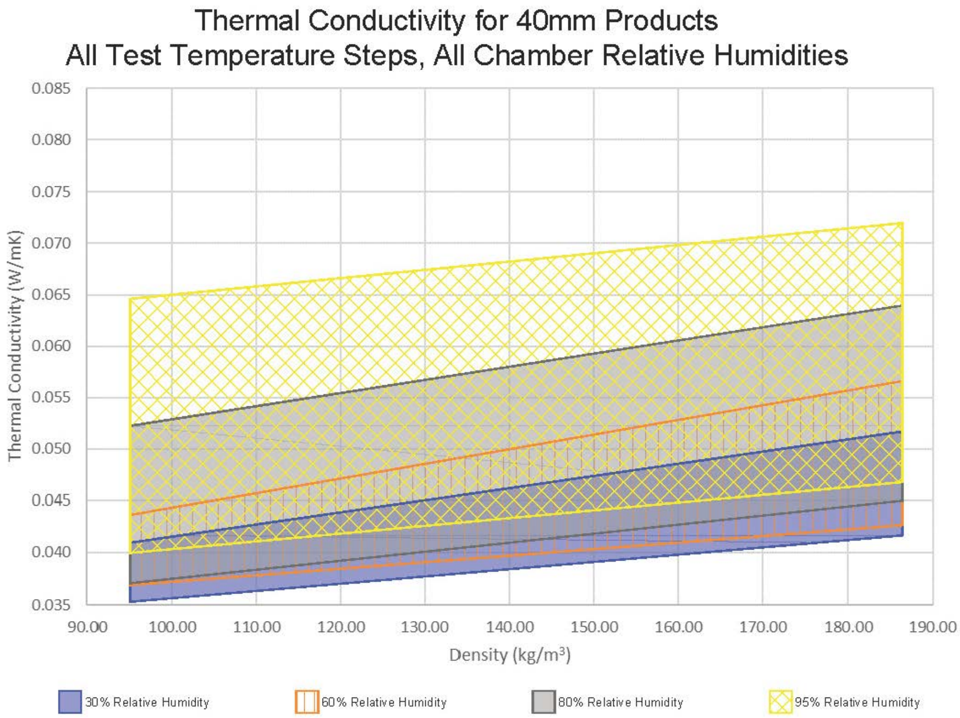


Figure 5.6 - Thermal Conductivity vs Density for all Test Temperatures for all Relative Humidities for all 40mm Products.

Table 5.3 presents the linear equation and coefficient of determination for thermal conductivity versus density for each temperature test step trendline at each relative humidity for 40mm products. As shown, the slope of the equation for 30%, 60%, and 80% relative humidity test steps generally increases with each increasing temperature test. Additionally, the slope of the equation for each temperature test step generally increases with relative humidities 30%, 60%, and 80%. The slope of the equation at 95% relative humidity test step does not increase with each increasing temperature test. Similarly, the slope of the equation for each temperature test step decreases between 80% and 95% relative humidity test steps. The lesser increase in thermal conductivity at 95% relative humidity may be associated with wood fibre swelling. Lower density WFIB has a greater amount of pore space than higher density WFIB, which may accommodate greater amounts of wood fibre swelling. Greater amounts of wood fibre swelling for lower density materials may further contribute to increased thermal conductivities due to increased contact of wood fibre materials. Additionally, as previously mentioned, for all test temperatures for WFIB preconditioned at 95% may be affected by the HFMA testing order (refer to Section 5.4.2.4).

Table 5.48 –Equation and Coefficient of Determination for Linear Trend Lines for Figure 5.6.

RH		-10˚C	0˚C	10˚C	20˚C	30˚C
30%	Eq.	$y = 6.95x10^{-5}x+0.0287$	$y = 6.79x10^{-5}x+0.0309$	$y = 9.13x10^{-5}x+0.0300$	$y = 8.96x10^{-5}x+0.0324$	$y = 1.17x10^{-4}x+0.0299$
	R^2	0.9792	0.9375	0.9651	0.9480	0.9581
60%	Eq.	$y = 6.29x10^{-5}x+0.0309$	$y = 8.90x10^{-5}x+0.0303$	$y = 1.06x10^{-4}x+0.0306$	$y = 1.15x10^{-4}x+0.0316$	$y = 1.42x10^{-4}x+0.0301$
	R^2	0.8477	0.9432	0.9985	0.9884	0.9569
80%	Eq.	$y = 8.72x10^{-5}x+0.0288$	$y = 1.05x10^{-4}x+0.0301$	$y = 1.19x10^{-4}x+0.0317$	$y = 1.29x10^{-4}x+0.0342$	$y = 1.28x10^{-4}x+0.0401$
	R^2	0.9915	0.9940	0.9995	0.9931	0.9666
95%	Eq.	$y = 7.47x10^{-5}x+0.0329$	$y = 8.57x10^{-5}x+0.0344$	$y = 8.46x10^{-5}x+0.0389$	$y = 6.09x10^{-5}x+0.0502$	$y = 7.99x10^{-5}x+0.057$
	R^2	0.9487	0.9858	0.8418	0.5691	0.5928

5.4.2.3.2 Thermal Conductivity Amongst Products with Thickness of 60mm

Table 5.49 presents the maximum and minimum thermal conductivity and the difference amongst all 60mm products for all test temperatures for all relative humidities. As presented, the variance in thermal conductivity does not appear to consistently correlate with temperature or moisture content.

The variance in thermal conductivity at -10˚C is largest at 30% relative humidity, though this difference is only marginally larger than the difference in thermal conductivity at 80% and 95% relative humidity. The variance in thermal conductivity at 0˚C is largest at 60% relative humidity. The variance in thermal conductivity at 10˚C, 20˚C, and 30˚C is largest at 95% relative humidity.

The largest variance in thermal conductivity amongst the products is 0.015 W/mK at a test temperature of 30˚C and 95% relative humidity. The highest thermal conductivity amongst all 60mm products is generally associated with product 6.2. At lower relative humidities (30%, 60%) and lower temperature (-10˚C, 0˚C), the highest thermal conductivity is associated with product 4.2. The highest thermal conductivity is consistently associated with high-density products. As discussed in Section 5.4.1.3.2, the higher thermal conductivities for product 6.2 at higher temperatures may be associated with the greater volumetric moisture content of product 6.2. Similarly, the higher thermal conductivities for product 6.2 at higher moisture contents may be associated with the greater volumetric moisture content of product 6.2.

The lowest thermal conductivity for each temperature test step for each relative humidity, excluding 95%, is associated with product 5.2 which is the lowest density 60mm product. The thermal conductivities for 60mm products at 95% relative humidity does not correlate well with density, especially with increasing temperature. This is discussed further below.

Table 5.49 – Maximum, Minimum, and Difference in Thermal Conductivity for 60mm Products for all Relative Humidities, All Temperature Test Steps.

RH(%)	Max/ Min/ Diff	Temp (˚C)				
		-10 ˚C	0 ˚C	10 ˚C	20 ˚C	30 ˚C
30%	Max	*0.044*	*0.043*	*0.045*	*0.049*	*0.053*
	Min	*0.041*	0.042	*0.044*	*0.047*	*0.050*
	Diff.	**0.003**	0.001	0.001	0.002	0.003
60%	Max	0.044	0.047	0.050	0.055	0.061
	Min	0.042	*0.042*	0.047	0.050	0.055
	Diff.	0.002	**0.005**	0.003	0.005	0.006
80%	Max	0.047	0.048	0.052	0.059	0.067
	Min	0.045	0.047	0.050	0.054	0.064
	Diff.	0.003	0.001	0.002	0.005	0.003
95%	Max	**0.050**	**0.051**	**0.056**	**0.069**	**0.084**
	Min	**0.047**	**0.048**	**0.053**	**0.061**	**0.069**
	Diff.	0.003	0.002	**0.003**	**0.008**	**0.015**

The thermal conductivity versus density for all 60mm products for all test temperature for each relative humidity test are provided in Appendix I. As previously discussed, Figure 5.4 depicts the thermal conductivity versus density for all 60mm products for all test temperatures for 30% relative humidity. Each graph depicts tests conducted for each relative humidity, illustrating the thermal conductivity obtained for each density at a specific temperature test. A summary of these graphs is depicted in Figure 5.7. The range of thermal conductivities at a specific density for each relative humidity reflects the variation of thermal conductivity as a result of temperature. The lower bound of each relative humidity reflects the lower thermal concavities obtained for tests conducted at -10˚C. The upper bound of each relative humidity reflects the higher thermal conductivities obtained for tests conducted at 30˚C.

As presented, the thermal conductivity generally increases linearly with increasing density for all relative humidities, with the exception of 95% relative humidity. The correlation of thermal conductivity and density for each temperature test step decreases as relative humidity increases. As previously discussed in Section 5.4.1.3.2, the general increase of thermal conductivity with density could not be correlated at 30% relative humidity. However, at 95% relative humidity the range of thermal conductivity increases considerably, particularly at higher temperature test steps. Furthermore, product 4.2 and 6.2 which have similar densities obtain large differences in thermal conductivity at 95% relative humidity, particularly at higher temperature test steps. Greater accuracy in correlating the thermal conductivity and density for 60mm products could be obtained through testing of additional lower and higher density products. Additionally, the thermal conductivity values for all test temperature for WFIB preconditioned at 95% may be affected by the HFMA testing order (refer to Section 5.4.2.4).

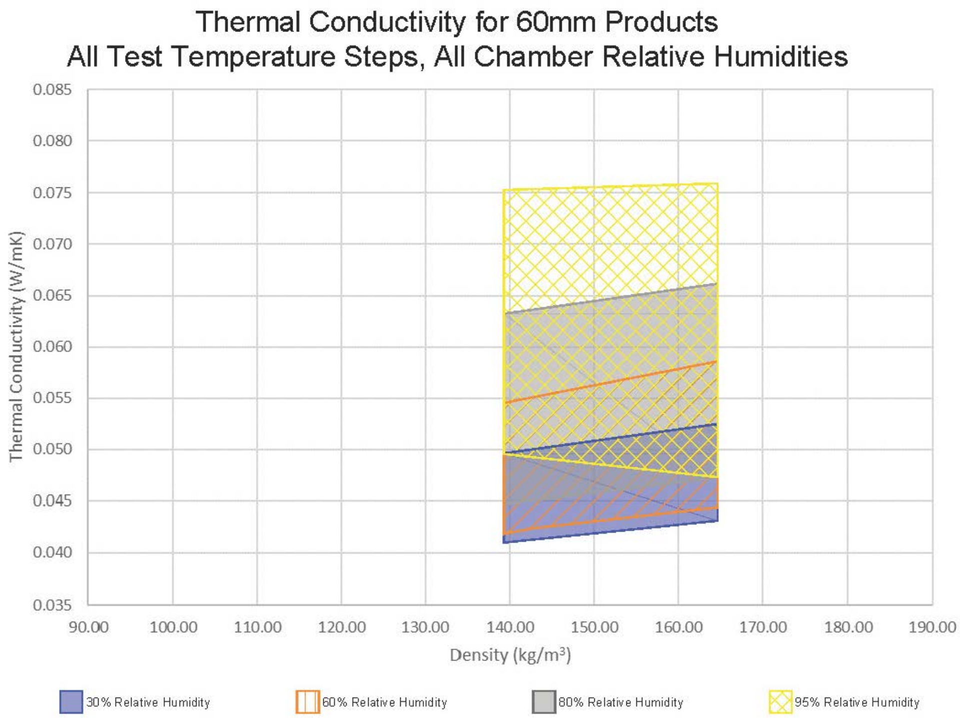


Figure 5.7 - Thermal Conductivity vs Density for all Test Temperatures for all Relative Humidities for all 60mm Products.

Table 5.50 presents the linear equation and coefficient of determination for thermal conductivity versus density for each temperature test step trendline at each relative humidity for 60mm products. A correlation cannot be made for the change in slope of the linear relationship between each temperature test step. Similarly, a correlation could not be made for the change in slope for each temperature test step for each relative humidity.

Table 5.50 –Equation and Coefficient of Determination for Linear Trend Lines for Figure 5.7.

RH		-10˚C	0˚C	10˚C	20˚C	30˚C
30%	Eq.	$y = 8.09x10^{-5}x+0.0298$	$y = 3.72x10^{-5}x+0.0370$	$y = 4.00x10^{-5}x+0.0384$	$y = 2.84x10^{-5}x+0.0434$	$y = 1.12x10^{-4}x+0.0341$
	R^2	0.4512	0.9694	0.9354	0.1182	0.8431
60%	Eq.	$y = 9.00x10^{-5}x+0.0295$	$y = 7.03x10^{-5}x+0.0368$	$y = 1.77x10^{-4}x+0.0249$	$y = 1.58x10^{-4}x+0.0326$	$y = 1.58x10^{-4}x+0.0326$
	R^2	0.8437	0.3368	0.8678	0.5805	0.5805
80%	Eq.	$y = 1.02x10^{-4}x+0.0306$	$y = 2.01x10^{-5}x+0.0442$	$y = 8.75x10^{-6}x+0.0152$	$y=-2.17x10^{-5}x+0.0601$	$y = 1.15x10^{-4}x+0.0472$
	R^2	0.9428	0.3679	0.0152	0.018	0.7676
95%	Eq.	$y=-8.93x10^{-5}x+0.0621$	$y=-4.31x10^{-5}x+0.0563$	$y=-9.50x10^{-6}x+0.0562$	$y = 4.57x10^{-5}x+0.0718$	$y = 2.55x10^{-5}x+0.0717$
	R^2	0.7164	0.1602	0.0061	0.0215	0.0022

The thermal conductivity of 60mm specimens is generally greater than that of 40mm specimens for the same density, temperature, and relative humidity test conditions. It is not expected that the greater thermal conductivity associated with thicker specimens is associated with differing density distributions due to board pressing (refer to Section 2.2). Relative to 40mm specimens, it is expected that 60mm specimens would have a lower percentage of higher density wood fibres due to board pressing, and therefore it would be expected that this would result in a lower thermal conductivity. Differences in wood fibre orientation (vertical versus horizontal) due to differences in product thickness may also impact the thermal conductivity. A greater proportion of vertical wood fibres may be associated with a higher thermal conductivity (refer to Section 2.3.1.2). Differences in quality of lumber by-products utilized in manufacturing amongst product differences may also be a factor effecting the permeability amongst product thicknesses.

5.4.2.4 Effect of Test Order on Thermal Conductivity Results

The average thermal conductivity versus test temperature for 95% relative humidity specimen 1.1.01, with temperature test order -10˚C to 30˚C and temperature test order from 30˚C to -10˚C is provided in Section 4.4.3.1, Figure 4.37. The average thermal conductivity versus test temperature for 95% relative humidity for specimen 01 for all other products for temperature test order -10˚C to 30˚C (original order) and temperature test order 30˚C to -10˚C (reverse order) is provided in Appendix I. Table 5.51 presents the thermal conductivities for each 01 specimen for all products for each temperature for 95% relative humidity for both original temperature test order and reverse temperature test order. The difference between the thermal conductivities obtained for each temperature test order is included.

For most test temperatures, the thermal conductivity obtained for the reverse temperature test order is greater than the thermal conductivity obtained for the original temperature test order. For products 2.1, 2.2, 3.1, 4.1, and 5.2 at test temperature -10˚C, the thermal conductivity obtained for the reverse temperature test order is less than the thermal conductivity for the original temperature test order. As previously discussed, the original temperature test order (-10˚C to 30˚C) subjected specimens to condensing and freezing of moisture throughout the material within the first temperature test step (-10C). A greater amount of condensation and freezing would occur on the colder specimen surface (bottom). For each subsequent test step, the average specimen temperature increased and the moisture throughout the material redistributed with some vapourization of liquid/solid water. Since the specimens were preconditioned at 25˚C, for the reverse temperature test order (30˚C to -10˚C) the specimens experienced lesser redistribution of moisture during the first temperature test step. It is expected that the greatest difference in thermal conductivity due to temperature test order would result for the highest relative humidity test, therefore the temperature test order was only analyzed for 95% relative humidity.

The greater thermal conductivity obtained for most temperature test steps for the reverse temperature test order may be a result of a nearer to equilibrium moisture distribution throughout the specimen for the specific temperature test step. Equilibrium moisture distribution for a temperature test step may provide a more continuous water molecule path for heat transfer. In contrast, a material with a higher moisture content near the bottom of the specimen may experience greater thermal conductivity for the bottom portion, however the lower moisture content near the top of the specimen may experience a lesser thermal conductivity for the top portion. Additionally, the moisture throughout the specimen may affect the swelling of the wood fibres throughout the specimen. For higher relative humidity test conditions equilibrium moisture distribution for a temperature test step may provide more continuous wood fibre contact. In contrast, a material with a higher moisture content near the bottom of the specimen may experience a greater amount of swelling for the bottom, however the lower moisture content near the top of the specimen may experience a lesser amount of swelling near the top. Therefore, the thermal conductivity may be greater for the bottom portion of the specimen, though the thermal conductivity may be lesser for the top of the specimen.

The correlation of thermal conductivity with density and specimen thickness may be impacted by the thermal conductivity results due to temperature test order. Though the correlation of increasing thermal conductivity with increasing temperature would remain, including increasing thermal conductivity with density and with thickness of material. Further testing for each individual test step to determine precise thermal conductivities for a specific temperature is required.

Table 5.51 - Thermal Conductivities of Specimen 01 for All Products over Full Temperature Range at 95% Relative Humidity - HFMA Test Temperatures Reversed

Specimen	Test Order.	Temperature Test Step				
		-10˚C	0˚C	10˚C	20˚C	30˚C
1.1.01	-10C to 30C	0.0411	0.0450	0.0475	0.0554	0.0634
	30C to -10C	0.0417	0.0460	0.0496	0.0592	0.0752
	Diff.	0.0007	0.0010	0.0022	0.0038	**0.0118**
2.1.01	-10C to 30C	0.0431	0.0462	0.0498	0.0566	0.0647
	30C to -10C	0.0425	0.0452	0.0504	0.0611	0.0736
	Diff.	-0.0006	-0.0011	0.0007	0.0045	0.0089
2.2.01	-10C to 30C	0.0463	0.0488	0.0551	0.0640	0.0753
	30C to -10C	0.0456	0.0514	0.0576	0.0690	0.0824
	Diff.	-0.0007	0.0026	0.0025	0.0050	0.0071
3.1.01	-10C to 30C	0.0405	0.0442	0.0459	0.0562	0.0665
	30C to -10C	0.0387	0.0457	0.0465	0.0572	0.0771
	Diff.	-0.0019	0.0016	***0.0006***	***0.0010***	0.0106
4.1.01	-10C to 30C	0.0473	0.0520	0.0548	0.0628	0.0724
	30C to -10C	0.0472	0.0515	0.0567	0.0672	0.0816
	Diff.	***-0.0001***	***-0.0005***	0.0018	0.0044	0.0091
4.2.01	-10C to 30C	0.0478	0.0494	0.0507	0.0538	0.0684
	30C to -10C	0.0487	0.0483	0.0584	0.0673	0.0778
	Diff.	0.0010	-0.0011	0.0077	0.0135	0.0095
5.2.01	-10C to 30C	0.0500	0.0524	0.0565	0.0674	0.0778
	30C to -10C	0.0483	0.0535	0.0601	0.0732	0.0894
	Diff.	-0.0017	0.0011	0.0035	0.0058	0.0115
5.3.01	-10C to 30C	0.0496	0.0509	0.0587	0.0684	0.0866
	30C to -10C	0.0528	0.0588	0.0676	0.0826	0.0900
	Diff.	**0.0033**	**0.0079**	**0.0089**	**0.0142**	0.0034
6.2.01	-10C to 30C	0.0480	0.0512	0.0580	0.0704	0.0829
	30C to -10C	0.0487	0.0534	0.0608	0.0718	0.0828
	Diff.	0.0007	0.0022	0.0029	0.0014	***-0.0001***
Max		0.0033	0.0079	0.0089	0.0142	0.0118
Min		0.0001	0.0005	0.0006	0.0010	0.0001

6 Conclusions

Understanding the material characteristics of thermal insulations in building envelopes is important for ensuring the longevity and performance of the control layer materials and the enclosure as a multi-layer composite assembly. The effect of temperature on water vapour sorption and the effect of moisture and temperature of vapour permeability and thermal conductively for WFIB materials must be better characterized to ensure adequate performance for building envelope designs in Canadian climates.

The density analysis from this research revealed the variability amongst WFIB products, within a single product, and from the declared density of a product. The results indicate that for some products, the variability of density amongst the product is significant (18 kg/m^3), and the percent difference of the product density from the declared density is also notable (7.7%). Whereas for other products, the variability of density amongst the product is less significant (1 kg/m^3), though the percent difference of the product density from the declared density is significant (8.1%). Lastly, other products experience an intermediate variability of density (4 kg/m^3), and the percent difference of the product density from the declared density is relatively small (1.3%). The variation in density within a product and amongst products does not correlate with a particular density, density range (ex. higher versus lower density), or material thickness.

The moisture sorption and volumetric moisture content research confirmed the general moisture sorption curve with increasing relative humidity, and analyzed differences within a product, amongst products, for different product thicknesses, at differing temperatures, and also the impact of oven drying prior to testing. Variation of volumetric moisture content within a product correlates with the variability of density within a product at both 10˚C and 25˚C. Variation of volumetric moisture content amongst WFIB products correlates with higher density products due to the larger number of wood cells available to adsorb moisture at both 10˚C and 25˚C. Variation of volumetric moisture content amongst WFIB products of different thickness does not correlate to product thickness, but rather to density. At relative humidities less than or equal to approximately 53%, specimens experience greater moisture contents at 10˚C than at 25˚C. This is likely associated with the larger amount of adsorption at lower relative humidities at lower temperatures. At relative humidities greater than or equal to approximately 77%, specimens experience greater moisture contents at 25˚C than at 10˚C. This may be associated with wood fibre swelling resulting in increased capillary condensation in small pore spaces. The moisture content for oven dried specimens is consistently lower than that of non-oven dried specimens, with differences decreasing at higher relative humidities. This is likely due to thermal modification of the wood cell during oven drying reducing adsorption in the wood cell. Product 5.3 consistently obtains larger than expected moisture contents and volumetric moisture contents. This may be associated with the manufacturing processes, including the coating and impregnation of the wood fibres and thermal modification throughout the manufacturing process. Additionally, the size, distribution, and connectivity of the pore spaces for product 5.3 may differ largely from all other WFIB products. The correlation of moisture content and volumetric moisture content with density is beneficial in accurately determining the performance of WFIB.

The vapour permeability research indicated the variation of vapour permeability with increasing relative humidity, as well as the wet cup and dry cup vapour permeabilities. Additionally, this research analyzed the variation of vapour permeability within a product, amongst products, for different product thicknesses, and at differing temperatures. Variation in vapour permeability within a product could not be correlated with density or a specific product. Therefore, variation is likely associated with testing conditions.

For modified cup test conditions at 10˚C and 25˚C, the largest vapour permeability is generally associated with products 5.2 and 5.3. At 25˚C, the next largest vapour permeability is generally associated with lower density materials, and the lowest vapour permeability is generally associated with higher density materials. A majority of materials exhibit an increase in permeability with increasing relative humidity until an average specimen relative humidity less than 50%, likely due to increased surface diffusion with increasing relative humidity. At relative humidities greater than 50% permeability decreases with increasing relative humidity, likely due to wood fibre swelling resulting in reduced pore space and thus reduced vapour diffusion, surface diffusion, and capillary transport. Several products which exhibit relatively greater moisture contents than expected demonstrate less variation in permeability with increasing permeability, though a general decrease in permeability with increasing relative humidity is demonstrated. At 10˚C, the next largest vapour permeability does not correlate with a specific product or density. The lowest vapour permeability correlates with a specific product, though does not correlate with higher density materials. A majority of materials exhibit a decrease in permeability with increasing relative humidity. However, 60mm products exhibit an increase in permeability at approximately 69% average specimen relative humidity.

At relative humidities less than 35-50%, the permeability at 10˚C is greater than the permeability at 25˚C. This is likely associated with larger amounts of adsorption at lower relative humidities at lower temperatures. At relative humidities greater than 35-50%, the permeability at 25˚C is greater than the permeability at 10˚C. This is likely associated with greater amounts of surface diffusion and capillary transport at higher temperatures. The vapour permeability at 10˚C and 25˚C is related to specimen thickness in addition to density, with thicker specimens exhibiting larger vapour permeabilities. This may be due to the non-linear moisture distribution throughout the thickness of the specimens, therefor a larger proportion of the thicker materials experience high relative humidities. Additionally, permeability may be impacted due to material differences between different product thicknesses, such as density distribution.

At 10˚C and 25˚C, the largest wet and dry cup permeability is associated with the lowest density product, and the lowest wet and dry cup permeability is generally associated with higher density products. The vapour permeability at 10˚C and 25˚C is related to specimen thickness in addition to density, with thicker specimens exhibiting larger vapour permeabilities.

The range of vapour permeability may impact the ability to accurately determine the performance of WFIB within a building assembly. For consideration of drying, a lower vapour permeability may be considered to determine the slowest drying mechanism, therefore providing a conservative approach towards material performance and potential degradation due to mould. However, alternative scenarios of wetting such as sun-driven vapour, in which a higher vapour permeability would result in a greater amount of moisture accumulation, should also be considered.

The moisture and temperature dependent thermal conductivity research confirmed the increase in thermal conductivity with increasing relative humidity and increasing temperature, and analyzed differences within a product, amongst products, for different product thicknesses, and studied cold climate temperatures. The research confirmed thermal conductivity increases with increasing temperature and increasing moisture content, and with increasing moisture contents the change in thermal conductivity is greater with increasing temperature, therefore polynomial. Additionally, thermal conductivity increases with increasing material density, with a correlation to specimen thickness such that thermal conductivity also increases with increasing specimen thickness.

The range of thermal conductivity may impact the ability to accurately determine the performance of WFIB within a building assembly. The correlation of density with thermal conductivity is beneficial in accurately determining the heat transfer of a material within a building assembly. If considering minimizing building energy consumption, use of the largest thermal conductivity value for each temperature would allow for designing building enclosures which approximate the largest expected heat transfer. However, assuming the highest thermal conductivity and thus the highest expected heat transfer may result in over-design of the building enclosure and mechanical systems. Accurately understanding the materials performance for each temperature and moisture condition for a specific product would allow for the most accurate design.

7 Further Work

This research investigated the characterization of several hygrothermal properties of WFIB, including moisture sorption and volumetric moisture content, temperature and relative humidity dependent vapour permeability, and temperature and moisture dependent thermal conductivity. Throughout the course of the research completed, the following related areas have been identified as potential future areas of research:

i. Additional materials testing including water uptake testing and air permeability.
ii. Further investigation of the effect of product thickness on vapour permeability and thermal conductivity, as the results from this study are limited to products that are 40mm, 60mm, and 80mm thick, though products are available in thicknesses up to 300mm.
iii. Analysis of the products to determine the density profile throughout specimens, particularly to determine density profile due to board pressing which may result in significantly higher densities on the surface layers relative to the inner core. Include products of various thicknesses.
iv. Investigation of the fibre orientation of products, particularly any variation that may exist between products of different densities and within products of different thicknesses.
v. Analysis of the components (ex. wood fibres, species of wood fibres, paraffin, polyurethane, etc.) within each product and each product thickness, including volumetric mass of each additive. Correlation of the components with the obtained results from this research.
vi. Investigation of the impact of cyclic moisture exposure on moisture sorption.
vii. Investigate thickness swelling due to moisture, impact of swelling on porosity, and impact of cyclic swelling and shrinkage on anchoring.
viii. The data from this research and others could be used to develop a hygrothermal model for various Canadian climates.
ix. Analysis of a constructed assembly hygrothermal monitoring for an assembly comprised of mostly/entirely WFIB, and an assembly comprised of WFIB exterior insulation with various other interior cavity insulations.

Appendix A - Moisture Sorption Test Results at 25˚C

Wood Growth and Structure

The wood growth process of trees is both the primary upward growth, and the secondary lateral growth which occurs in rings. The innermost layers of a tree are heartwood, while the outermost layers are sapwood (Stamm, 1964). Sapwood layers of the tree are responsible for the conduction and storage of water. As time passes and secondary growth progresses, sapwood that was once closer to the exterior of the tree becomes more central. Through the deposition of extractives and extraneous materials, the sapwood becomes heartwood as secondary growth progresses. Seasonal growth of trees includes early wood and late wood which is visible throughout the secondary growth tree rings. Early wood includes rapid growth in the spring, typically comprising larger cells with thinner walls. Slower growth which takes place throughout the summer and fall results in late wood, comprising relatively smaller and denser cells. The cell structure and layer thickness of early wood late wood varies by trees species, geographical location, and seasonal climate during (Ramage et al., 2017).

Cellular Structure

The wood cell structure consists of the cell wall and a cavity space inside the cell wall known as a lumen. The cell wall structure of all wood species is comprised of cellulose, hemiceullose, lignin, and extractives and extraneous materials (Siau, 1971). The quantity of each material within the cell structure varies from species to species. Cellulose is typically 50% of the dry cell by weight and is the main source of wood mechanical and hygroscopic properties, with an affinity towards water less than hemicellulose but greater than lignin. Hemicellulose is 20-35% of the dry cell by weight and has the greatest affinity towards water. Lignin is 15-25% of the dry cell wall by weight, and is associated with hydrophobic properties, rigidity, and compressive strength of the cell wall. Extractives and extraneous materials are 0-25% of the dry cell by weight and are primarily located in the lumens though may also occur in the cell wall (Siau, 1984). Extractives and extraneous materials consist of a variety of compounds including terpenes, wood resins, polyphenols, sugars, fatty acids, tannins, and ash content (calcium, potassium, and magnesium). The extractives and extraneous materials significantly contribute to properties such as colour, odour, decay resistance, specific gravity, and permeability (Siau, 1984).

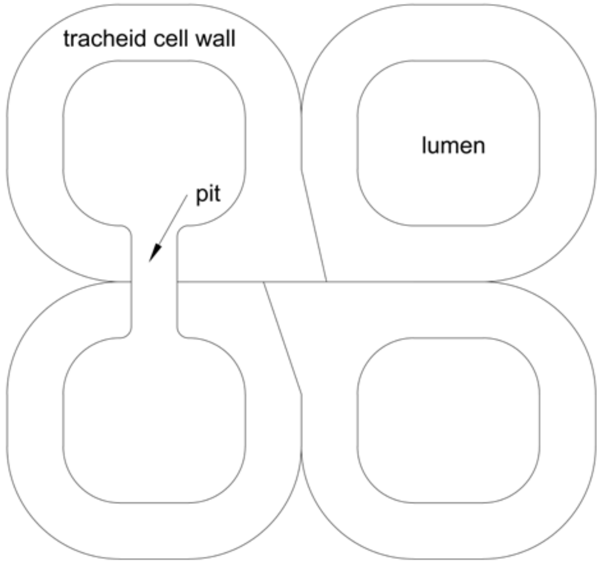
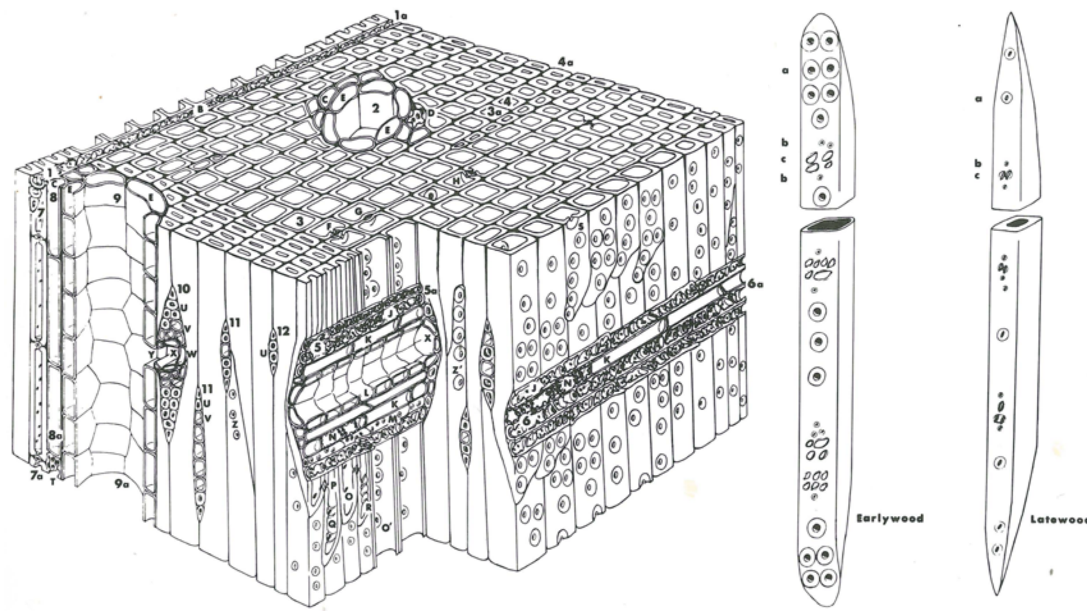


Figure A.1 - Wood Cell Structure.

Physical Structure

Softwood is a series of long, longitudinally oriented, tapered cells called tracheid. Tracheid cells are typically 1.5-5.0mm in length, and 15-80μm in diameter, though the length and diameter vary depending on species and location within the tree. The tracheid serves to conduct water through the lumen and provide structural support. Lumen size varies depending on the tracheid cell diameter and the cell wall thickness. The tracheid are interconnected via pits to allow the continued conduction of water from one tracheid to the next. Ray parenchyma cells are positioned radially, therefore facilitating water movement in the radial direction (Siau, 1984).



(a) (b)

Figure A.2 - Softwood a) Physical Structure, and b) Tracheid Structure (Siau, 1971)

Appendix B - Dry Density Test Results

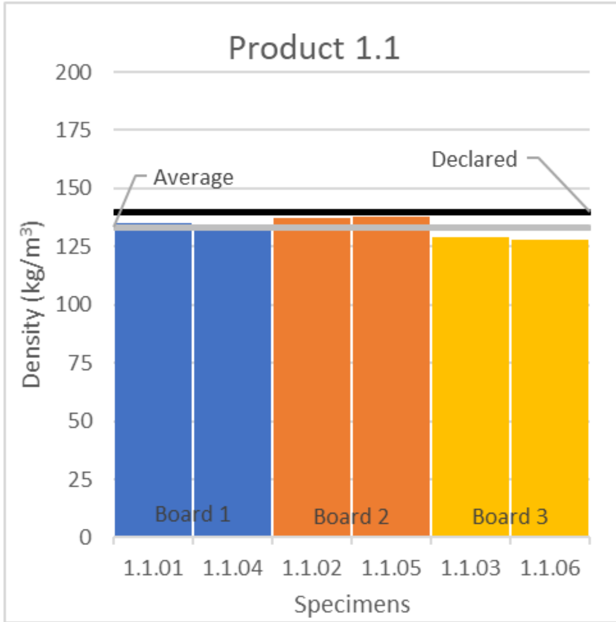


Figure B.1 - Dry Density of Moisture Sorption Specimens for Product 1.1.

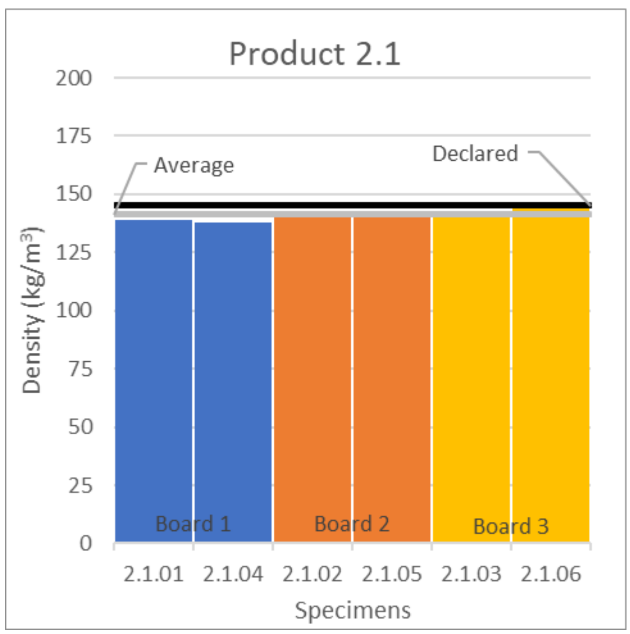


Figure B.2 - Dry Density of Moisture Sorption Specimens for Product 2.1.

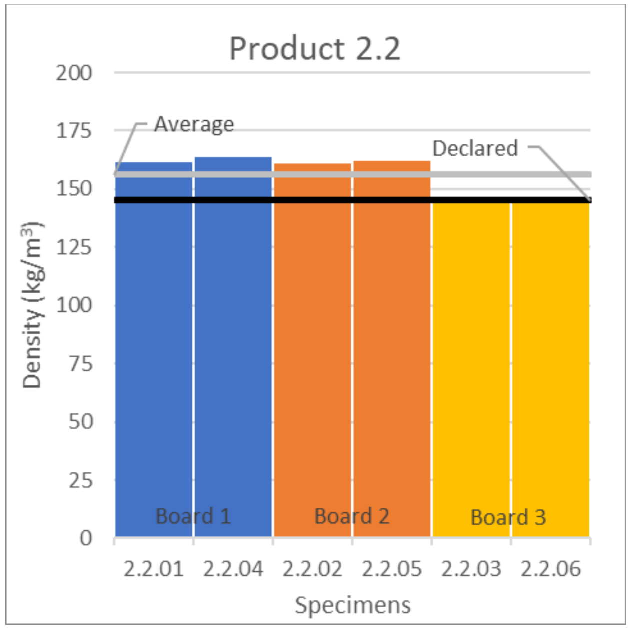


Figure B.3 - Dry Density of Moisture Sorption Specimens for Product 2.2.

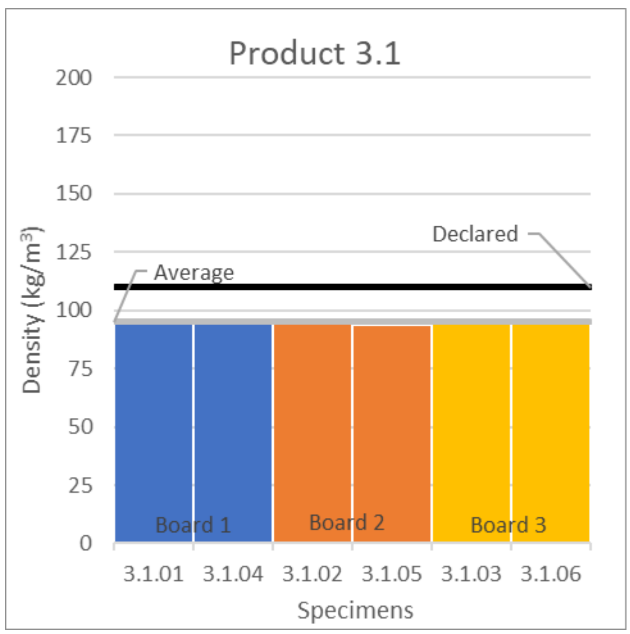


Figure B.4 - Dry Density of Moisture Sorption Specimens for Product 3.1.

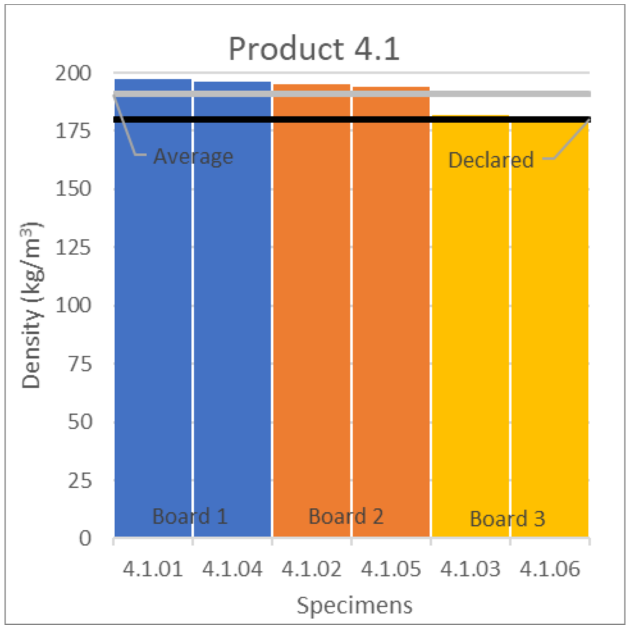


Figure B.5 - Dry Density of Moisture Sorption Specimens for Product 4.1.

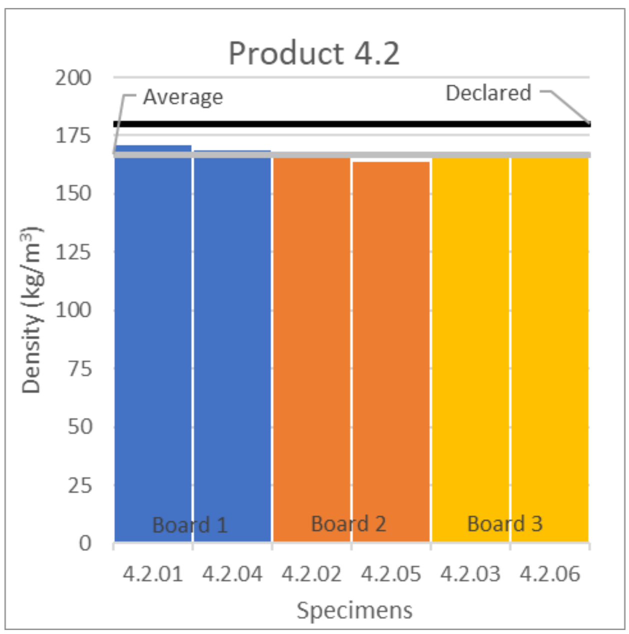


Figure B.6 - Dry Density of Moisture Sorption Specimens for Product 4.2.

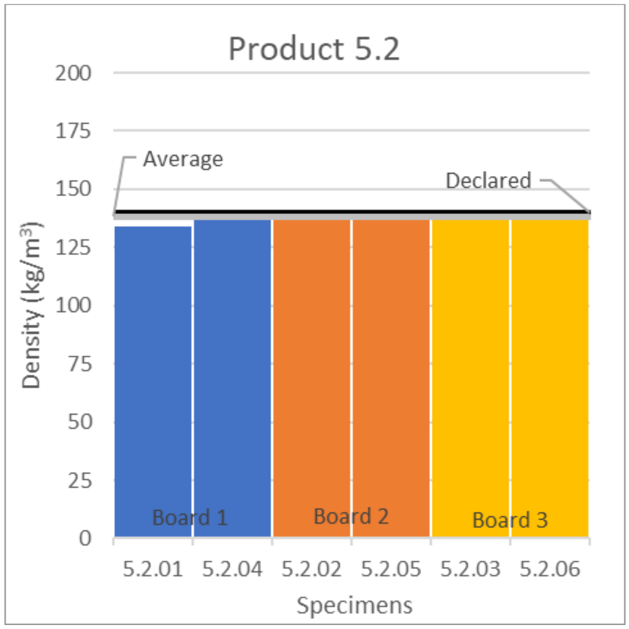


Figure B.7 - Dry Density of Moisture Sorption Specimens for Product 5.2.

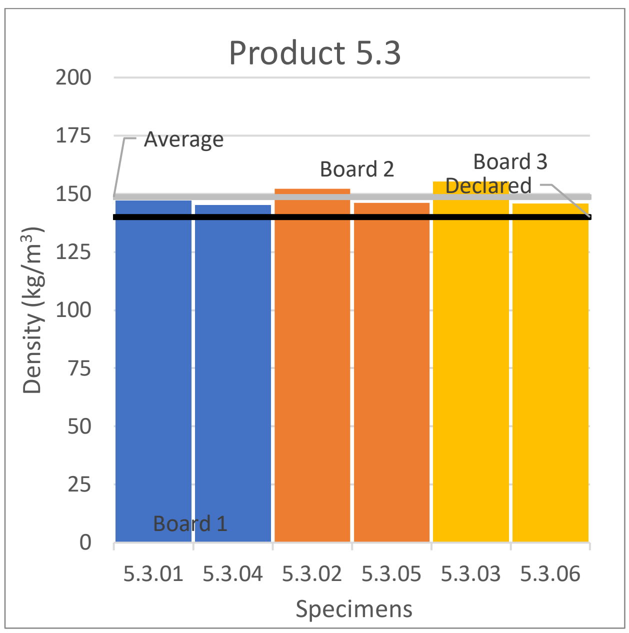


Figure B.8 - Dry Density of Moisture Sorption Specimens for Product 5.3.

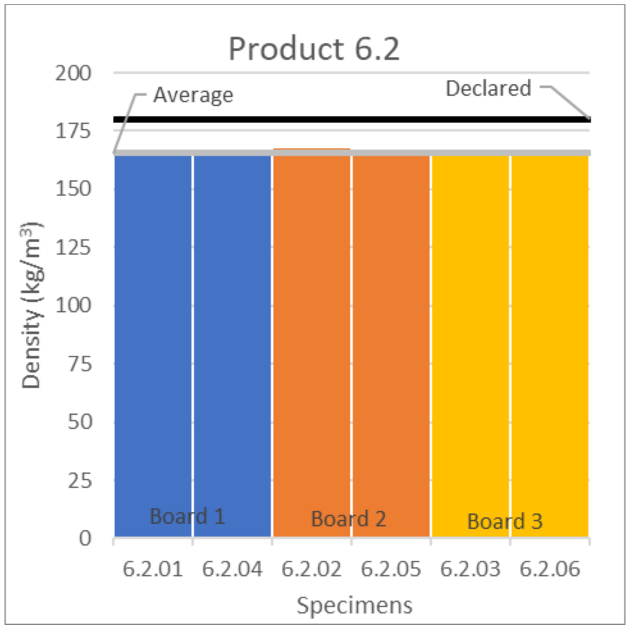


Figure B.9 - Dry Density of Moisture Sorption Specimens for Product 6.2.

Appendix C - Moisture Sorption Test Results at 25˚C

Table C.1 – Moisture Contents for Specimens 1.1.04, 1.1.05, 1.1.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			1.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	1.1.01	1.1.02	1.1.03			
					MC(%)					
.1	24.21	0.03, 0.13%	34.5%	0.19, 0.57%	6.9%	6.9%	6.9%	6.9%	0.00%	0.05%
.2	24.23	0.05, 0.23%	49.6%	1.73, 3.49%	8.3%	8.3%	8.2%	8.3%	0.07%	0.81%
.3	24.40	0.08, 0.34%	77.2%	1.68, 2.18%	11.7%	11.6%	11.5%	11.6%	0.10%	0.82%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	14.0%	14.0%	13.7%	13.9%	0.19%	1.35%
.5	24.44	0.13, 0.54%	98.0%	-	19.2%	19.2%	19.5%	19.3%	0.15%	0.78%

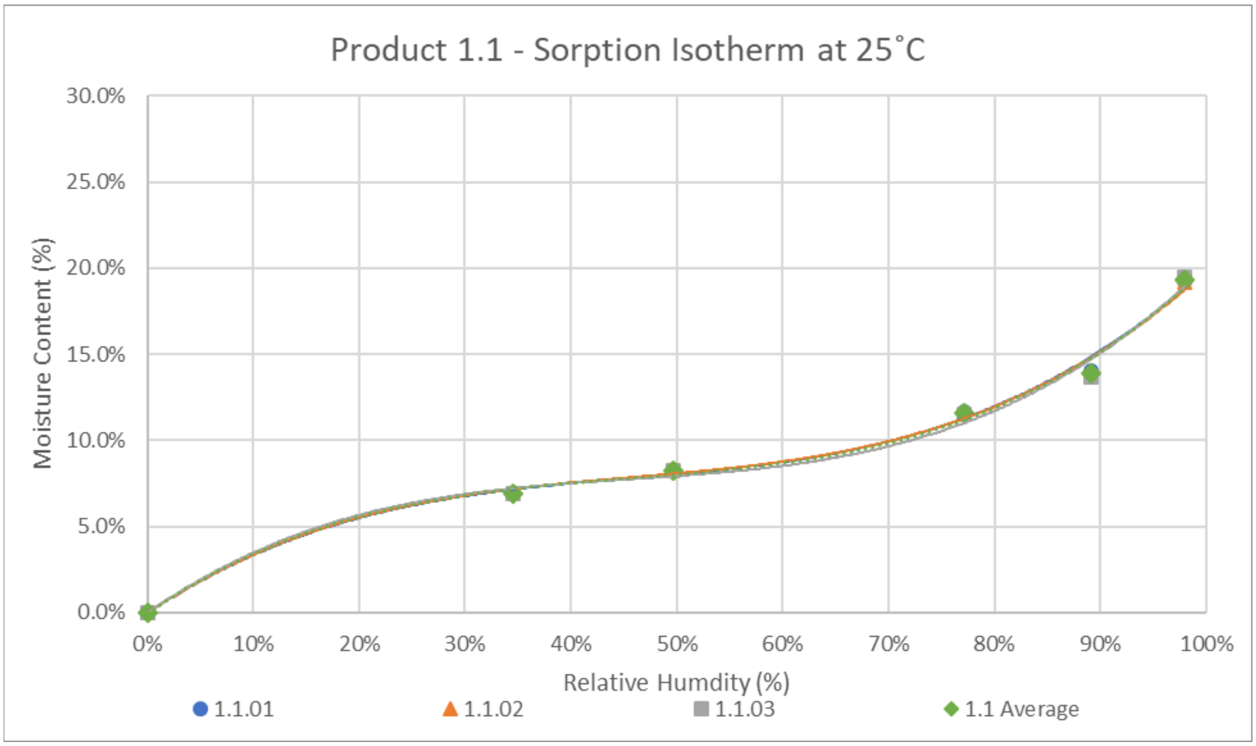


Figure C.1 - Product 1.1 Moisture Sorption Isotherm at 25˚C

Table C.2 – Moisture Contents for Specimens 2.1.04, 2.1.05, 2.1.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			2.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	2.1.01	2.1.02	2.1.03			
					MC(%)					
.1	24.21	0.03, 0.13%	34.5%	0.19, 0.57%	7.1%	7.0%	7.0%	7.0%	0.07%	0.95%
.2	24.23	0.05, 0.23%	49.6%	1.73, 3.49%	8.5%	8.4%	8.3%	8.4%	0.07%	0.85%
.3	24.40	0.08, 0.34%	77.2%	1.68, 2.18%	12.0%	11.9%	11.8%	11.9%	0.09%	0.78%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	13.9%	13.9%	13.7%	13.8%	0.10%	0.70%
.5	24.44	0.13, 0.54%	98.0%	-	19.3%	19.2%	18.9%	19.1%	0.20%	1.04%

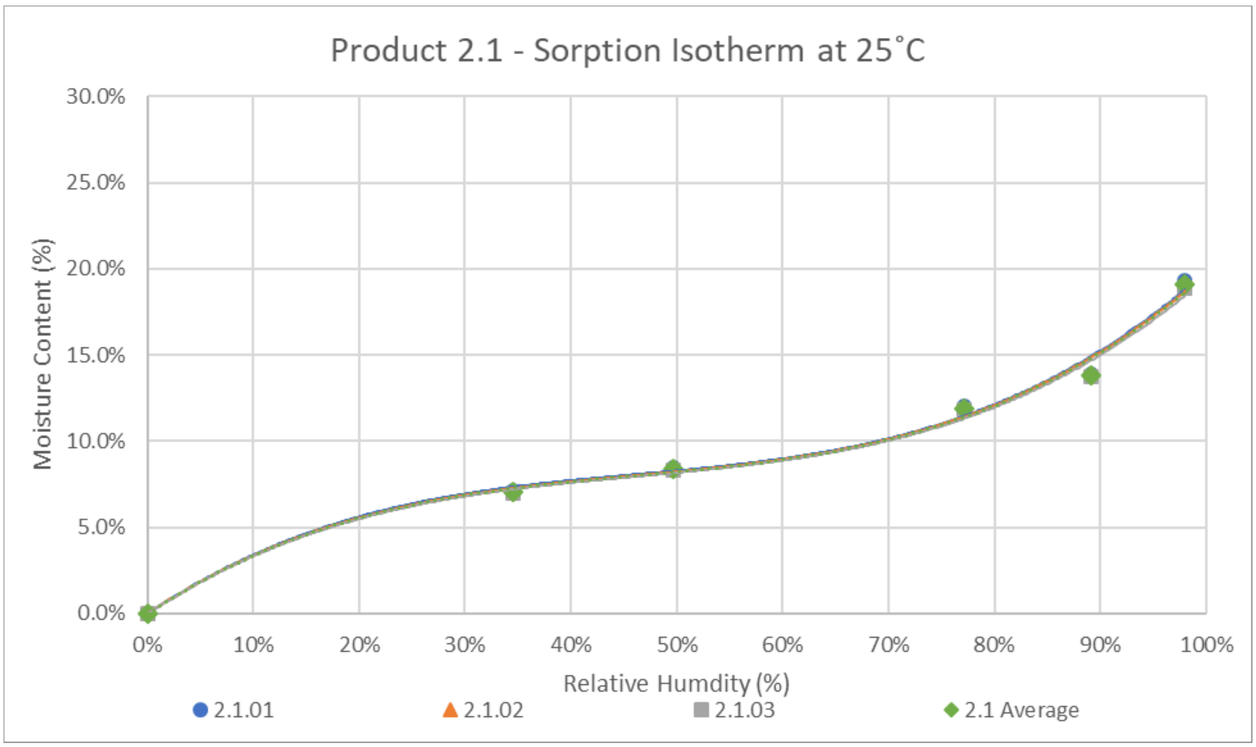


Figure C.2 - Product 2.1 Moisture Sorption Isotherm at 25˚C

Table C.3 – Moisture Contents for Specimens 2.2.04, 2.2.05, 2.2.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			2.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	2.2.01	2.2.02	2.2.03			
					MC(%)					
.1	24.21	0.03, 0.13%	34.5%	0.19, 0.57%	6.9%	6.9%	7.0%	6.9%	0.05%	0.67%
.2	24.23	0.05, 0.23%	49.6%	1.73, 3.49%	8.2%	8.3%	8.3%	8.3%	0.01%	0.17%
.3	24.40	0.08, 0.34%	77.2%	1.68, 2.28%	11.8%	11.8%	11.9%	11.9%	0.01%	0.12%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	13.7%	13.7%	13.7%	13.7%	0.01%	0.08%
.5	24.44	0.13, 0.54%	98.0%	-	18.9%	18.8%	18.8%	18.8%	0.05%	0.29%

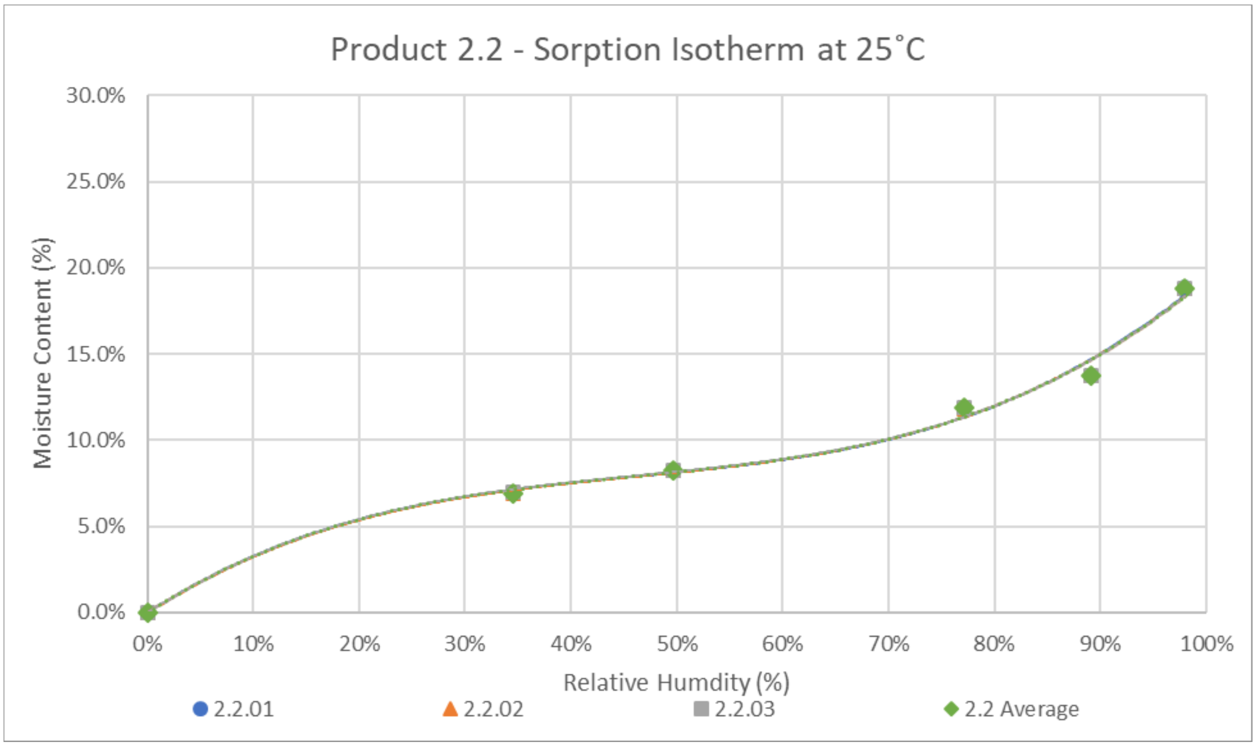


Figure C.3 - Product 2.2 Moisture Sorption Isotherm at 25˚C

Table C.4 – Moisture Contents for Specimens 3.1.04, 3.1.05, 3.1.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			3.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	3.1.01(*B*)	3.1.02(*B*)	3.1.03(*B*)			
					MC(%)					
.1	24.20	0.10, 0.43%	35.4%	1.59, 4.49%	*6.3%*	*6.4%*	*6.5%*	6.4%	0.07%	1.17%
.2	24.31	0.03, 0.14%	50.3%	0.08, 0.17%	*7.7%*	*7.9%*	*7.9%*	7.8%	0.09%	1.14%
.3	24.36	0.09, 0.35%	77.9%	1.96, 2.52%	*11.0%*	*11.2%*	*11.2%*	11.1%	0.10%	0.94%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	13.1%	13.3%	13.1%	13.2%	0.07%	0.55%
.5	24.44	0.13, 0.54%	98.0%	-	18.0%	18.1%	17.8%	18.0%	0.12%	0.68%

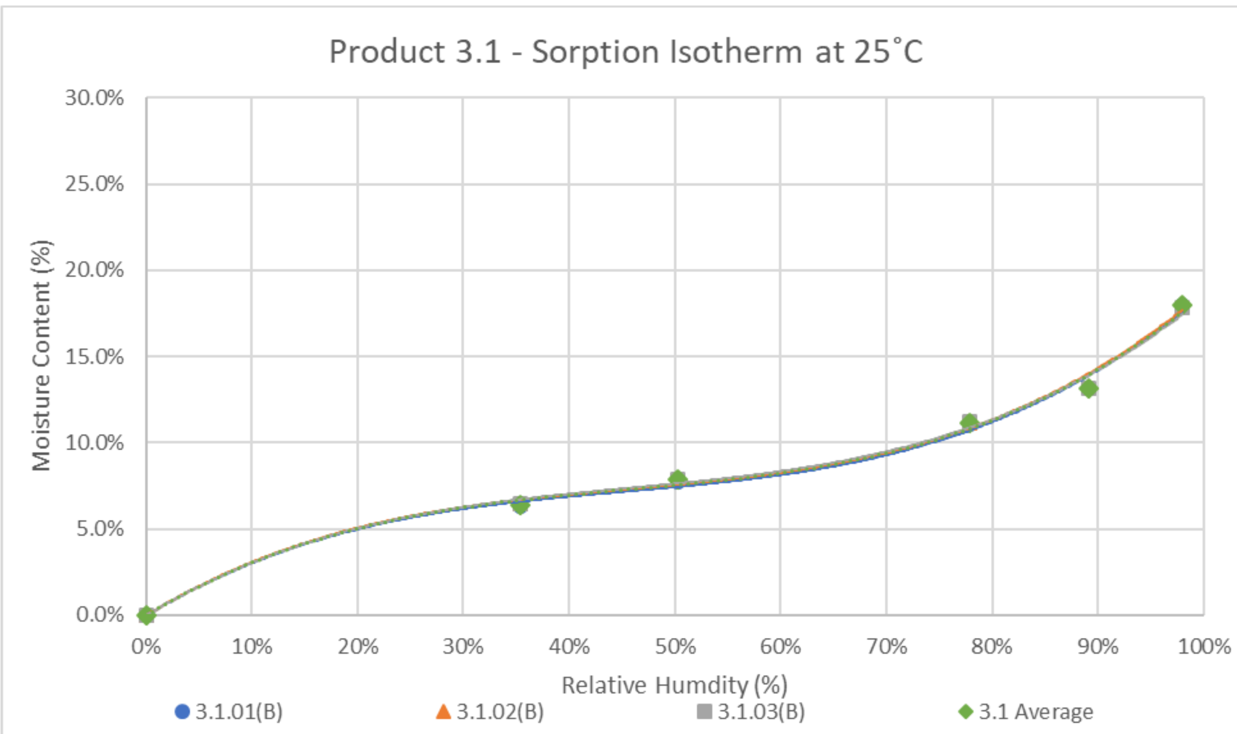


Figure C.4 - Product 3.1 Moisture Sorption Isotherm at 25˚C

Table C.5 – Moisture Contents for Specimens 4.1.04, 4.1.05, 4.1.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			4.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	4.1.01(*B*)	4.1.02(*B*)	4.1.03(*B*)			
					MC(%)					
.1	24.20	0.10, 0.43%	35.4%	1.59, 4.49%	*6.5%*	*6.4%*	*6.3%*	6.4%	0.08%	1.30%
.2	24.31	0.03, 0.14%	50.3%	0.08, 0.17%	*7.8%*	*7.8%*	*7.7%*	7.8%	0.09%	1.15%
.3	24.36	0.09, 0.35%	77.9%	1.96, 2.52%	*10.8%*	*10.7%*	*10.7%*	10.7%	0.06%	0.55%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	13.0%	12.9%	12.9%	12.9%	0.02%	0.14%
.5	24.44	0.13, 0.54%	98.0%	-	17.3%	18.0%	17.8%	17.7%	0.38%	2.16%

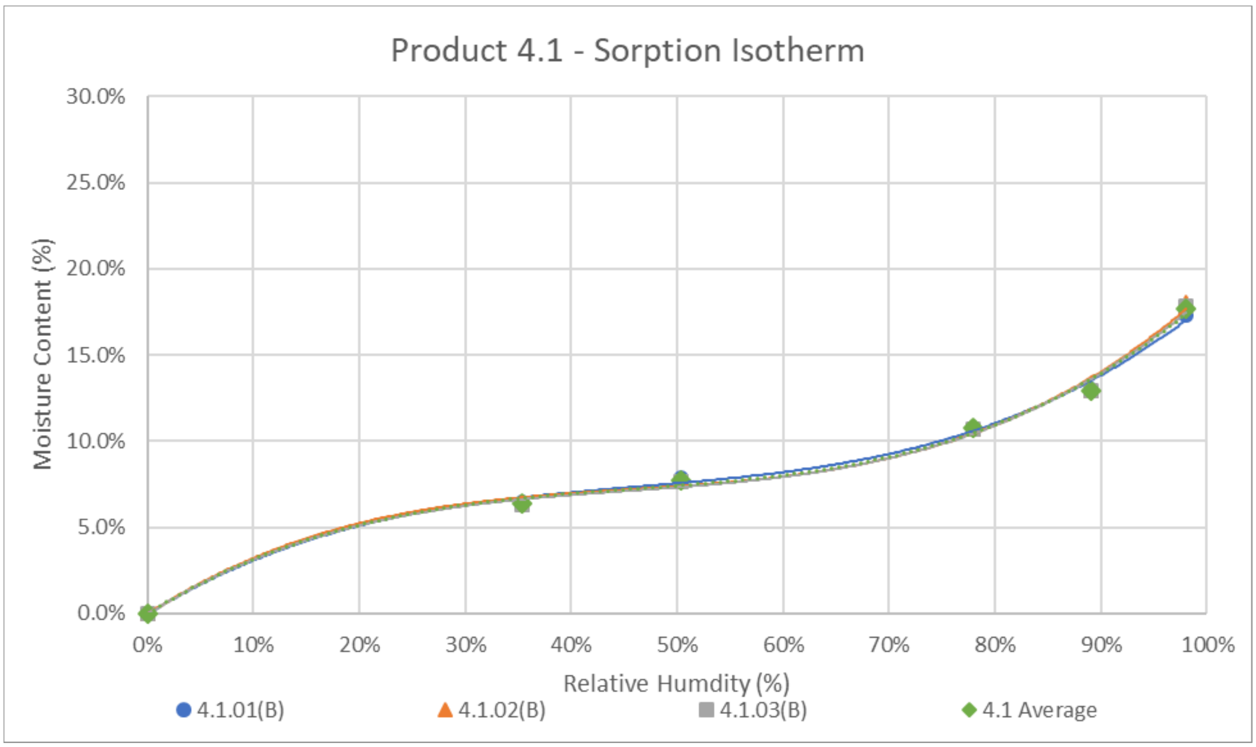


Figure C.5 - Product 4.1 Moisture Sorption Isotherm at 25˚C

Table C.6 – Moisture Contents for Specimens 4.2.04, 4.2.05, 4.2.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			4.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	4.2.01(*B*)	4.2.02(*B*)	4.2.03(*B*)			
					MC(%)					
.1	24.20	0.10, 0.43%	35.4%	1.59, 4.49%	*6.4%*	*6.5%*	*6.5%*	6.5%	0.03%	0.47%
.2	24.31	0.03, 0.14%	50.3%	0.08, 0.17%	*7.9%*	*7.9%*	*7.9%*	7.9%	0.03%	0.41%
.3	24.36	0.09, 0.35%	77.9%	1.96, 2.52%	*11.1%*	*11.3%*	*11.2%*	11.2%	0.08%	0.73%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	13.3%	13.4%	13.3%	13.3%	0.05%	0.36%
.5	24.44	0.13, 0.54%	98.0%	-	18.3%	18.3%	17.9%	18.1%	0.23%	1.25%

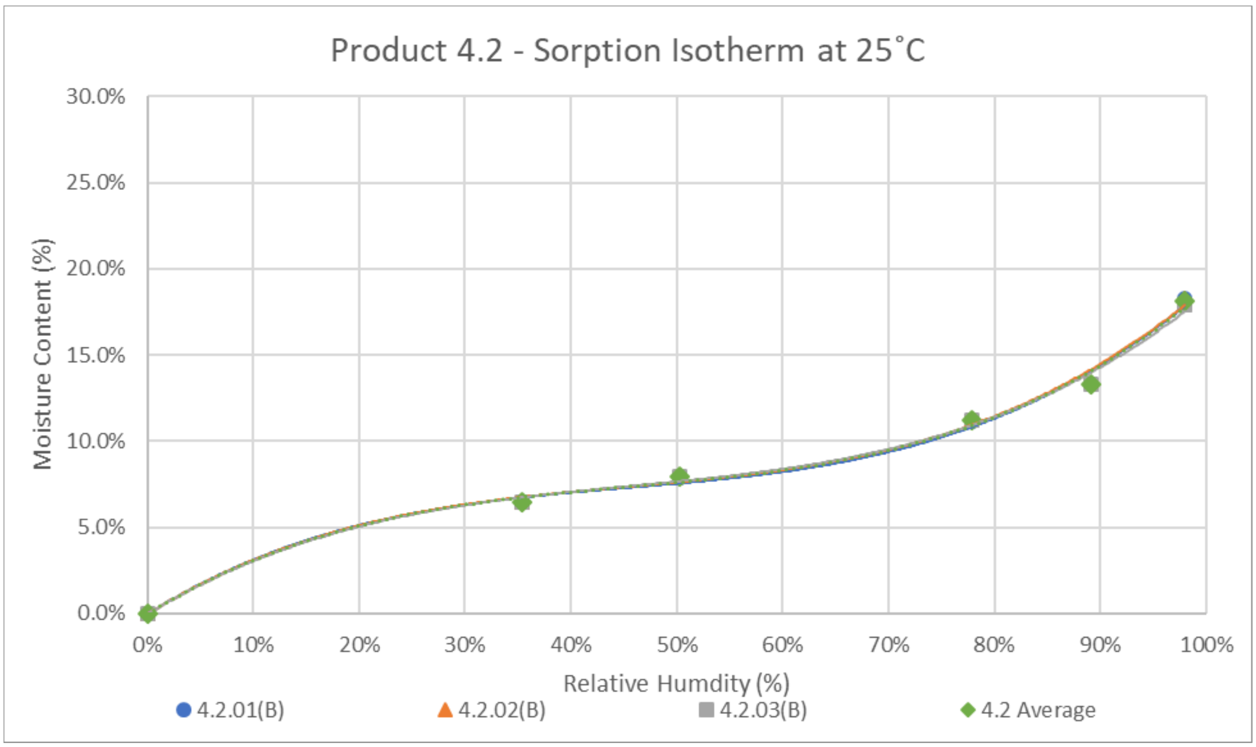


Figure C.6 - Product 4.2 Moisture Sorption Isotherm at 25˚C

Table C.7 – Moisture Contents for Specimens 5.2.04, 5.2.05, 5.2.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			5.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	5.2.01(*B*)	5.2.02(*B*)	5.2.03(*B*)			
					MC(%)					
.1	24.20	0.10, 0.43%	35.4%	1.59, 4.49%	6.9%	6.8%	6.8%	6.8%	0.08%	1.15%
.2	24.31	0.03, 0.14%	50.3%	0.08, 0.17%	8.4%	8.3%	8.4%	8.4%	0.07%	0.80%
.3	24.36	0.09, 0.35%	77.9%	1.96, 2.52%	11.8%	11.8%	11.8%	11.8%	0.04%	0.35%
.4	24.28	1.07, 4.41%	89.2%	1.75, 1.96%	14.0%	13.9%	13.9%	13.9%	0.05%	0.34%
.5	25.00*	-	98.0%	-	19.4%	19.2%	19.3%	19.3%	0.12%	0.60%

*data was not collected for the duration of this test step.

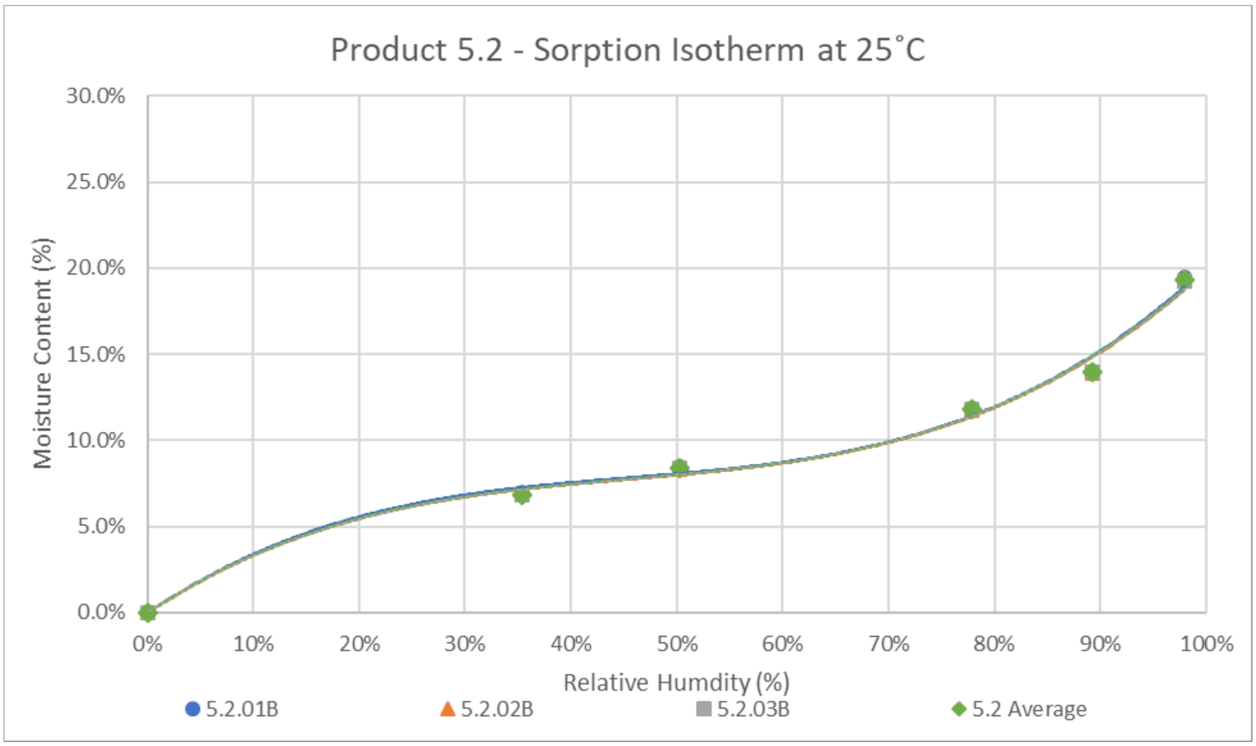


Figure C.7 - Product 5.2 Moisture Sorption Isotherm at 25˚C.

Table C.8 – Moisture Contents for Specimens 5.3.04, 5.3.05, 5.3.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			5.3 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	5.3.01(*B*)	5.3.02(*B*)	5.3.03(*B*)			
					MC(%)					
.1	24.20	0.10, 0.43%	35.4%	1.59, 4.49%	9.1%	9.2%	9.3%	9.2%	0.07%	0.77%
.2	24.31	0.03, 0.14%	50.3%	0.08, 0.17%	11.0%	11.0%	11.1%	11.0%	0.06%	0.58%
.3	24.36	0.09, 0.35%	77.9%	1.96, 2.52%	15.6%	15.6%	15.7%	15.6%	0.07%	0.47%
.4	24.28	1.07, 4.41%	89.2%	1.75, 1.96%	19.4%	19.4%	19.5%	19.4%	0.08%	0.42%
.5	25.00*	-	98.0%*	-	27.3%	27.1%	27.2%	27.2%	0.13%	0.46%

*data was not collected for the duration of this test step.

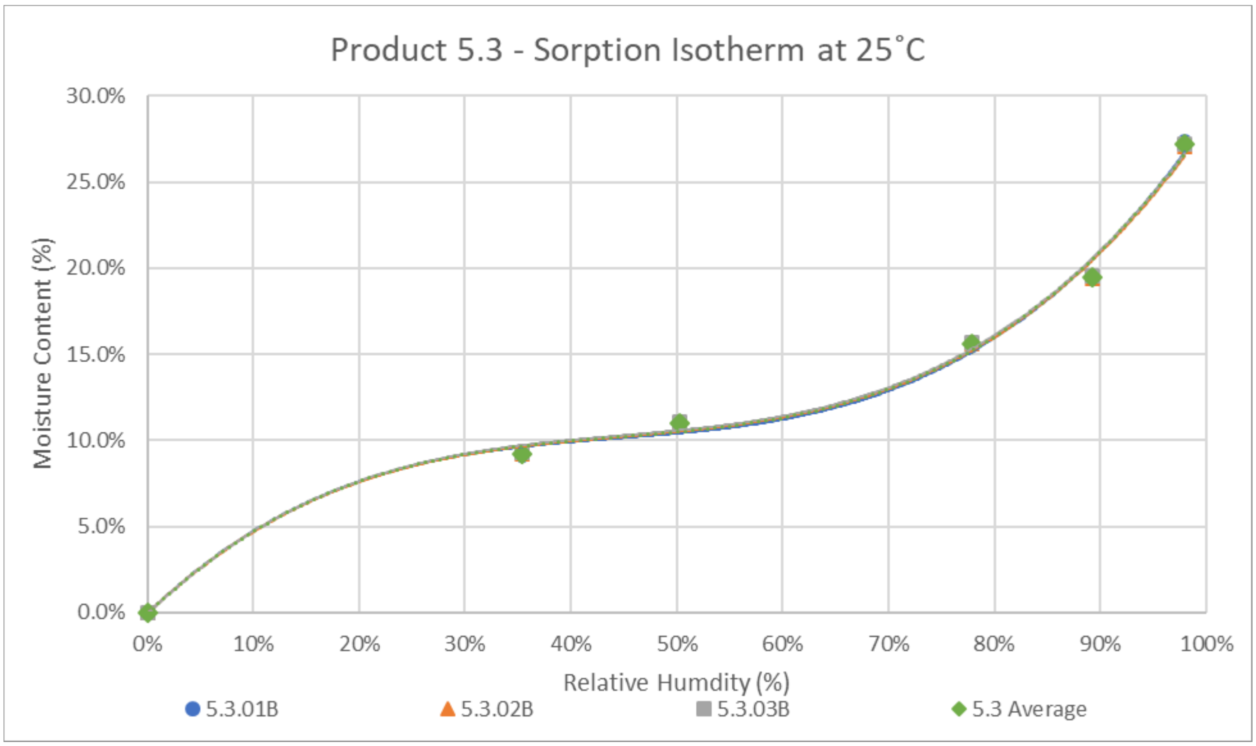


Figure C.8 – Product 5.3 Moisture Sorption Isotherm at 25˚C.

Table C.9 – Moisture Contents for Specimens 6.2.04, 6.2.05, 6.2.06, and Average over Full Relative Humidity Range at 25˚C.

Test No.	Temp		RH		Specimen			6.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	6.2.01	6.2.02	6.2.03			
					MC(%)					
.1	24.21	0.03, 0.13%	34.5%	0.19, 0.57%	6.9%	6.9%	6.9%	6.9%	0.02%	0.27%
.2	24.23	0.05, 0.23%	49.6%	1.73, 3.49%	8.4%	8.3%	8.3%	8.3%	0.05%	0.58%
.3	24.40	0.08, 0.34%	77.2%	1.68, 6.28%	11.6%	11.5%	11.5%	11.5%	0.07%	0.60%
.4	24.44	0.15, 0.62%	89.1%	2.66, 2.99%	14.3%	14.2%	14.2%	14.2%	0.07%	0.46%
.5	24.44	0.13, 0.54%	98.0%	-	19.2%	19.1%	18.9%	19.0%	0.14%	0.73%

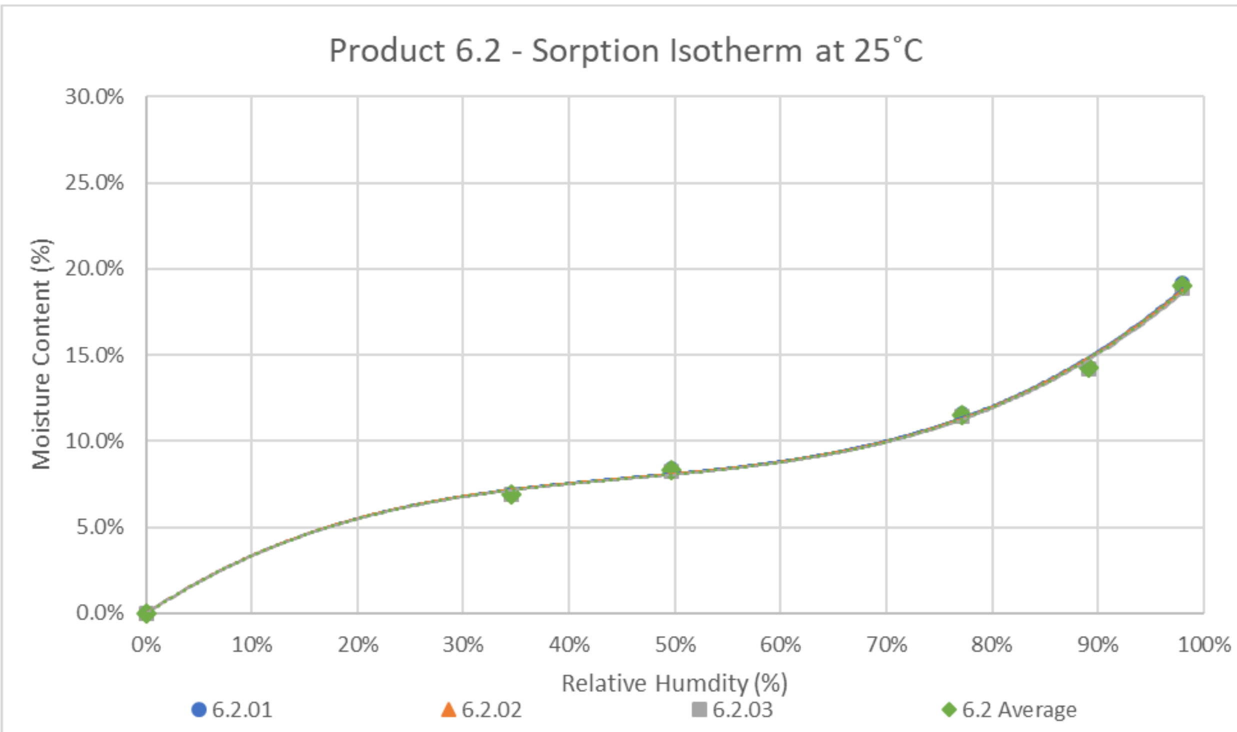


Figure C.9 - Product 6.2 Moisture Sorption Isotherm at 25˚C.

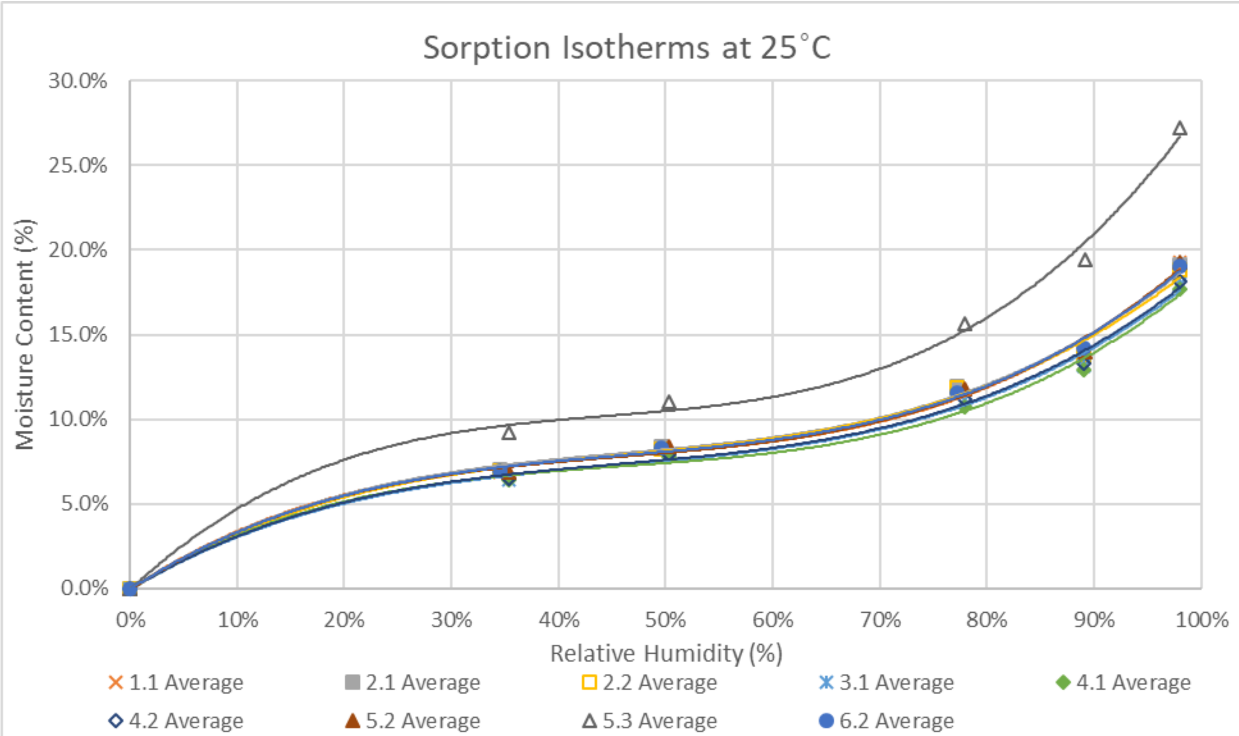


Figure C.10 – All Products Moisture Sorption Isotherm at 25˚C.

Table C.10 – Volumetric Moisture Contents for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen			1.1 Average	VMC SD	VMC CV(%)
			1.1.01	1.1.02	1.1.03			
			Volumetric MC ($kg_w/m^3{}_{WFIB}$)					
.1	24.21	34.5%	9.31	9.46	8.89	9.22	0.30	3.22%
.2	24.23	49.6%	11.15	11.43	10.57	11.05	0.44	3.95%
.3	24.4	77.2%	15.77	15.96	14.82	15.51	0.61	3.93%
.4	24.44	89.1%	18.96	19.18	17.65	18.59	0.83	4.45%
.5	24.44	98.0%	25.98	26.27	25.08	25.78	0.62	2.42%

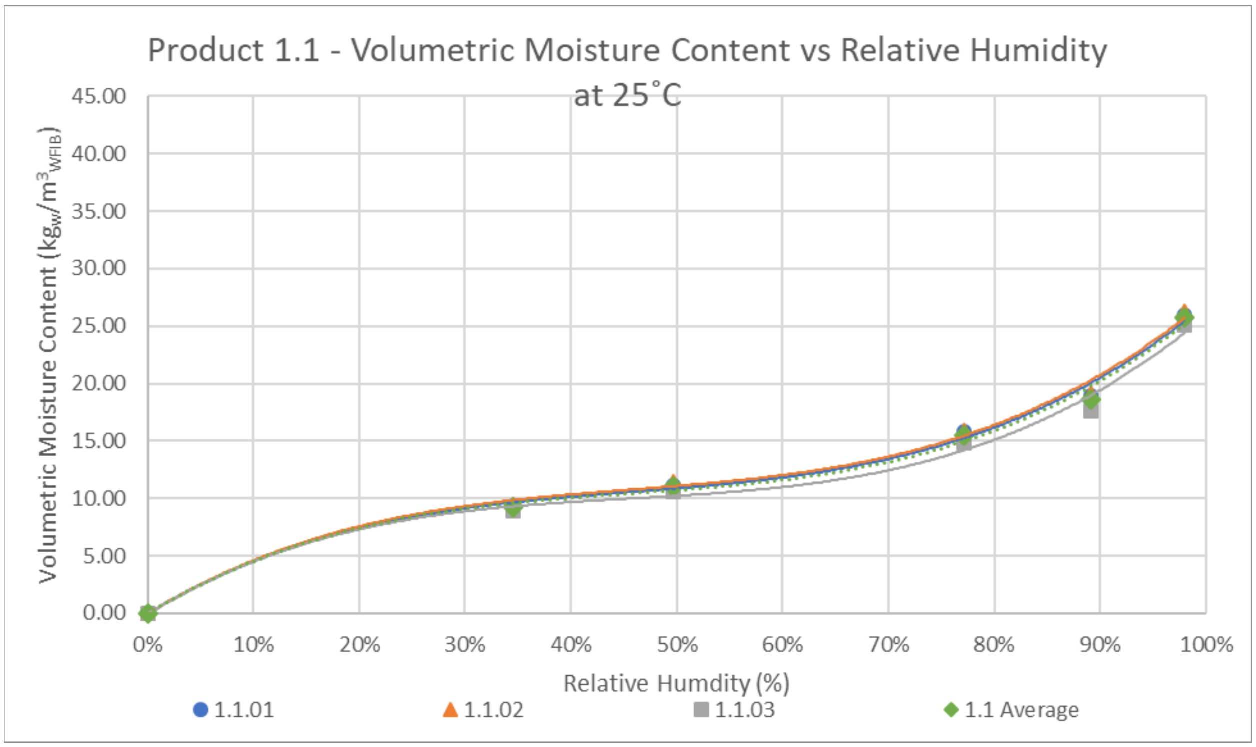


Figure C.11 – Product 1.1 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.11 – Volumetric Moisture Contents for Specimens 2.1.01, 2.1.02, 2.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 2.1.01	Specimen 2.1.02	Specimen 2.1.03	2.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.21	34.5%	9.86	10.01	9.84	9.90	0.09	0.92%
.2	24.23	49.6%	11.74	11.90	11.74	11.80	0.09	0.78%
.3	24.4	77.2%	16.65	16.98	16.67	16.76	0.18	1.09%
.4	24.44	89.1%	19.32	19.72	19.38	19.47	0.21	1.10%
.5	24.44	98.0%	26.77	27.25	26.67	26.90	0.31	1.14%

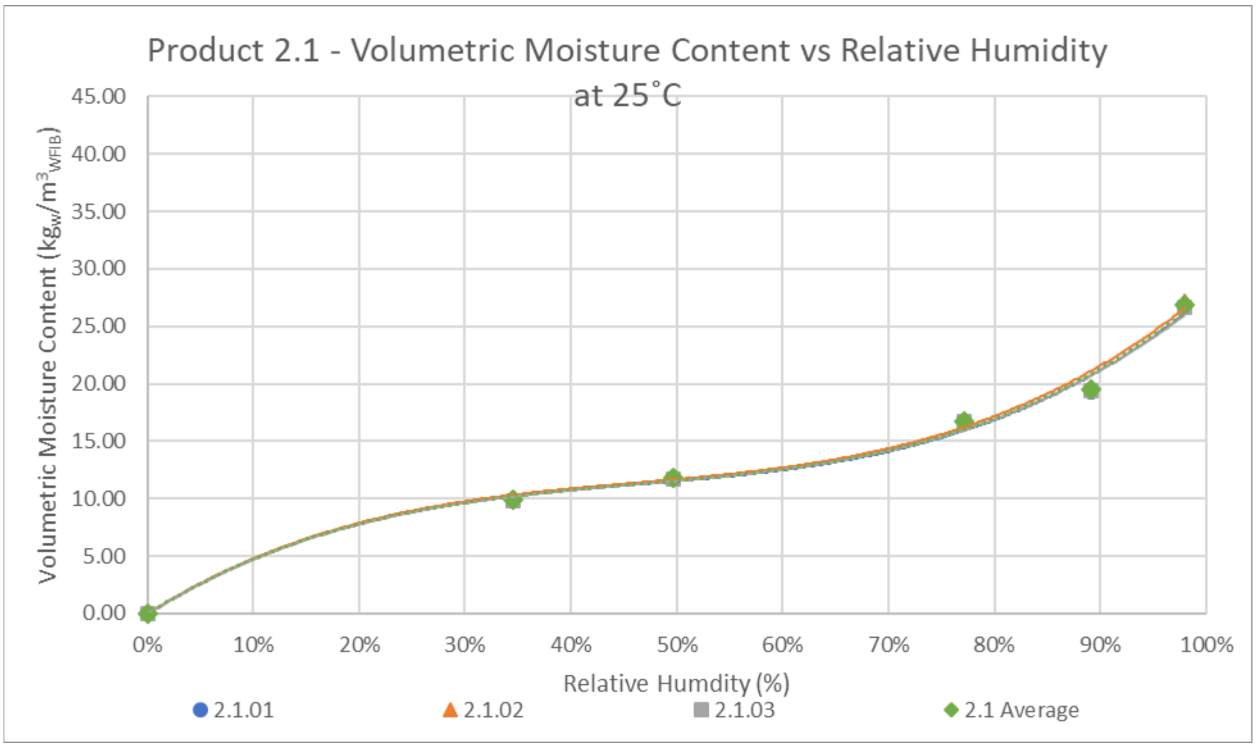


Figure C.12 – Product 2.1 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.12 – Volumetric Moisture Contents for Specimens 2.2.01, 2.2.02, 2.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 2.2.01	Specimen 2.2.02	Specimen 2.2.03	2.2 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.21	34.5%	11.17	11.06	10.05	10.76	0.62	5.76%
.2	24.23	49.6%	13.32	13.31	11.92	12.85	0.81	6.29%
.3	24.4	77.2%	19.15	19.06	17.12	18.44	1.15	6.22%
.4	24.44	89.1%	22.20	22.06	19.80	21.35	1.35	6.32%
.5	24.44	98.0%	30.50	30.24	27.06	29.27	1.91	6.54%

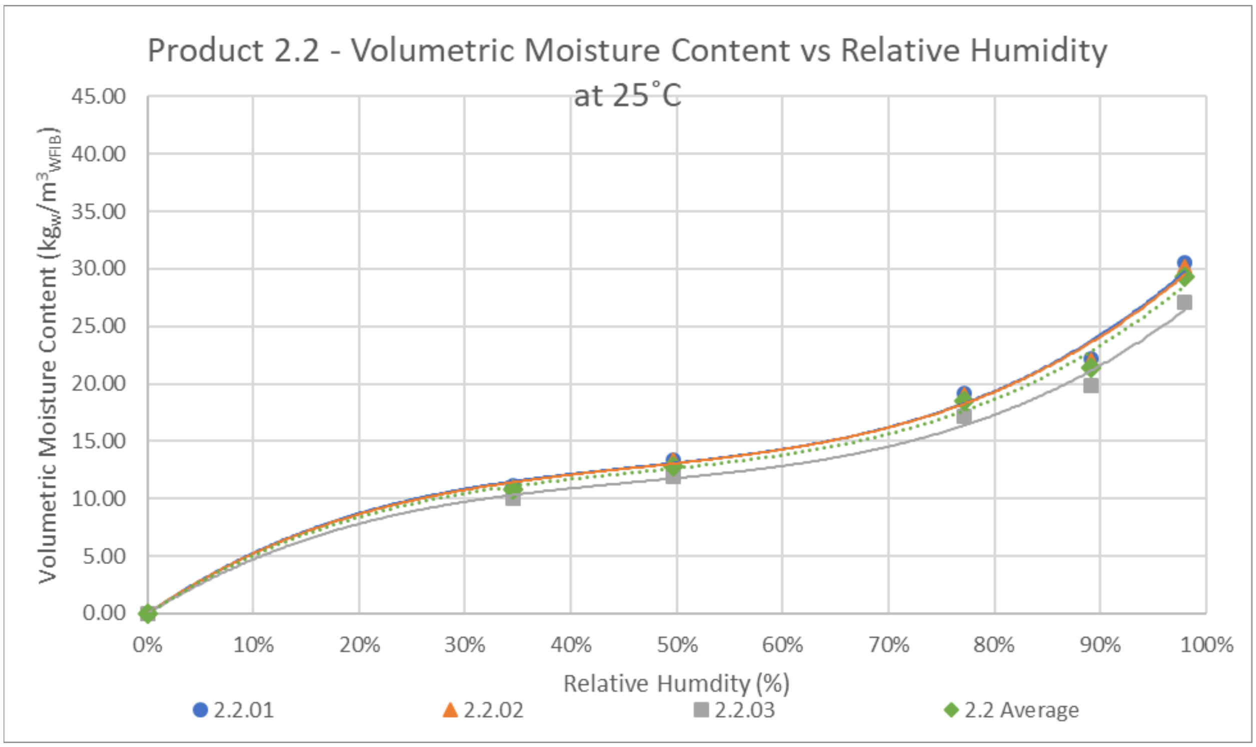


Figure C.13 – Product 2.2 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.13 – Volumetric Moisture Contents for Specimens 3.1.01, 3.1.02, 3.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 3.1.01(*B*)	Specimen 3.1.02(*B*)	Specimen 3.1.03(*B*)	3.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.20	35.4%	*5.93*	*6.06*	*5.96*	5.98	0.07	1.16%
.2	24.31	50.3%	*7.27*	*7.42*	*7.30*	7.33	0.08	1.10%
.3	24.36	77.9%	*10.37*	*10.55*	*10.37*	10.43	0.10	0.96%
.4	24.44	89.1%	12.64	12.56	12.47	12.56	0.08	0.67%
.5	24.44	98.0%	17.27	17.13	16.97	17.12	0.15	0.87%

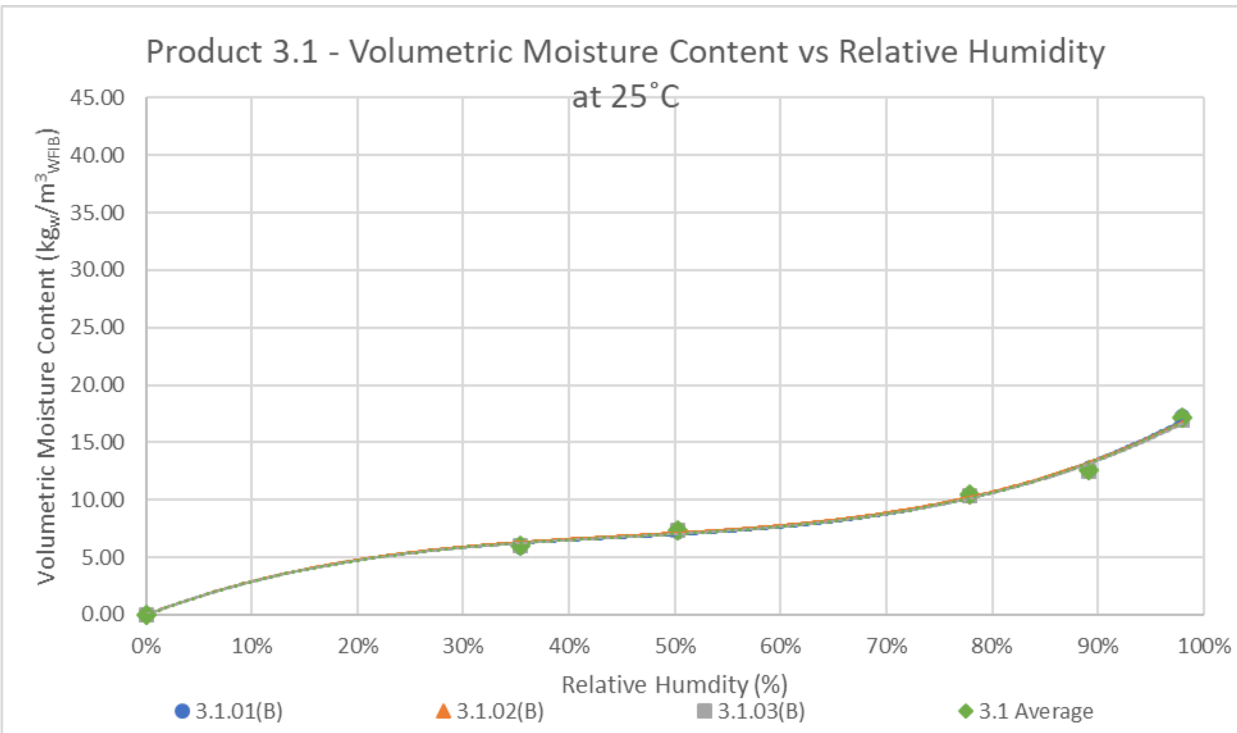


Figure C.14 – Product 3.1 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.14 – Volumetric Moisture Contents for Specimens 4.1.01, 4.1.02, 4.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 4.1.01(*B*)	Specimen 4.1.02(*B*)	Specimen 4.1.03(*B*)	4.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.20	35.4%	*12.32*	*12.19*	*11.57*	12.03	0.40	3.35%
.2	24.31	50.3%	*14.89*	*14.80*	*14.02*	14.57	0.48	3.28%
.3	24.36	77.9%	*20.50*	*20.43*	*19.54*	20.16	0.54	2.66%
.4	24.44	89.1%	25.61	25.20	23.53	24.78	1.10	4.45%
.5	24.44	98.0%	34.15	35.16	32.37	33.89	1.42	4.18%

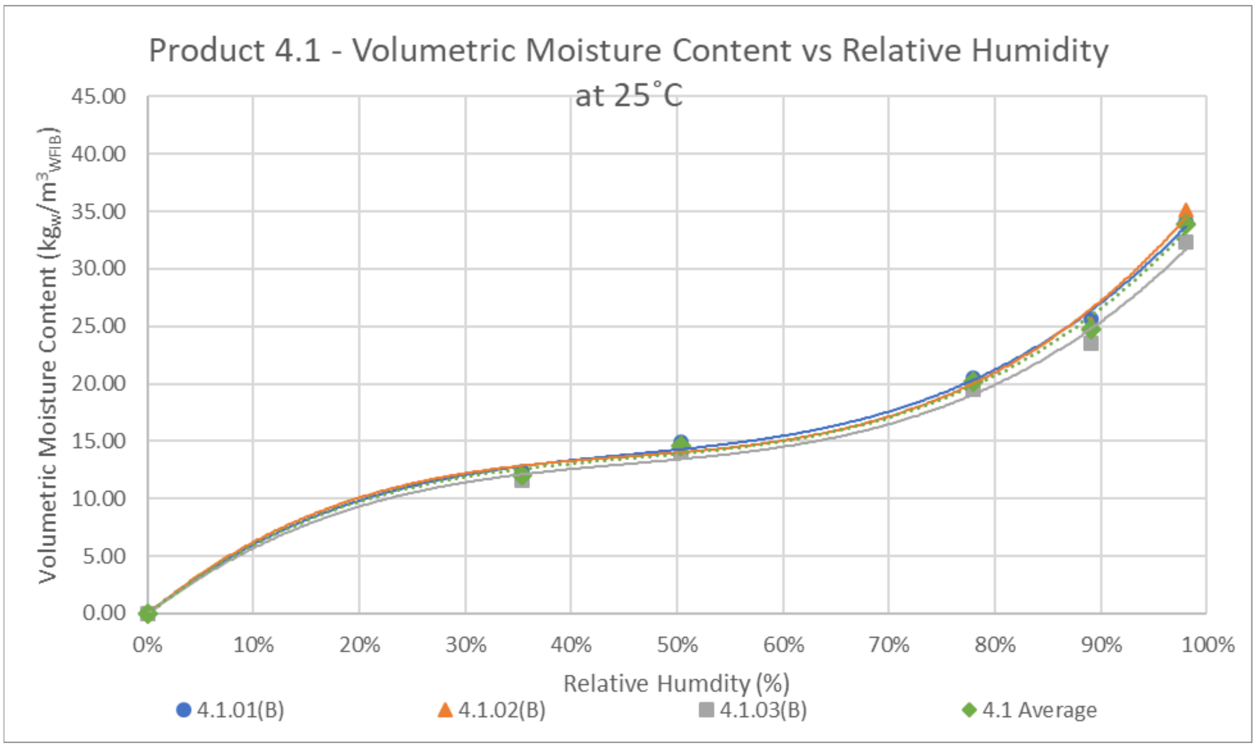


Figure C.15 – Product 4.1 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.15 – Volumetric Moisture Contents for Specimens 4.2.01, 4.2.02, 4.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 4.2.01(*B*)	4.2.02(*B*)	4.2.03(*B*)	4.2 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.20	35.4%	*10.76*	*10.64*	*10.70*	10.70	0.06	0.55%
.2	24.31	50.3%	*13.20*	*13.03*	*13.11*	13.11	0.09	0.66%
.3	24.36	77.9%	*18.63*	*18.54*	*18.53*	18.56	0.05	0.28%
.4	24.44	89.1%	22.72	22.15	22.16	22.34	0.32	1.45%
.5	24.44	98.0%	31.13	30.25	29.80	30.39	0.68	2.23%

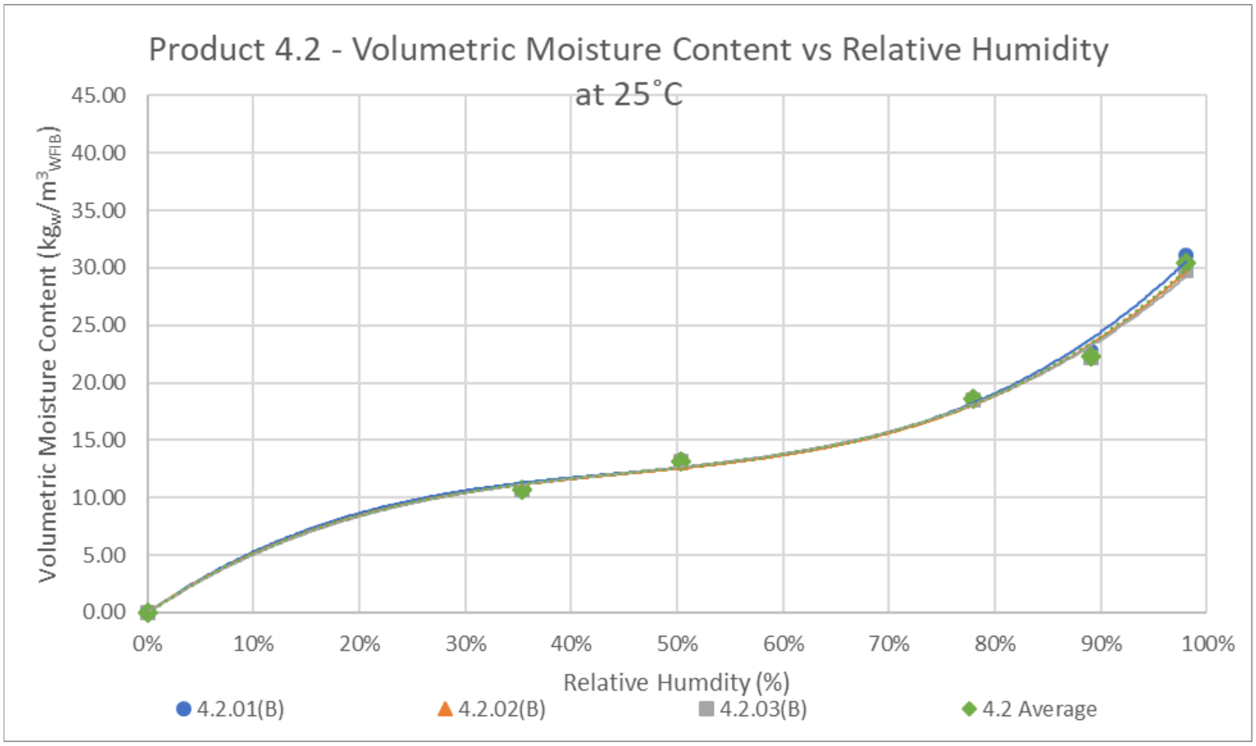


Figure C.16 – Product 4.2 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.16 – Volumetric Moisture Contents for Specimens 5.2.01, 5.2.02, 5.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 5.2.01(*B*)	Specimen 5.2.02(*B*)	Specimen 5.2.03(*B*)	5.2 Average	VMC SD	VMC CV(%)
			Volumetric MC ($kg_w/m^3{}_{WFIB}$)					
.1	25.20	35.4%	9.45	9.50	9.45	9.47	0.03	0.32%
.2	24.31	50.3%	11.50	11.61	11.63	11.58	0.07	0.60%
.3	24.36	77.9%	16.12	16.43	16.37	16.31	0.16	1.00%
.4	24.28	89.2%	19.06	19.42	19.37	19.28	0.20	1.02%
.5	25.00*	98.0%	26.46	26.84	26.76	26.69	0.20	0.75%

*data was not collected for the duration of this test step.

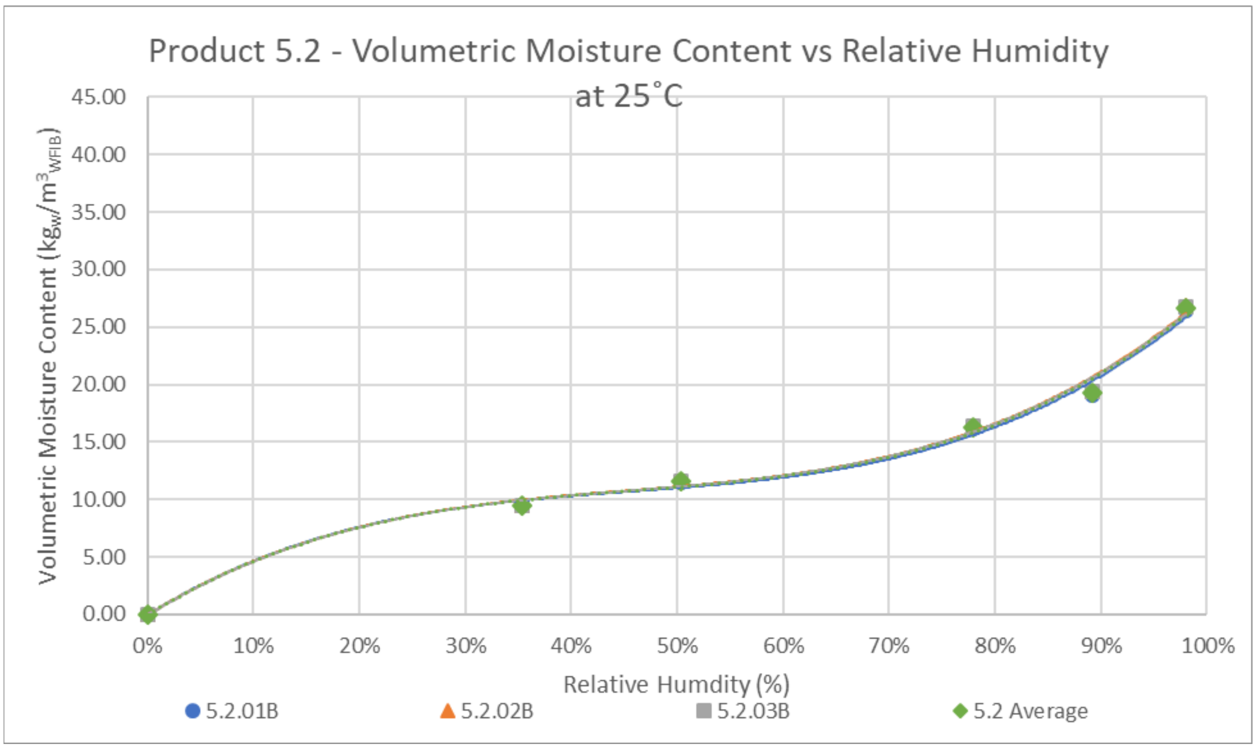


Figure C.17 – Product 5.2 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.17 – Volumetric Moisture Contents for Specimens 5.3.01, 5.3.02, 5.3.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 5.3.01(*B*)	Specimen 5.3.02(*B*)	Specimen 5.3.03(*B*)	5.3 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	25.30	35.4%	13.26	13.64	13.81	13.57	0.28	2.05%
.2	24.31	50.3%	15.91	16.26	16.50	16.22	0.29	1.81%
.3	24.36	77.9%	22.58	23.11	23.37	23.02	0.40	1.74%
.4	24.28	89.2%	28.15	28.74	29.09	28.66	0.48	1.66%
.5	25.00*	98.0%	39.70	40.09	40.55	40.11	0.43	1.06%

*data was not collected for the duration of this test step.

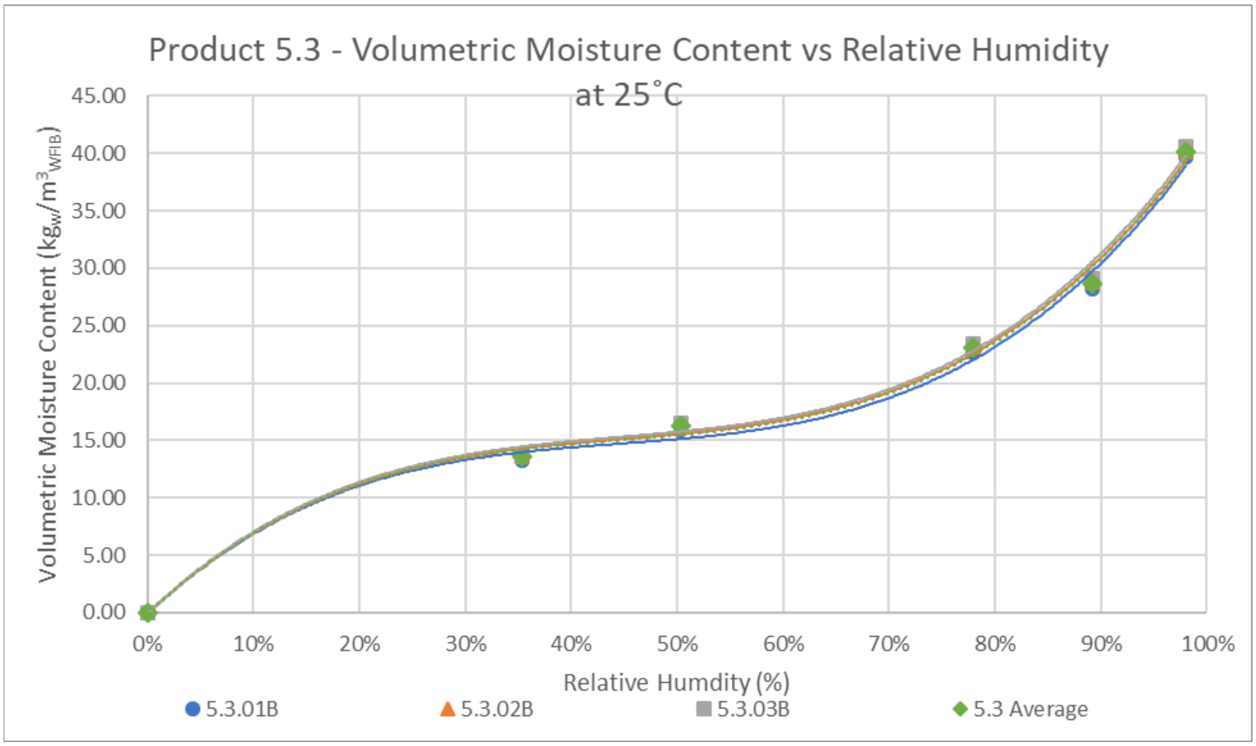


Figure C.18 – Product 5.3 Volumetric Moisture Content versus Relative Humidity at 25˚C.

Table C.18 – Volumetric Moisture Contents for Specimens 6.2.01, 6.2.02, 6.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen			6.2 Average	VMC SD	VMC CV(%)
			6.2.01	6.2.02	6.2.03			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	24.21	34.5%	11.40	11.58	11.45	11.48	0.09	0.83%
.2	24.23	49.6%	13.76	13.95	13.73	13.82	0.12	0.87%
.3	24.4	77.2%	19.05	19.30	19.00	19.12	0.16	0.82%
.4	24.44	89.1%	23.50	23.83	23.50	23.61	0.19	0.81%
.5	24.44	98.0%	31.50	31.92	31.34	31.58	0.30	0.95%

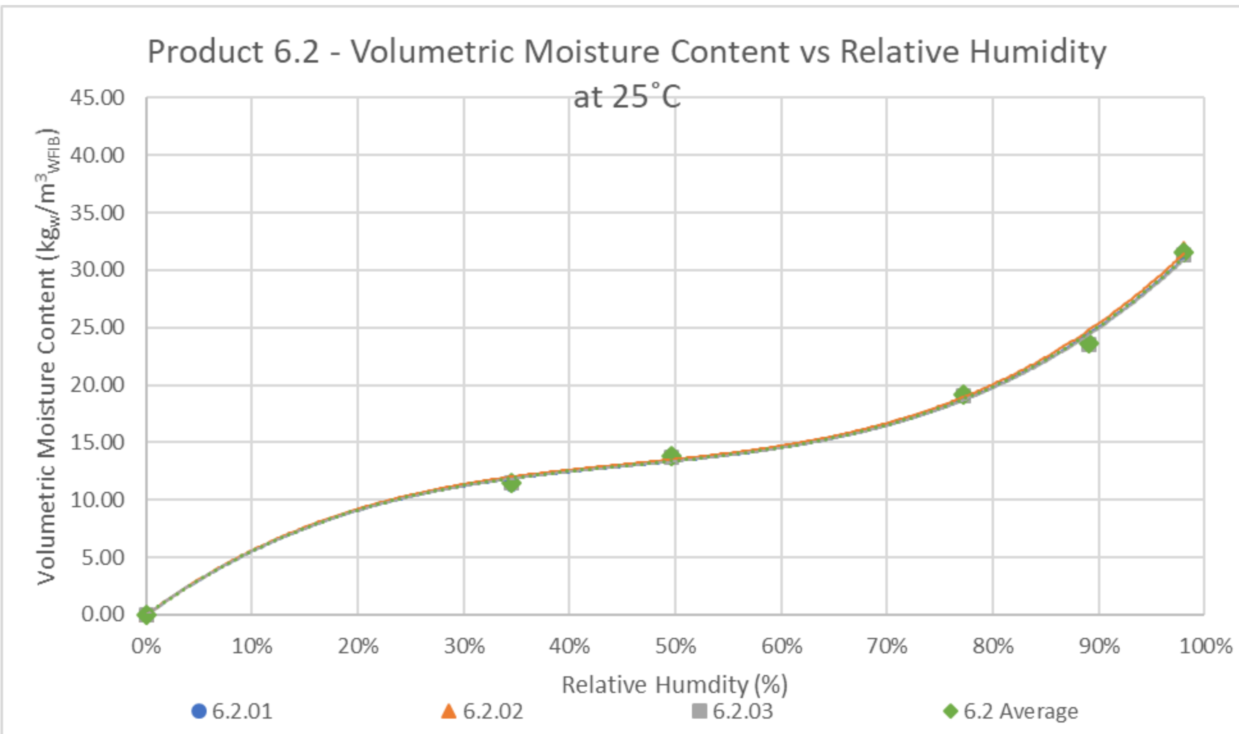


Figure C.19 – Product 6.2 Volumetric Moisture Content versus Relative Humidity at 25˚C.

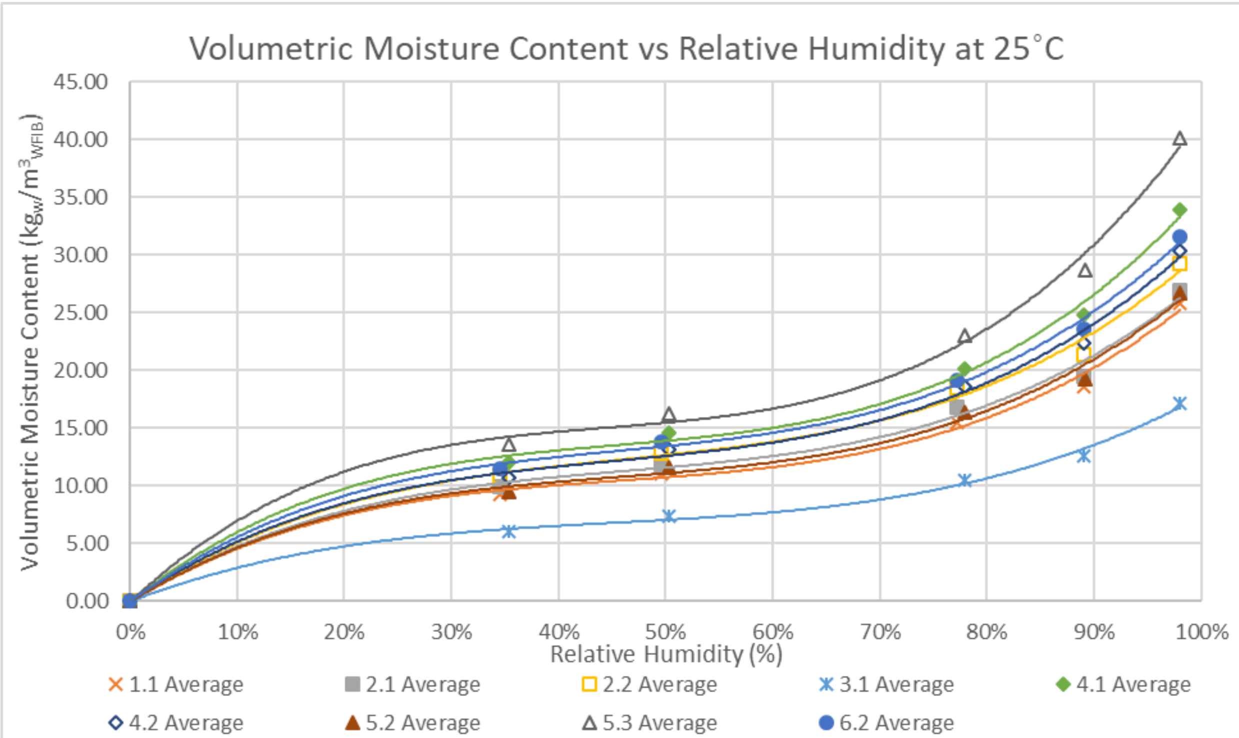


Figure C.20 – Product 2.2 Volumetric Moisture Content versus Relative Humidity at 25˚C.

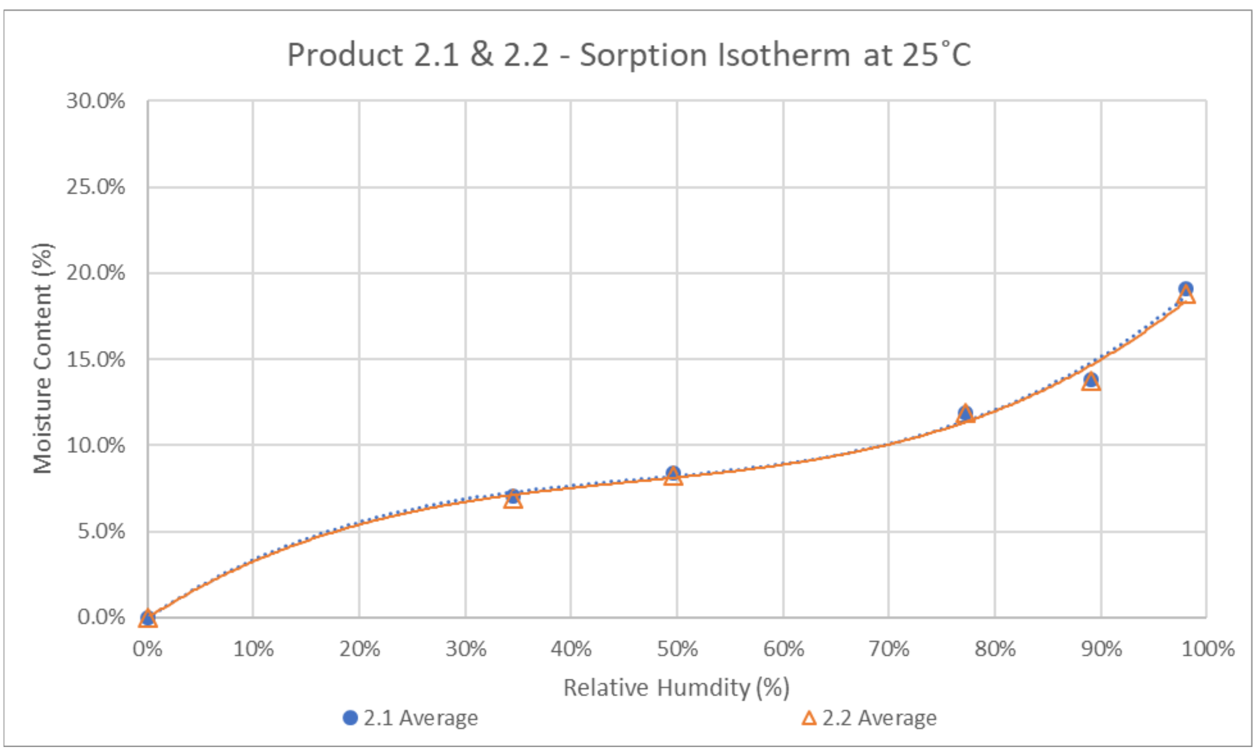


Figure C.21 – Product 2.1 and 2.2 Moisture Sorption Isotherm at 25˚C.

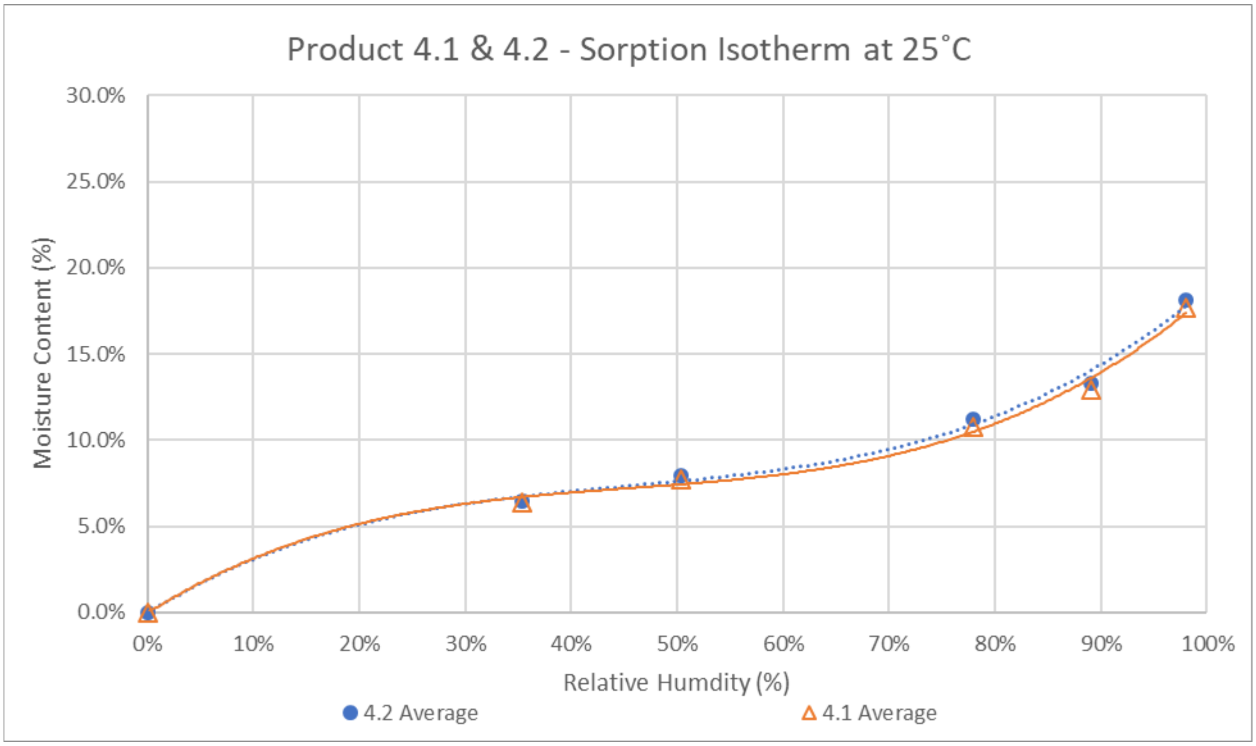


Figure C.22 – Product 4.1 and 4.2 Moisture Sorption Isotherm at 25˚C.

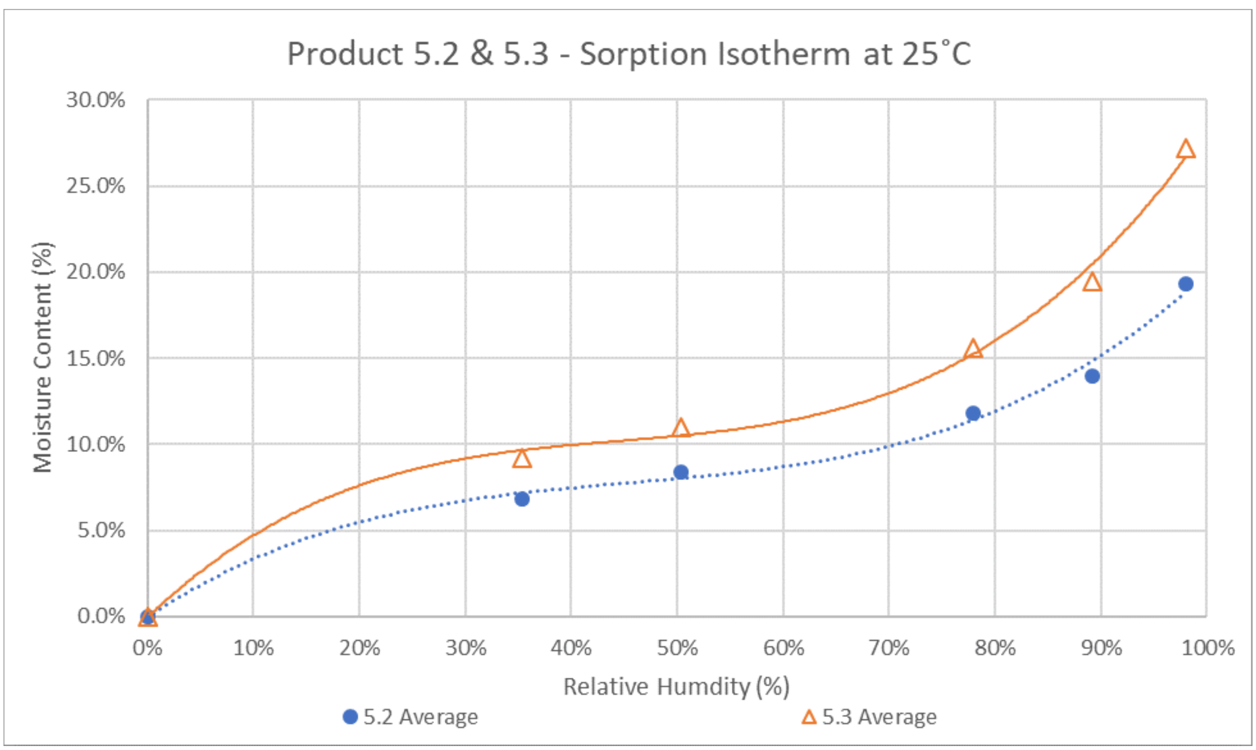


Figure C.23 – Product 5.2 and 5.3 Moisture Sorption Isotherm at 25˚C.

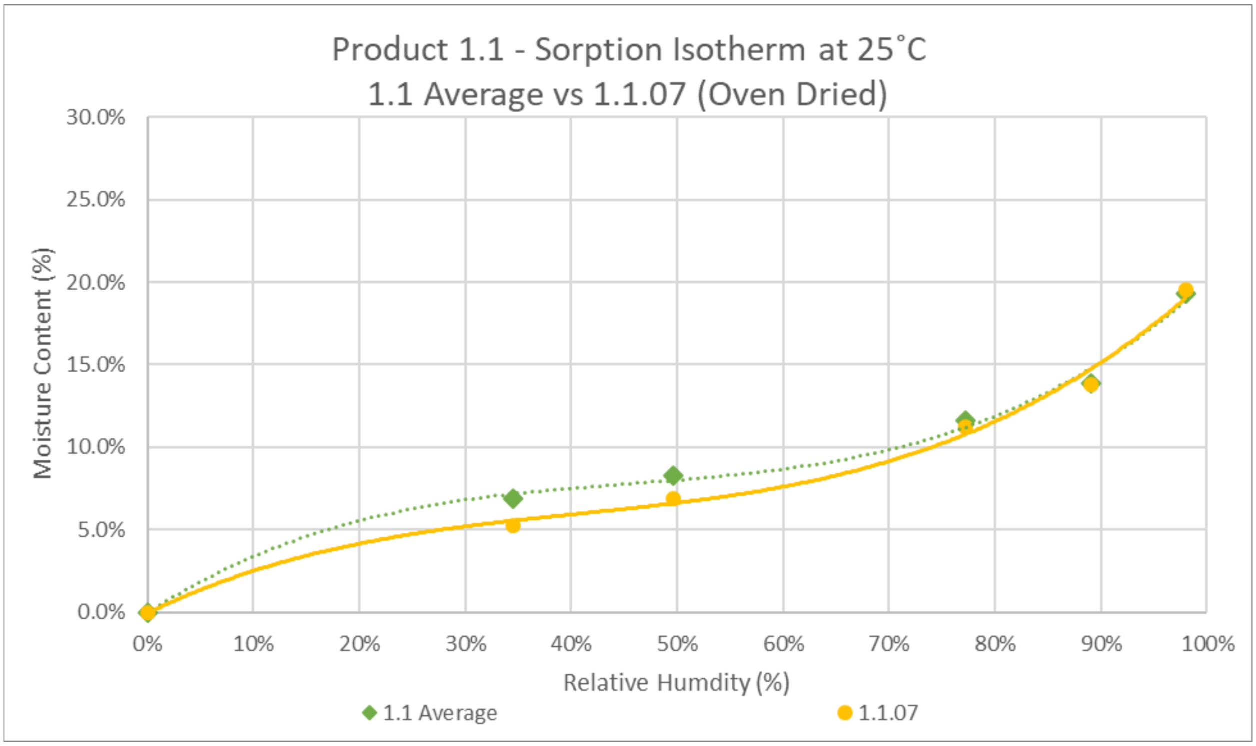


Figure C.24 – Product 1.1 Average and Oven Dried Specimen 1.1.07 Moisture Sorption Isotherm at 25˚C.

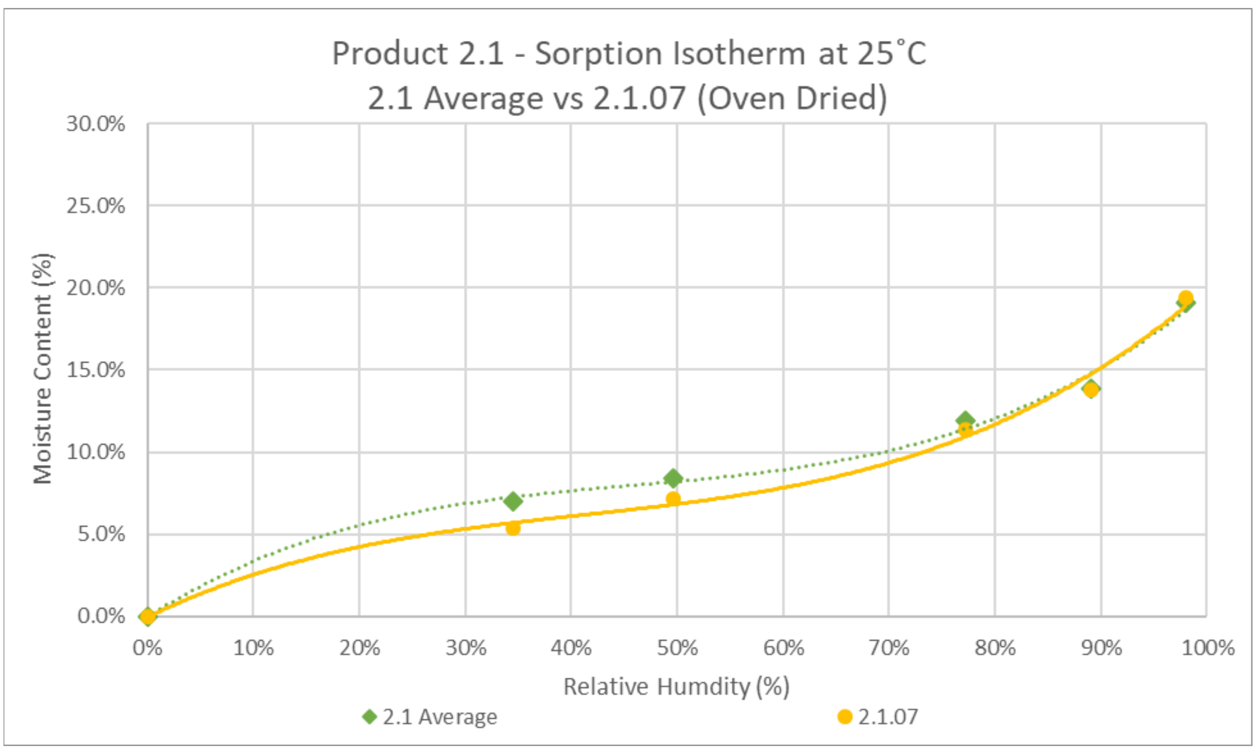


Figure C.25 – Product 2.1 Average and Oven Dried Specimen 2.1.07 Moisture Sorption Isotherm at 25˚C.

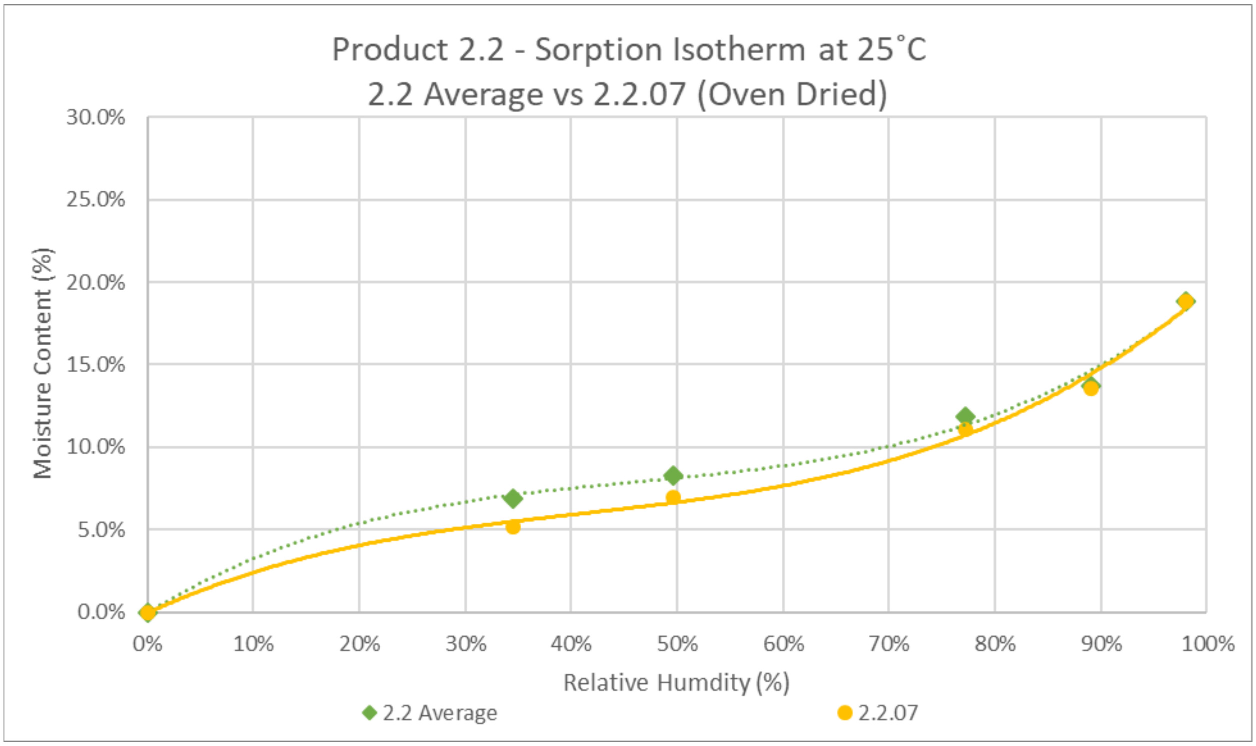


Figure C.26 – Product 2.2 Average and Oven Dried Specimen 2.2.07 Moisture Sorption Isotherm at 25˚C.

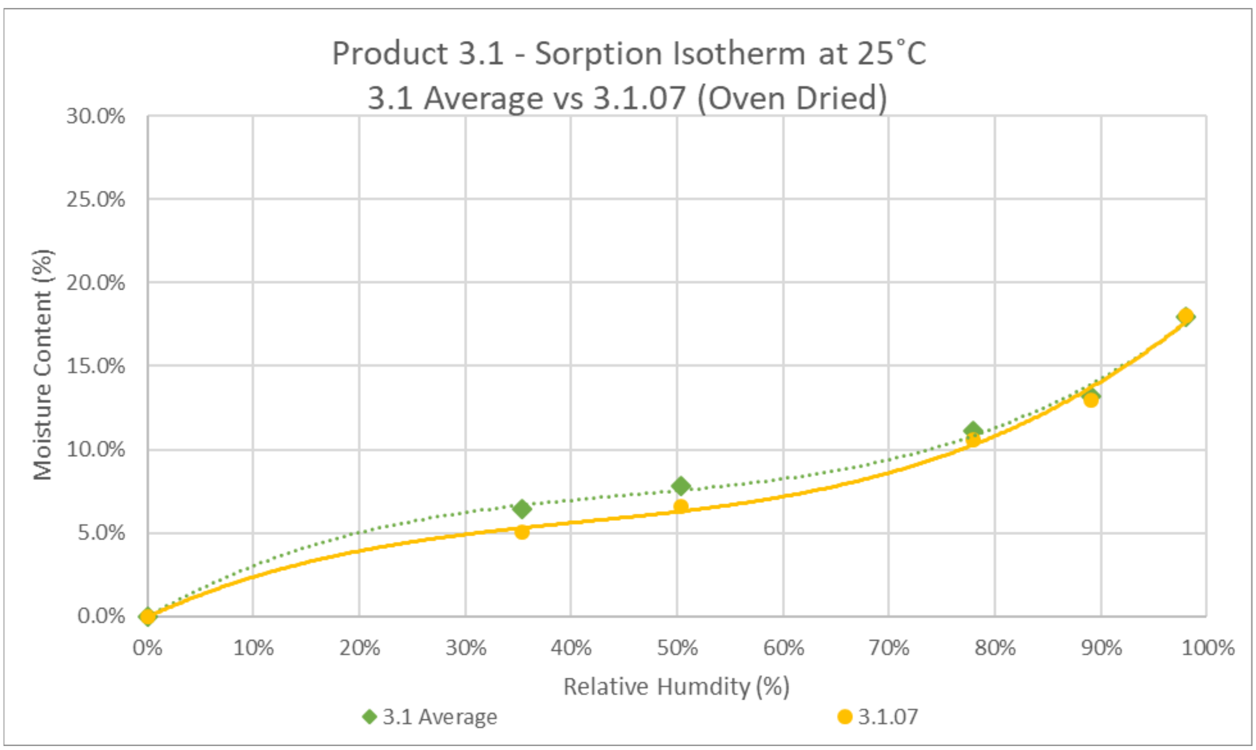


Figure C.27 – Product 3.1 Average and Oven Dried Specimen 3.1.07 Moisture Sorption Isotherm at 25˚C.

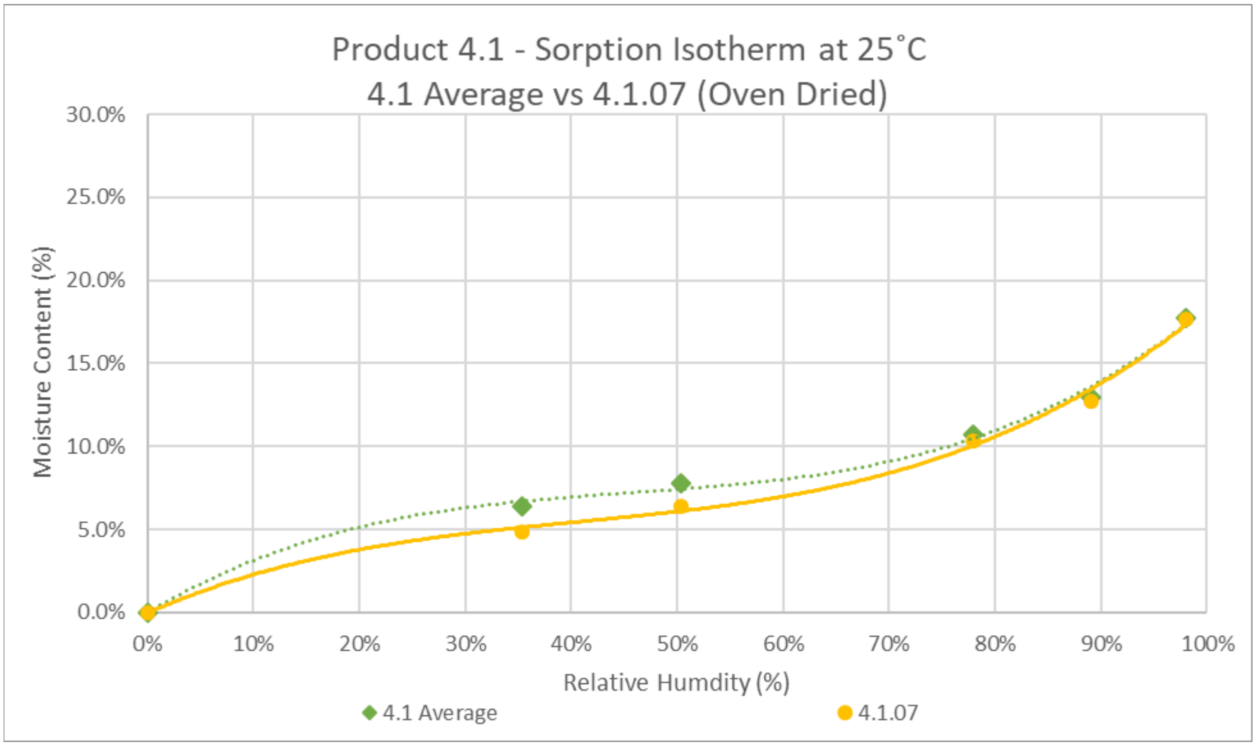


Figure C.28 – Product 4.1 Average and Oven Dried Specimen 4.1.07 Moisture Sorption Isotherm at 25˚C.

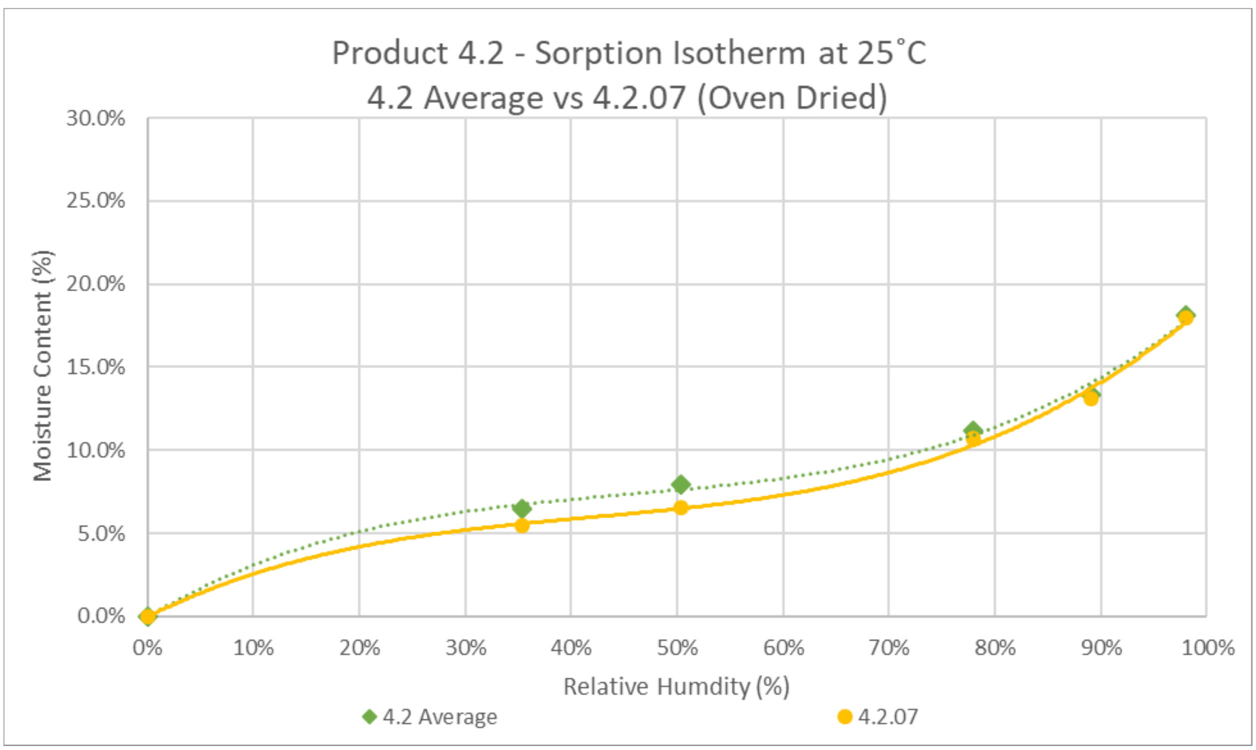


Figure C.29 – Product 4.2 Average and Oven Dried Specimen 4.2.07 Moisture Sorption Isotherm at 25˚C.

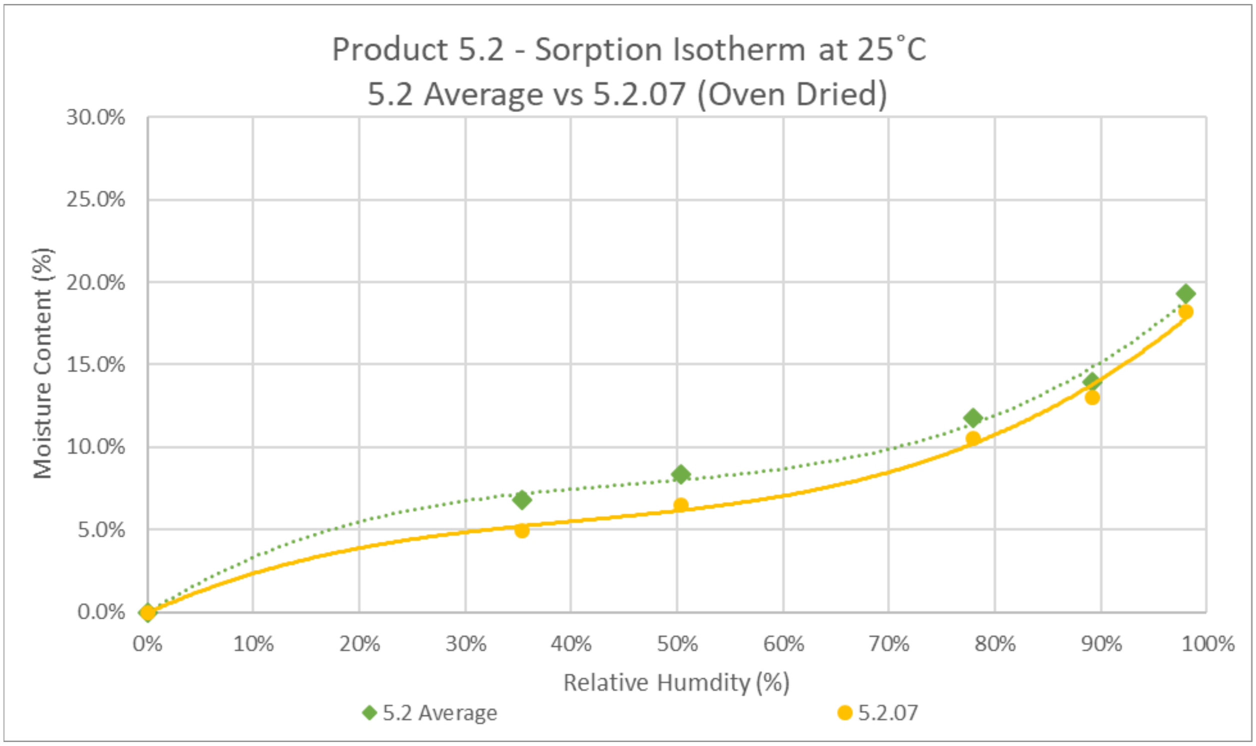


Figure C.30 – Product 5.2 Average and Oven Dried Specimen 5.2.07 Moisture Sorption Isotherm at 25˚C.

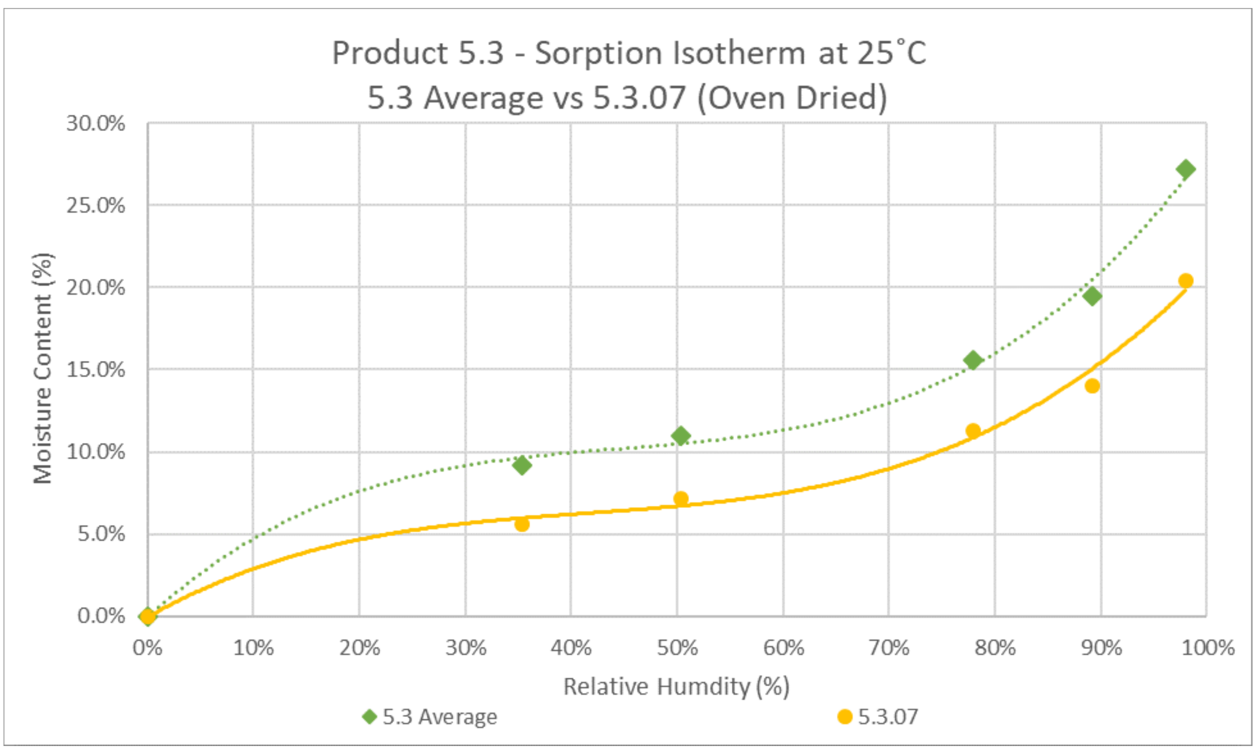


Figure C.31 – Product 5.3 Average and Oven Dried Specimen 5.3.07 Moisture Sorption Isotherm at 25˚C.

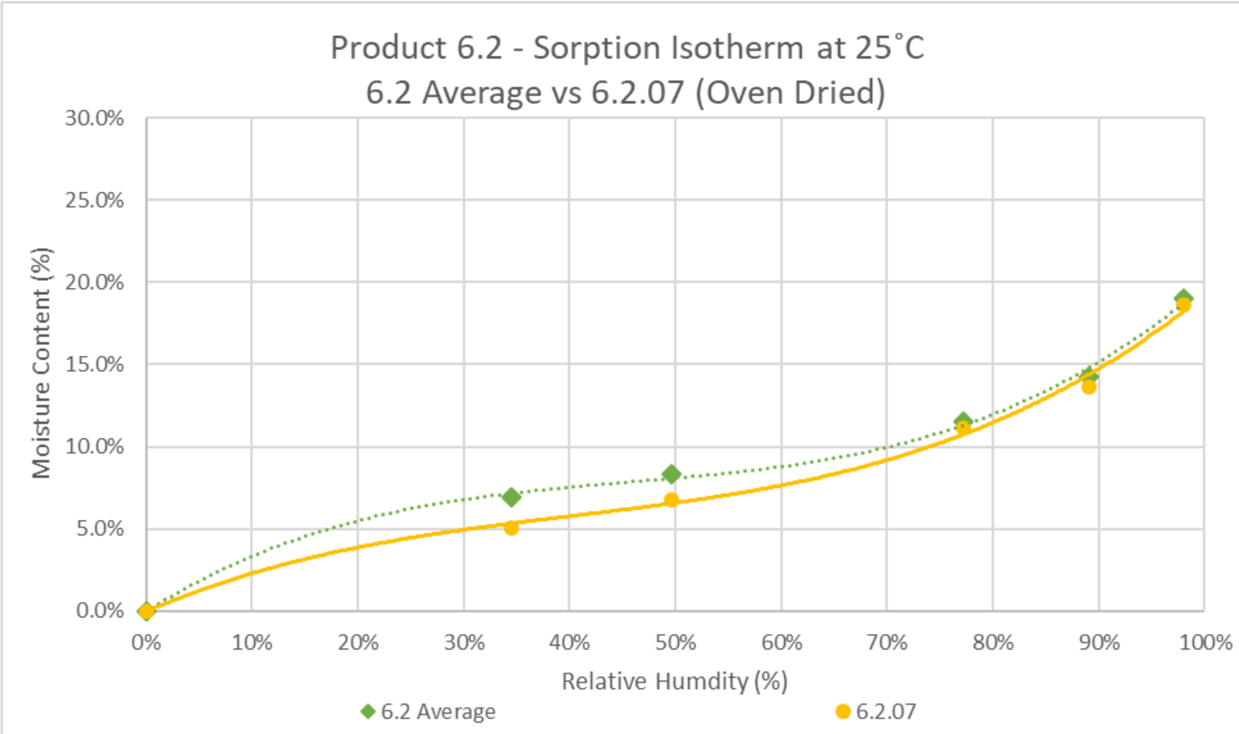


Figure C.32 – Product 6.2 Average and Oven Dried Specimen 6.2.07 Moisture Sorption Isotherm at 25˚C.

Appendix D - Moisture Sorption Test Results at 10˚C

Table C.1 -Maximum and Average Moisture Content Coefficient of Variation within a Product at 10˚C.

Test No.	RH(%)	CV(%) MC(%)									
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	35/40%	0.82%	0.35%	0.65%	**2.13%**	0.67%	0.80%	1.70%	0.35%	0.96%	0.94%
.2	51/54%	0.44%	0.34%	0.73%	**1.90%**	0.47%	0.77%	1.75%	1.16%	0.78%	0.93%
.3	80/81%	**2.15%**	1.54%	0.80%	1.58%	0.50%	1.34%	1.86%	1.32%	1.60%	1.41%
.4	91/92%	**2.85%**	1.62%	1.46%	1.03%	1.16%	1.65%	2.15%	2.47%	2.45%	1.87%
									Average		1.29%

Table C.2 -Maximum and Average Volumetric Moisture Content Coefficient of Variation within a Product at 10˚C.

Test No.	RH(%)	CV (%) VMC (kg_w/m^3_{WFIB})									
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Avg
.1	35/40%	4.13%	1.96%	**7.65%**	4.03%	2.98%	*0.71%*	0.92%	1.23%	1.65%	2.81%
.2	51/54%	4.05%	1.97%	**7.71%**	3.82%	2.97%	1.35%	1.05%	*0.66%*	1.50%	2.79%
.3	80/81%	5.48%	1.44%	**8.12%**	3.48%	2.94%	1.41%	1.25%	*0.60%*	2.22%	2.99%
.4	91/92%	6.11%	1.71%	**8.89%**	*1.42%*	8.64%	1.88%	1.50%	1.79%	3.14%	3.90%
									Average		3.12%

Table C.3 - Moisture Content for all Products at 10˚C for all Relative Humidity Steps with Maximum, Minimum, and Difference in Moisture Content Percentage.

Test No.	RH(%)	MC (%)											
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max*	Min	Diff*
.1	35/40%	7.6%	7.6%	7.5%	7.4%	7.4%	7.4%	7.4%	9.7%	7.5%	7.6%	7.4%	0.2%
.2	51/54%	8.7%	8.7%	8.6%	8.8%	8.6%	8.9%	8.9%	11.4%	8.6%	8.9%	8.6%	0.4%
.3	80/81%	11.7%	12.0%	12.0%	11.3%	11.0%	11.6%	11.6%	15.0%	11.4%	12.0%	11.0%	1.0%
.4	91/92%	13.4%	13.6%	13.5%	12.8%	12.8%	13.2%	13.3%	17.8%	13.4%	13.6%	12.8%	0.8%

Table C.4 – Volumetric Moisture Content for all Products at 10˚C for all Relative Humidity Steps with Maximum, Minimum, and Difference in Volumetric Moisture Content Percentage.

Test No.	RH(%)	VMC (kg_w/m^3_{WFIB})											
		1.1	2.1	2.2	3.1	4.1	4.2	5.2	5.3	6.2	Max*	Min	Diff.*
.1	35/40%	10.12	10.72	11.75	6.99	13.85	12.27	10.21	14.48	12.45	13.85	6.99	6.86
.2	51/54%	11.55	12.24	13.43	8.32	16.17	14.80	12.27	17.03	14.22	16.17	8.32	7.85
.3	80/81%	15.64	17.02	18.81	10.61	20.69	19.15	15.86	22.33	18.88	20.69	10.61	10.07
.4	91/92%	17.81	19.26	21.20	12.13	23.73	21.98	18.21	26.59	22.04	23.73	12.13	11.59

Table C.5 - Moisture Content for Products in Various Thicknesses at 10˚C for all Relative Humidity Steps with Difference between Same Product of Different Thickness.

Test No.	RH(%)	MC (%)								
		2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	35/40%	7.6%	*7.5%*	0.08%	*7.4%*	7.4%	0.03%	*7.4%*	9.7%	2.27%
.2	51/54%	8.7%	*8.6%*	0.08%	*8.6%*	8.9%	0.33%	*8.9%*	11.4%	2.49%
.3	80/81%	12.0%	*12.0%*	0.03%	*11.0%*	11.6%	0.55%	*11.6%*	15.0%	3.42%
.4	91/92%	13.6%	*13.5%*	0.10%	*12.8%*	13.2%	0.41%	*13.3%*	17.8%	4.57%

Table C.6 – Volumetric Moisture Content for Products in Various Thicknesses at 10˚C for all Relative Humidity Steps with Difference between Same Product of Different Thickness.

Test No.	RH(%)	VMC (kg_w/m^3_{WFIB})								
		2.1	2.2	Diff.	4.1	4.2	Diff.	5.2	5.3	Diff.
.1	35/40%	10.72	11.75	1.03	13.85	*12.27*	1.58	10.21	14.48	4.27
.2	51/54%	12.24	13.43	1.19	16.17	*14.80*	1.37	12.27	17.03	4.77
.3	80/81%	17.02	18.81	1.79	20.69	*19.15*	1.54	15.86	22.33	6.47
.4	91/92%	19.26	21.20	1.94	23.73	*21.98*	1.75	18.21	26.59	8.38

Table C.7 – Moisture Contents for Specimens 1.1.04, 1.1.05, 1.1.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			1.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	1.1.01	1.1.02	1.1.03			
					MC(%)					
.1	10.07	0.07, 0.70%	35.2%	0.62, 1.76%	7.7%	7.6%	7.6%	7.6%	0.06%	0.82%
.2	10.05	0.12, 1.20%	50.6%	1.16, 2.29%	8.7%	8.7%	8.6%	8.7%	0.04%	0.44%
.3	9.96	0.06, 0.62%	80.0%	0.59, 0.73%	12.0%	11.8%	11.5%	11.7%	0.25%	2.15%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	13.7%	13.4%	13.0%	13.4%	0.38%	2.85%

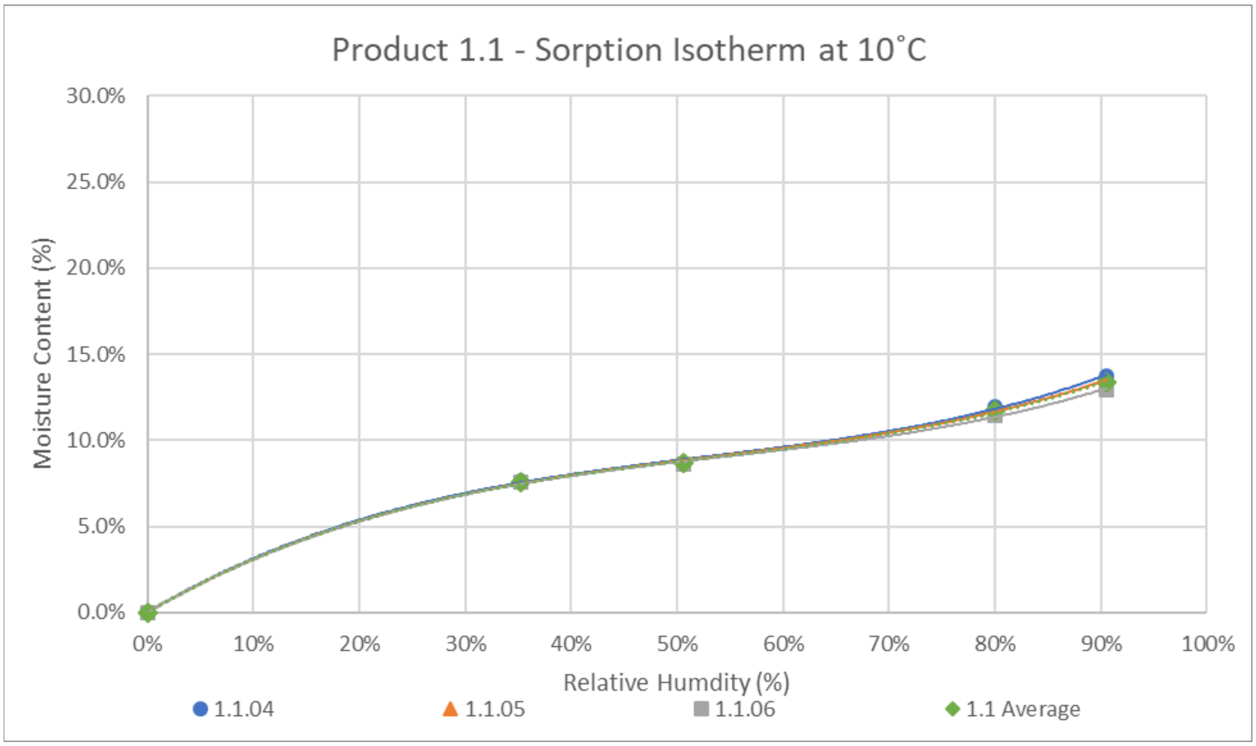


Figure C.1 – Product 1.1 Moisture Sorption Isotherm at 10˚C.

Table C.8 – Moisture Contents for Specimens 2.1.04, 2.1.05, 2.1.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			2.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	2.1.01	2.1.02	2.1.03			
					MC(%)					
.1	10.07	0.07, 0.70%	35.2%	0.62, 1.76%	7.6%	7.6%	7.5%	7.6%	0.03%	0.35%
.2	10.05	0.12, 1.20%	50.6%	2.16, 2.29%	8.7%	8.7%	8.6%	8.7%	0.03%	0.34%
.3	9.96	0.06, 0.62%	80.0%	0.59, 0.73%	12.2%	12.1%	11.8%	12.0%	0.18%	1.54%
.4	10.14	0.11, 2.11%	90.5%	1.58, 1.75%	13.7%	13.7%	13.4%	13.6%	0.22%	1.62%

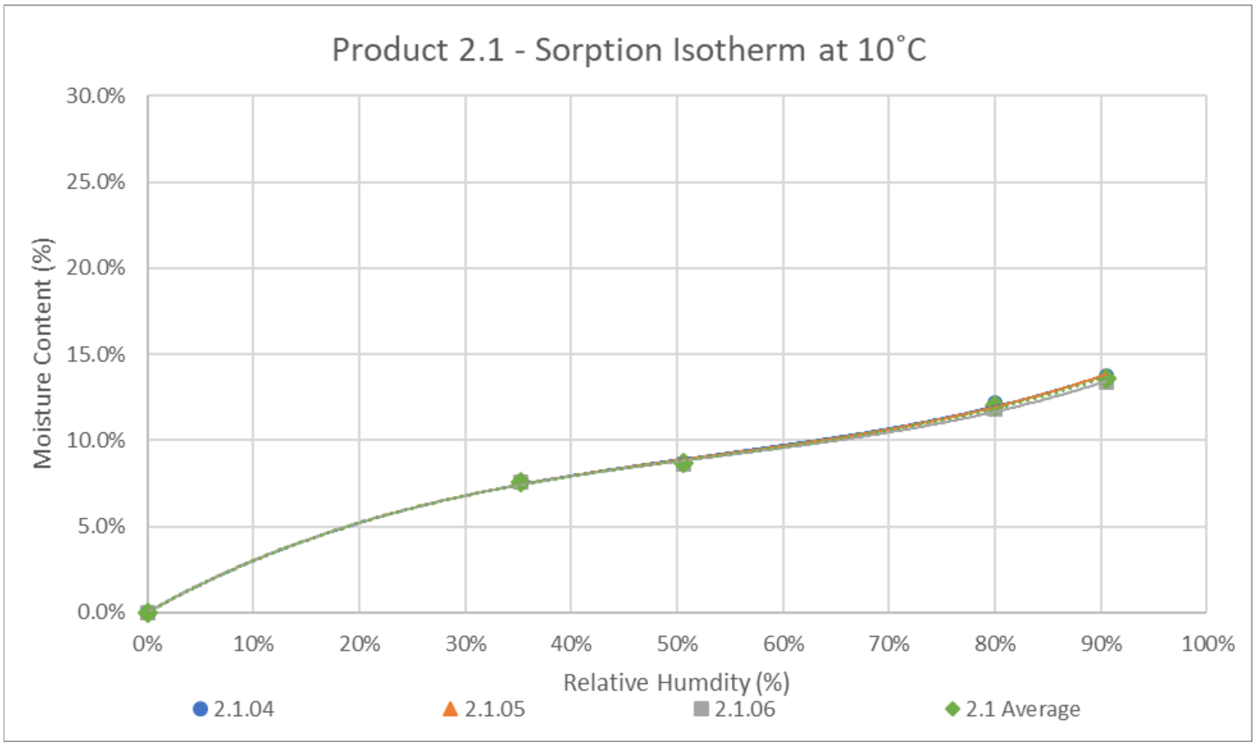


Figure C.2 – Product 2.1 Moisture Sorption Isotherm at 10˚C.

Table C.9 – Moisture Contents for Specimens 2.2.04, 2.2.05, 2.2.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			2.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	2.2.01	2.2.02	2.2.03			
					MC(%)					
.1	10.07	0.07, 0.70%	35.2%	0.62, 1.76%	7.5%	7.5%	7.5%	7.5%	0.05%	0.65%
.2	10.05	0.12, 1.20%	50.6%	2.26, 2.29%	8.6%	8.5%	8.5%	8.6%	0.06%	0.73%
.3	9.96	0.06, 0.62%	80.0%	0.59, 0.73%	12.1%	12.0%	11.9%	12.0%	0.10%	0.80%
.4	10.14	0.11, 2.21%	90.5%	1.58, 1.75%	13.7%	13.6%	13.3%	13.5%	0.20%	1.46%

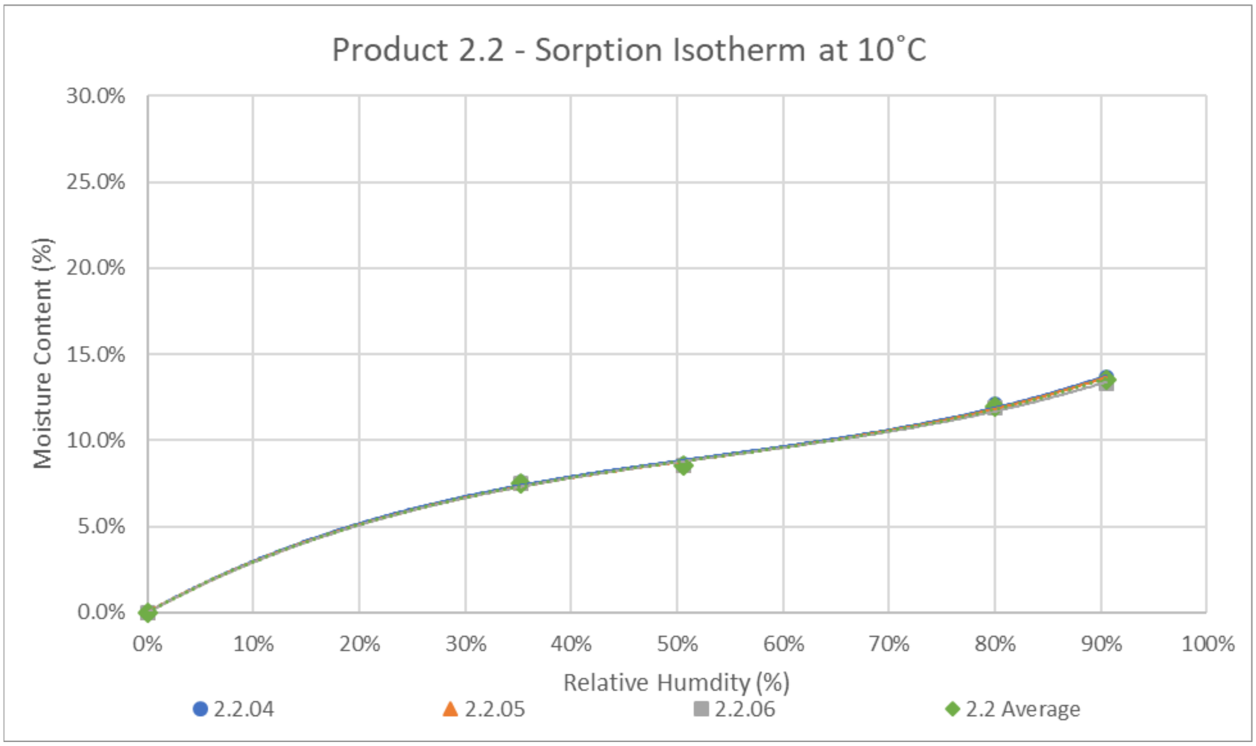


Figure C.3 – Product 2.2 Moisture Sorption Isotherm at 10˚C.

Table C.10 – Moisture Contents for Specimens 3.1.04, 3.1.05, 3.1.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			3.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	3.1.01(*B*)	3.1.02(*B*)	3.1.03(*B*)			
					MC(%)					
.1	9.81	0.15, 1.57%	40.4%	5.50, 13.61%	*7.6%*	*7.4%*	*7.3%*	*7.4%*	0.16%	2.13%
.2	9.77	0.21, 2.13%	54.1%	5.94, 10.97%	*9.0%*	*8.8%*	*8.7%*	*8.8%*	0.17%	1.90%
.3	9.8	0.11, 1.07%	81.0%	0.56, 0.69%	*11.5%*	*11.2%*	*11.1%*	*11.3%*	0.18%	1.58%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	13.0%	12.9%	12.7%	12.8%	0.13%	1.03%

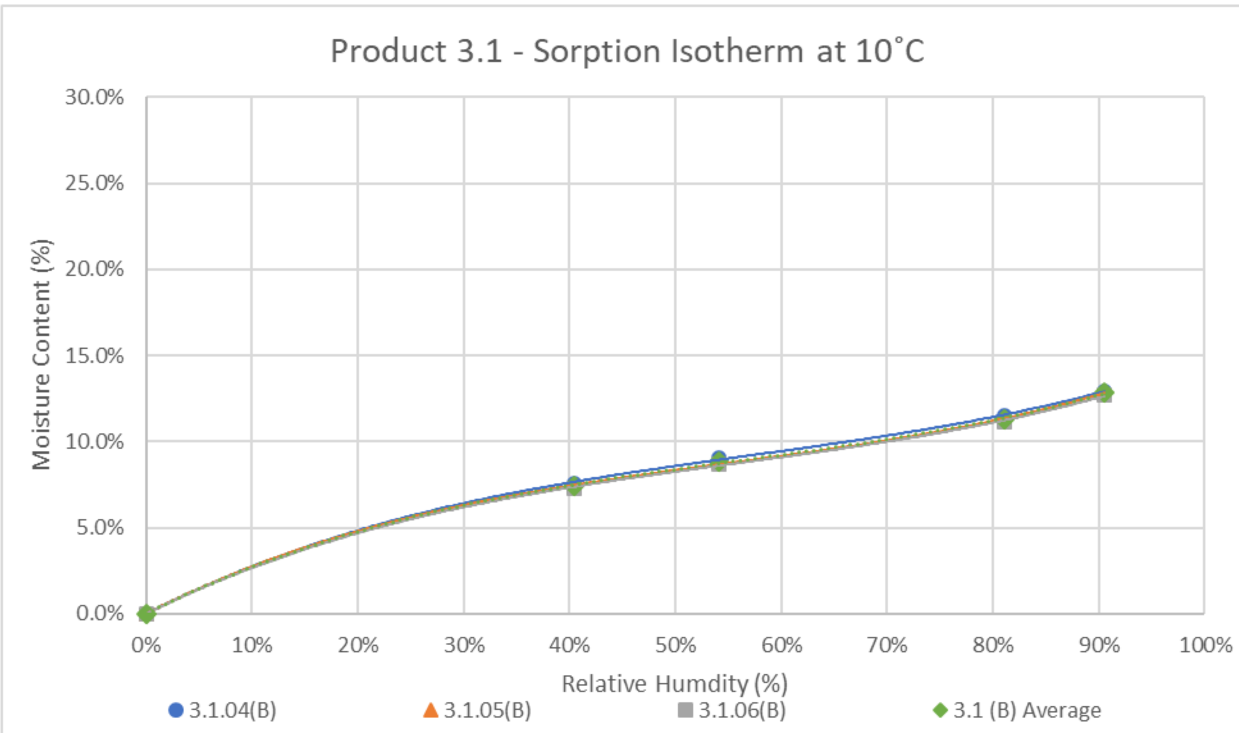


Figure C.4 – Product 3.1 Moisture Sorption Isotherm at 10˚C.

Table C.11 – Moisture Contents for Specimens 4.1.04, 4.1.05, 4.1.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			4.1 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	4.1.01(*B*)	4.1.02(*B*)	4.1.03(*B*)			
					MC(%)					
.1	9.81	0.15, 1.57%	40.4%	5.50, 13.61%	*7.4%*	*7.3%*	*7.4%*	7.4%	0.05%	0.67%
.2	9.77	0.21, 2.13%	54.1%	5.94, 10.97%	*8.6%*	*8.6%*	*8.7%*	8.6%	0.04%	0.47%
.3	9.8	0.11, 1.07%	81.0%	0.56, 0.69%	*11.0%*	*11.0%*	*11.1%*	11.0%	0.06%	0.50%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	12.7%	12.7%	13.0%	12.8%	0.15%	1.16%

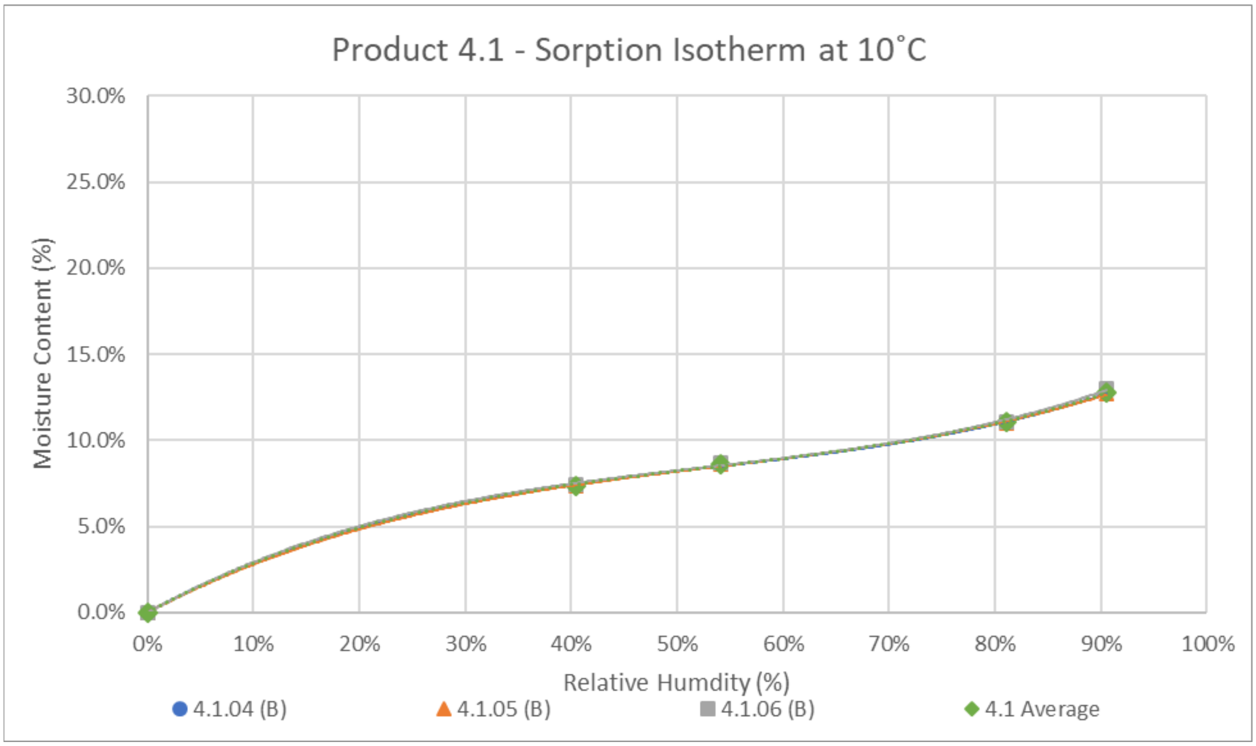


Figure C.5 – Product 4.1 Moisture Sorption Isotherm at 10˚C.

Table C.12 – Moisture Contents for Specimens 4.2.04, 4.2.05, 4.2.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			4.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	4.2.01(*B*)	4.2.02(*B*)	4.2.03(*B*)			
					MC(%)					
.1	9.81	0.15, 1.57%	40.4%	5.50, 13.61%	*7.4%*	*7.5%*	*7.4%*	7.4%	0.06%	0.80%
.2	9.77	0.21, 2.13%	54.1%	5.94, 10.97%	*8.9%*	*9.0%*	*8.9%*	8.9%	0.07%	0.77%
.3	9.8	0.11, 1.07%	81.0%	0.56, 0.69%	*11.5%*	*11.8%*	*11.5%*	11.6%	0.15%	1.34%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	13.3%	13.4%	13.0%	13.2%	0.22%	1.65%

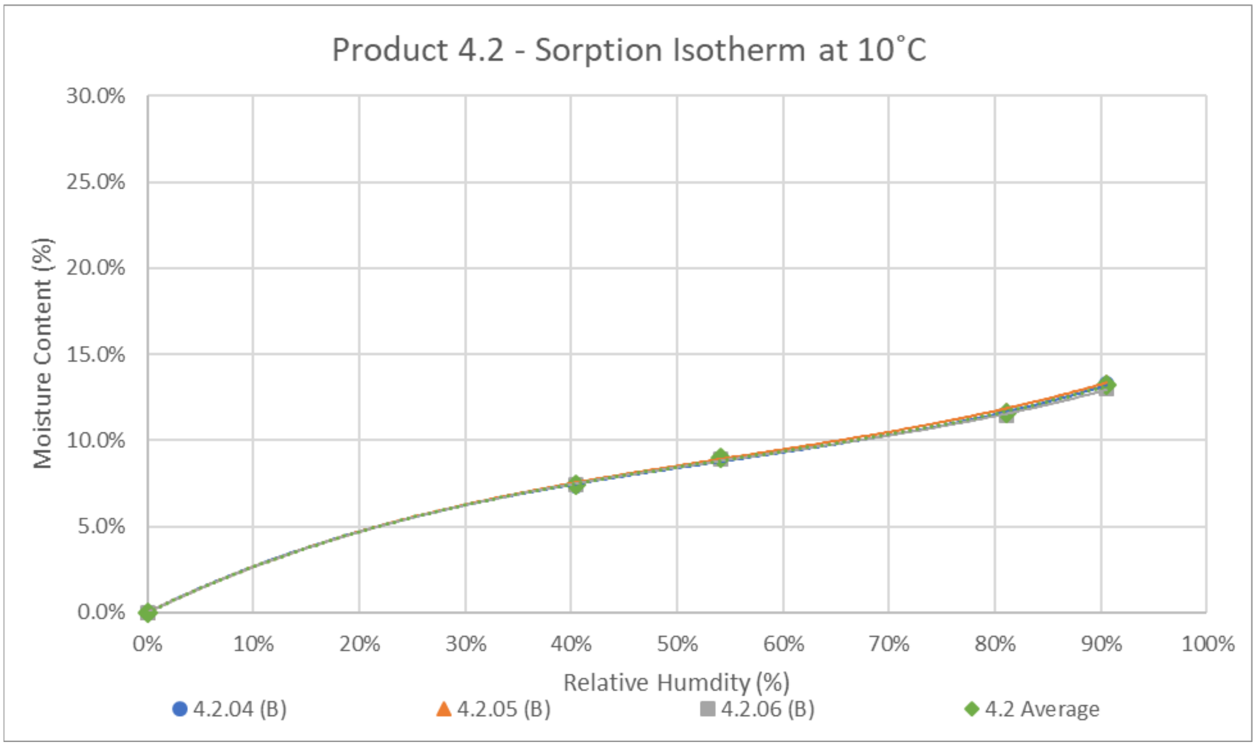


Figure C.6 – Product 4.2 Moisture Sorption Isotherm at 10˚C.

Table C.13 – Moisture Contents for Specimens 5.2.04, 5.2.05, 5.2.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			5.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	5.2.01(*B*)	5.2.02(*B*)	5.2.03(*B*)			
					MC(%)					
.1	9.81	0.15, 1.57%	40.4%	5.50, 13.61%	*7.6%*	*7.4%*	*7.3%*	7.4%	0.13%	1.70%
.2	9.77	0.21, 2.13%	54.1%	5.94, 10.97%	*9.1%*	*9.0%*	*8.8%*	8.9%	0.16%	1.75%
.3	9.8	0.11, 1.07%	81.0%	0.56, 0.69%	*11.7%*	*11.6%*	*11.3%*	11.6%	0.22%	1.86%
.4	9.96	0.09, 0.92%	91.5%	0.74, 0.81%	13.5%	13.4%	13.0%	13.3%	0.29%	2.15%

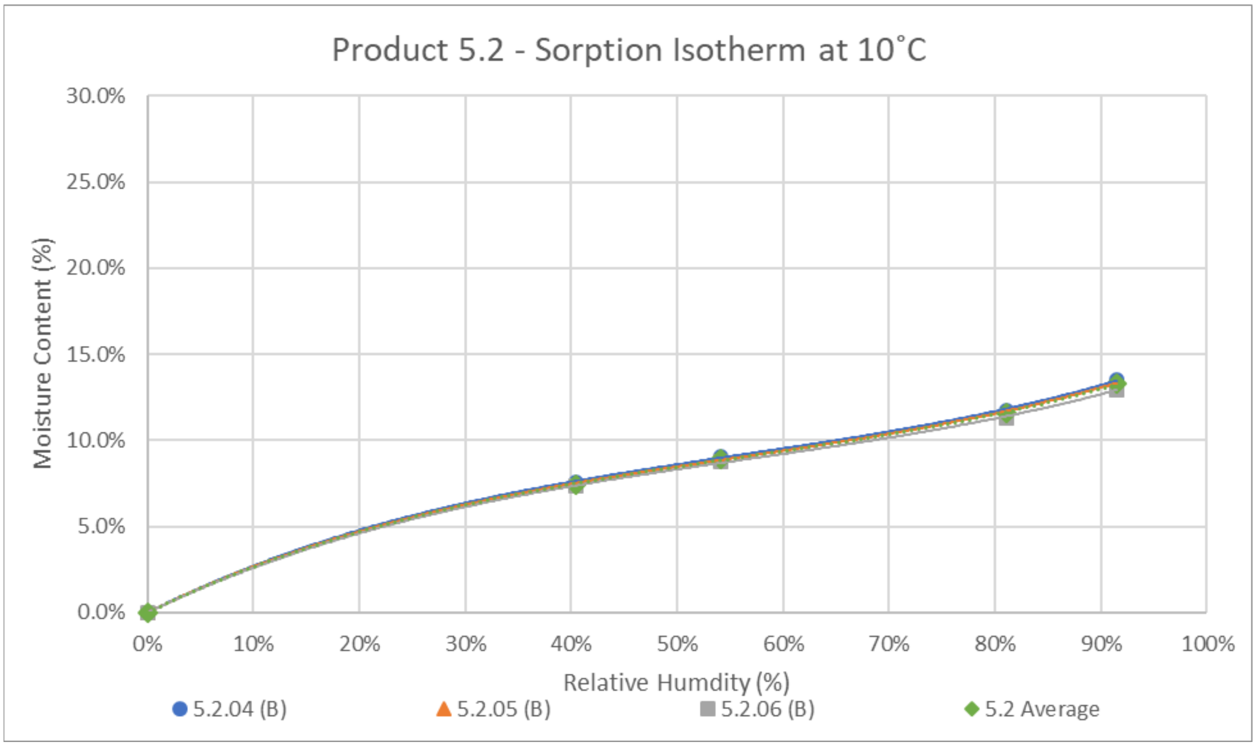


Figure C.7 – Product 5.2 Moisture Sorption Isotherm at 10˚C.

Table C.14 – Moisture Contents for Specimens 5.3.04, 5.3.05, 5.3.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			5.3 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	5.3.01(*B*)	5.3.02(*B*)	5.3.03(*B*)			
					MC(%)					
.1	9.81	0.15, 1.57%	40.4%	5.50, 13.61%	*9.7%*	*9.7%*	*9.7%*	9.7%	0.03%	0.35%
.2	9.77	0.21, 2.13%	54.1%	5.94, 10.97%	*11.6%*	*11.4%*	*11.3%*	11.4%	0.13%	1.16%
.3	9.8	0.11, 1.07%	81.0%	0.56, 0.69%	*15.2%*	*15.0%*	*14.8%*	15.0%	0.20%	1.32%
.4	9.96	0.09, 0.92%	91.5%	0.74, 0.81%	18.2%	18.0%	17.3%	17.8%	0.44%	2.47%

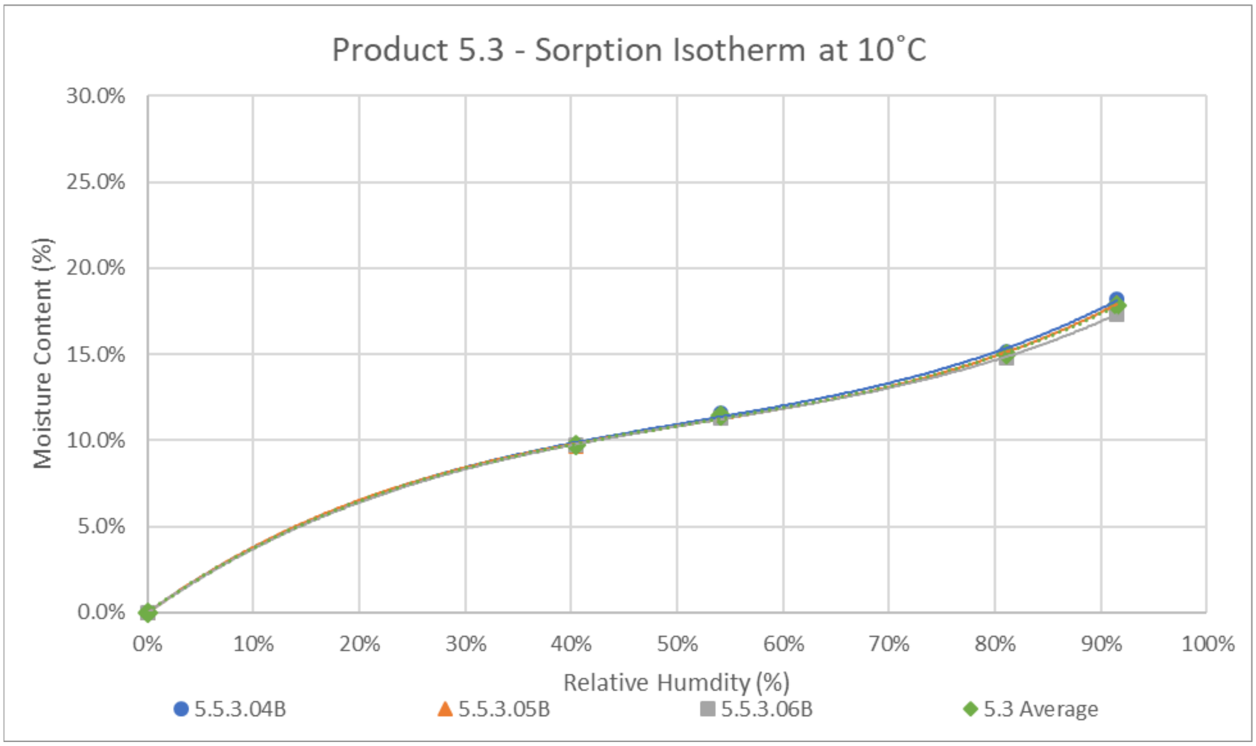


Figure C.8 – Product 5.3 Moisture Sorption Isotherm at 10˚C.

Table C.15 – Moisture Contents for Specimens 6.2.04, 6.2.05, 6.2.06, and Average over Full Relative Humidity Range at 10˚C.

Test No.	Temp		RH		Specimen			6.2 Avg	MC SD	MC CV(%)
	(˚C)	SD, CV (%)	(%)	SD, CV (%)	6.2.01	6.2.02	6.2.03			
					MC(%)					
.1	10.07	0.07, 0.70%	35.2%	0.62, 1.76%	7.6%	7.6%	7.5%	7.5%	0.07%	0.96%
.2	10.05	0.12, 1.20%	50.6%	1.16, 2.29%	8.7%	8.6%	8.5%	8.6%	0.07%	0.78%
.3	9.96	0.06, 0.62%	80.0%	0.59, 0.73%	11.6%	11.5%	11.2%	11.4%	0.18%	1.60%
.4	10.14	0.11, 1.11%	90.5%	1.58, 1.75%	13.6%	13.5%	13.0%	13.4%	0.33%	2.45%

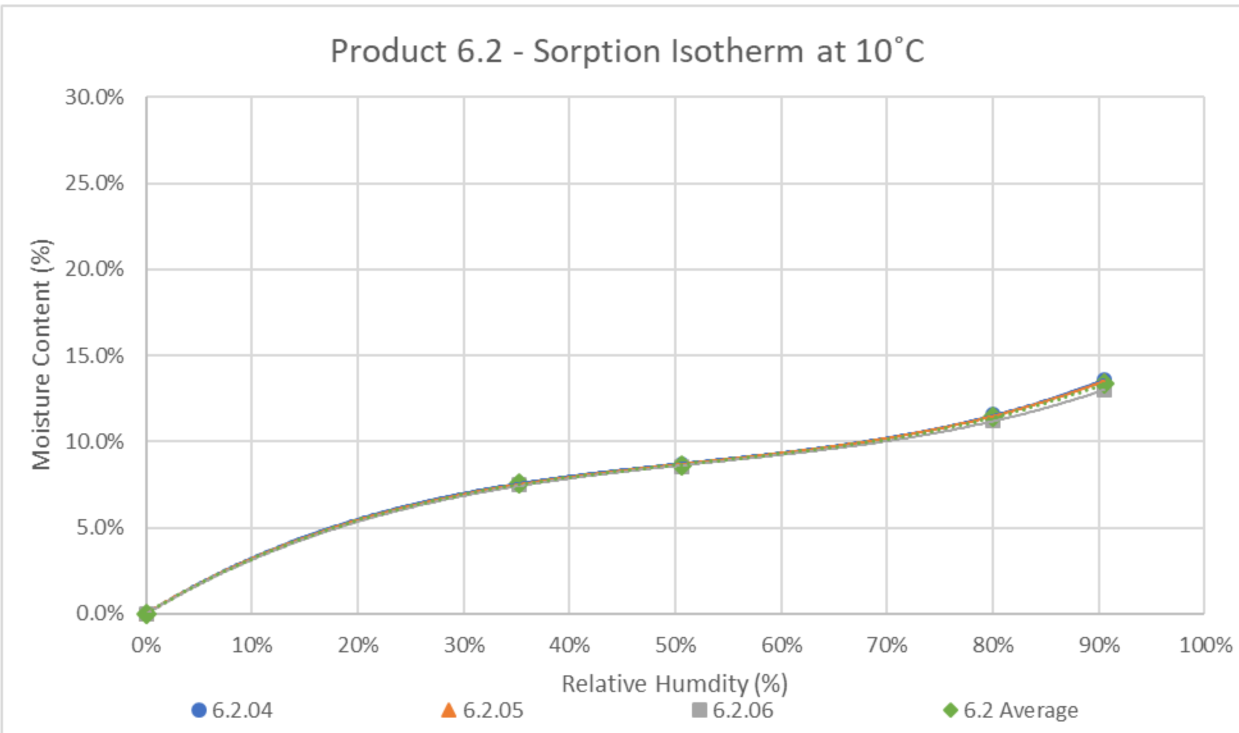


Figure C.9 – Product 6.2 Moisture Sorption Isotherm at 10˚C.

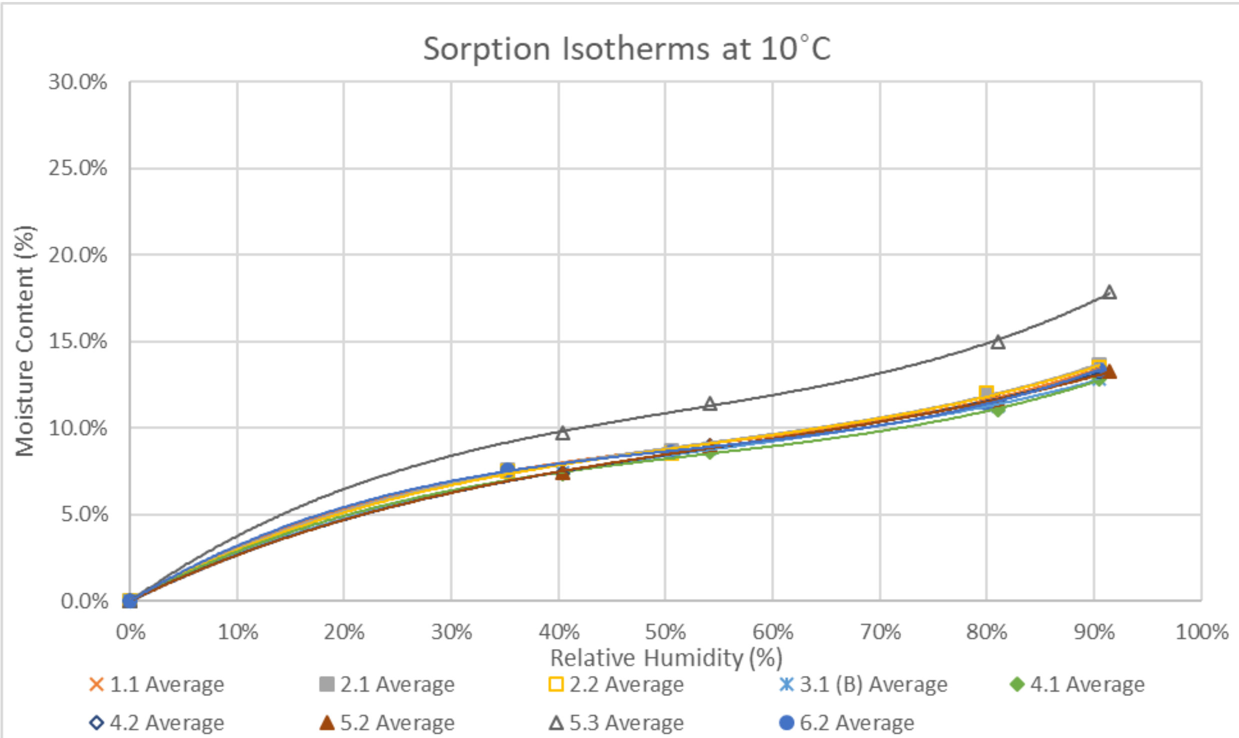


Figure C.10 – All Products Moisture Sorption Isotherm at 10˚C.

Table C.16 – Volumetric Moisture Contents for Specimens 1.1.01, 1.1.02, 1.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen			1.1 Average	VMC SD	VMC CV(%)
			1.1.01	1.1.02	1.1.03			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	10.07	35.2%	10.29	10.43	9.65	10.12	0.42	4.13%
.2	10.05	50.6%	11.68	11.93	11.03	11.55	0.47	4.05%
.3	9.96	80.0%	16.05	16.22	14.65	15.64	0.86	5.48%
.4	10.14	90.5%	18.39	18.49	16.56	17.81	1.09	6.11%

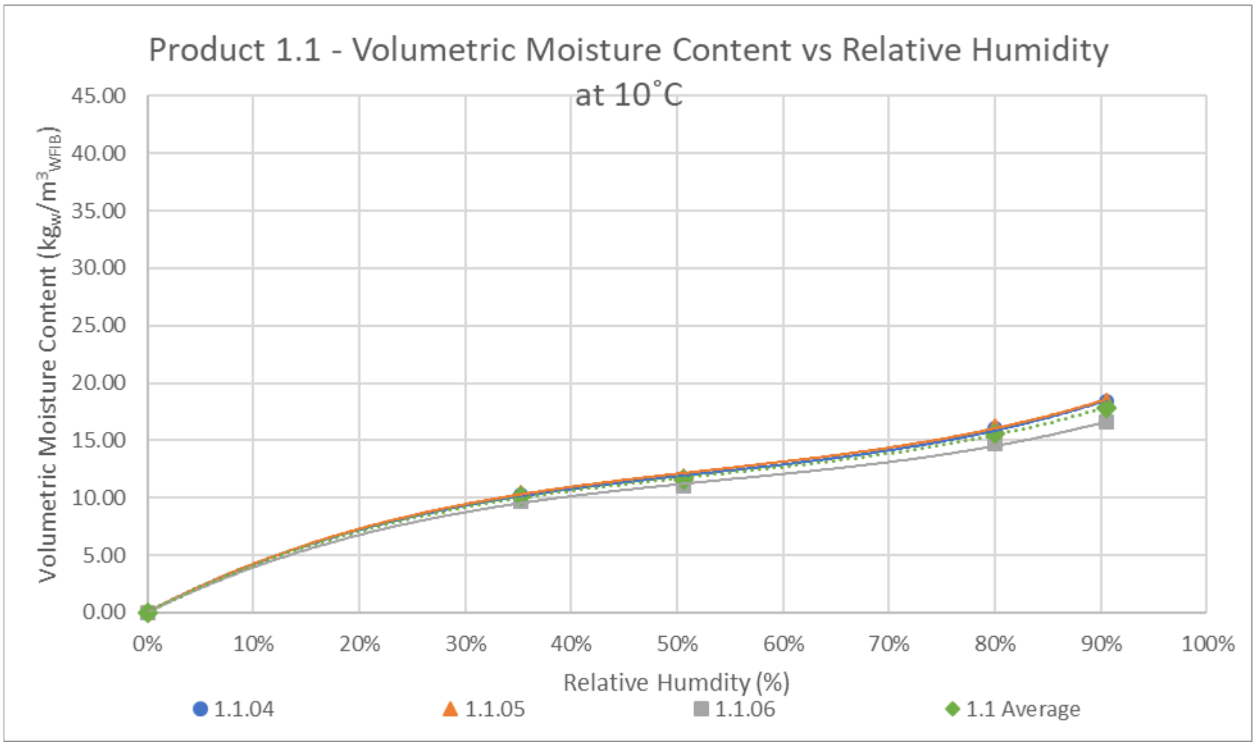


Figure C.11 – Product 1.1 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.17 – Volumetric Moisture Contents for Specimens 2.1.01, 2.1.02, 2.1.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen			2.1 Average	VMC SD	VMC CV(%)
			2.1.01	2.1.02	2.1.03			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	10.07	35.2%	10.48	10.80	10.88	10.72	0.21	1.96%
.2	10.05	50.6%	11.97	12.33	12.43	12.24	0.25	1.97%
.3	9.96	80.0%	16.77	17.26	17.04	17.02	0.25	1.44%
.4	10.14	90.5%	18.93	19.59	19.26	19.26	0.33	1.71%

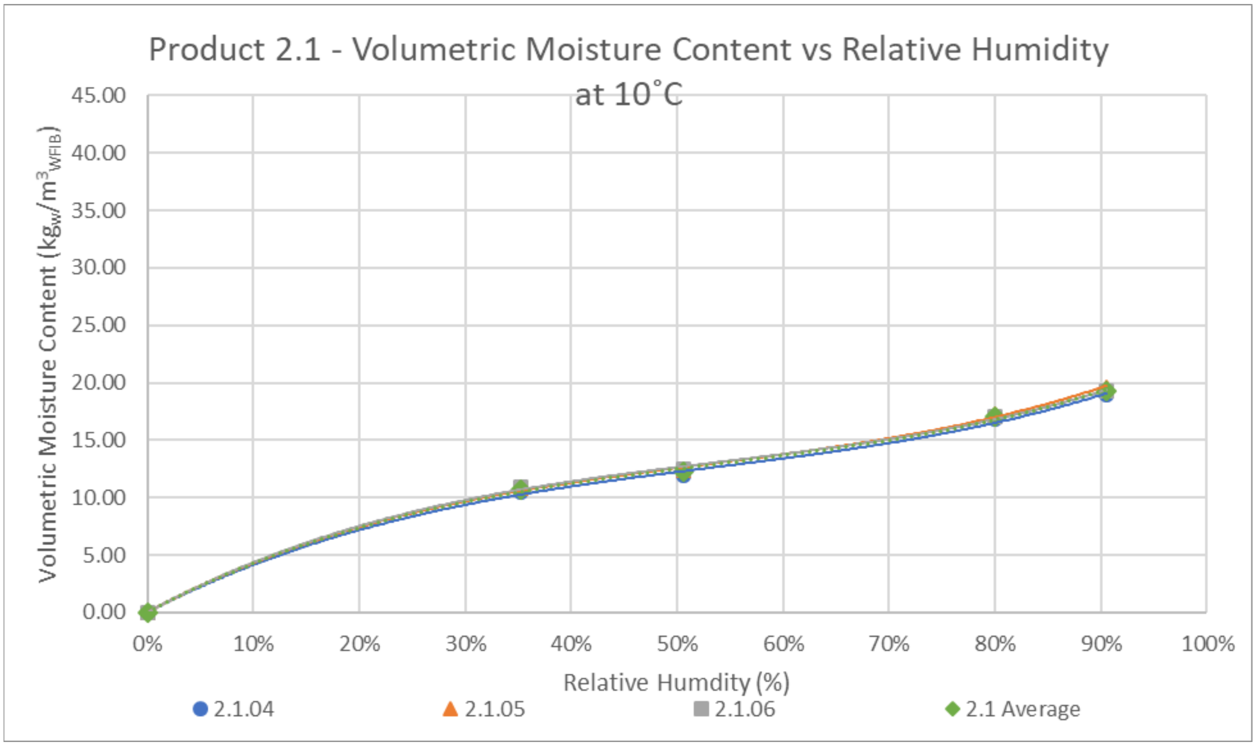


Figure C.12 – Product 2.1 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.18 – Volumetric Moisture Contents for Specimens 2.2.01, 2.2.02, 2.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen 2.2.01	Specimen 2.2.02	Specimen 2.2.03	2.2 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	10.07	35.2%	12.34	12.10	10.80	11.75	0.83	7.65%
.2	10.05	50.6%	14.12	13.83	12.35	13.43	0.95	7.71%
.3	9.96	80.0%	19.75	19.49	17.21	18.81	1.40	8.12%
.4	10.14	90.5%	22.35	22.01	19.23	21.20	1.71	8.89%

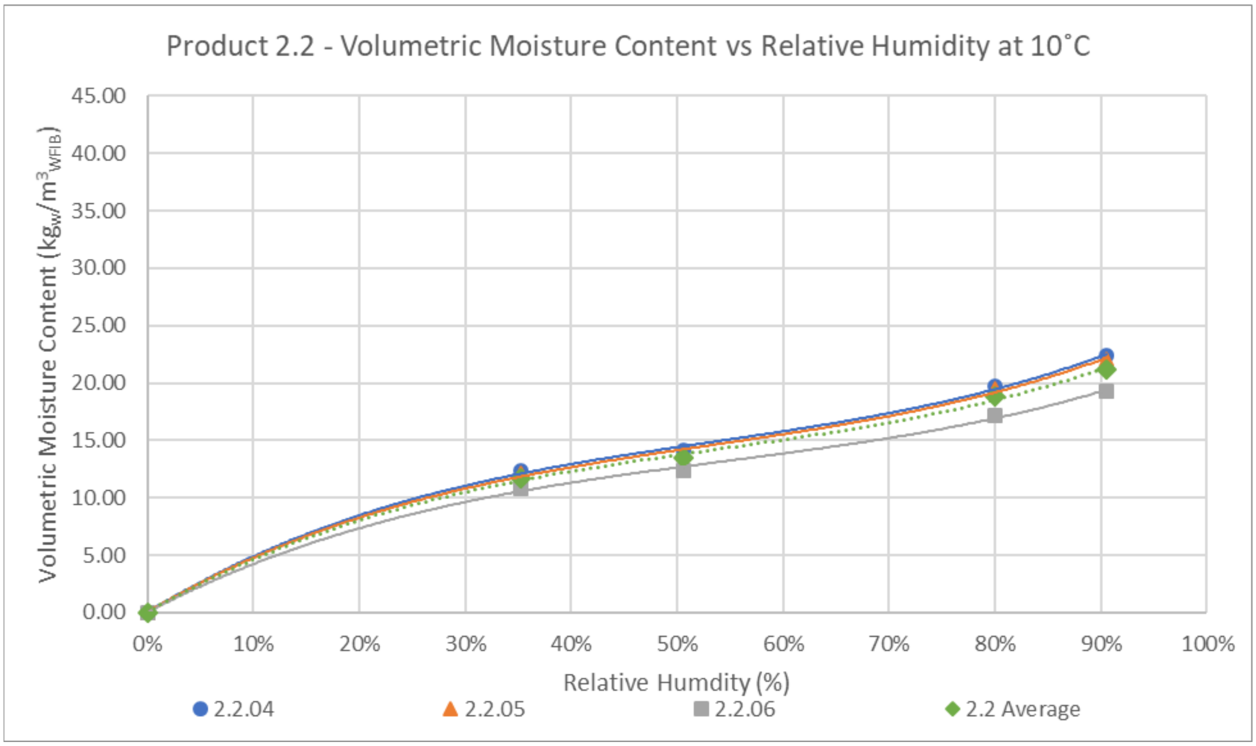


Figure C.13 – Product 2.2 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.19 – Volumetric Moisture Contents for Specimens 3.1.04, 3.1.05, 3.1.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen			3.1 Average	VMC SD	VMC CV(%)
			3.1.04(*B*)	3.1.05(*B*)	3.1.06(*B*)			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	9.81	40.4%	*7.31*	*6.85*	*6.81*	*6.99*	0.27	4.03%
.2	9.77	54.1%	*8.68*	*8.15*	*8.13*	*8.32*	0.31	3.82%
.3	9.8	81.0%	*11.03*	*10.42*	*10.40*	*10.61*	0.36	3.48%
.4	10.14	90.5%	12.33	12.04	12.03	12.13	0.17	1.42%

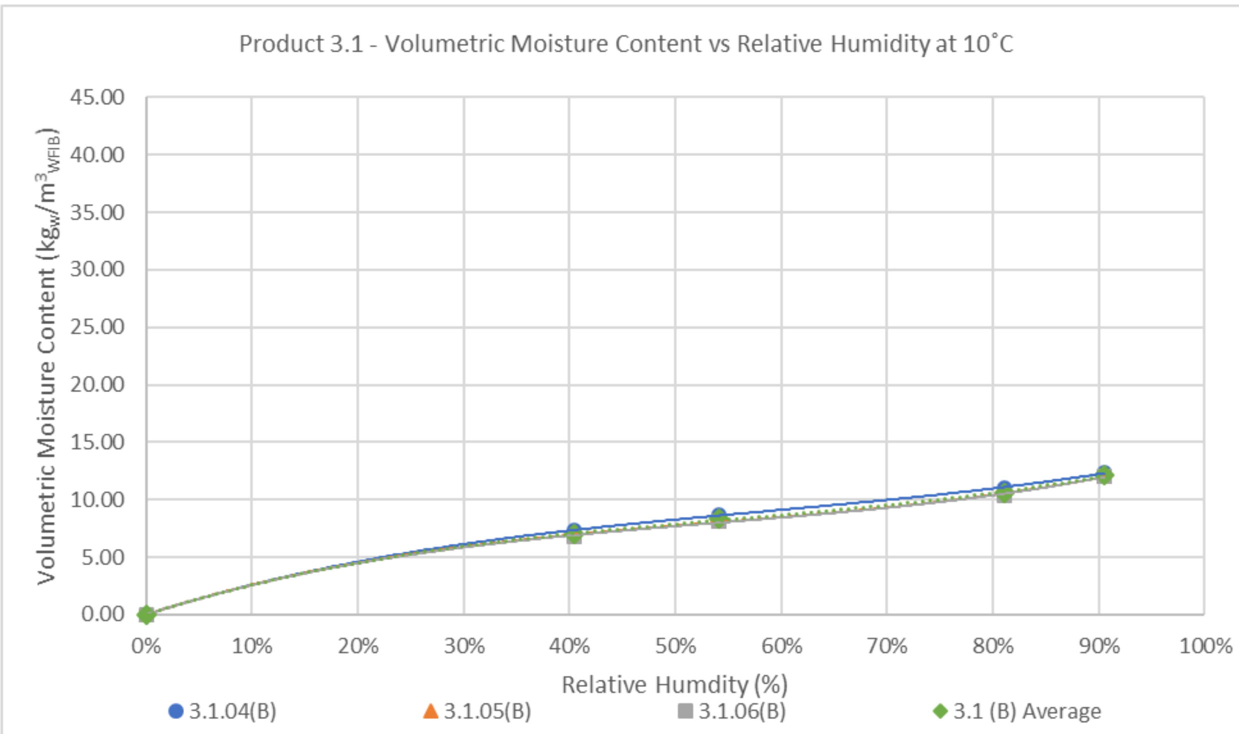


Figure C.14 – Product 3.1 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.20 – Volumetric Moisture Contents for Specimens 4.1.04, 4.1.05, 4.1.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen 4.1.04(*B*)	4.1.05(*B*)	4.1.06(*B*)	4.1 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	9.81	40.4%	*12.37*	*12.23*	*12.21*	12.27	0.09	0.71%
.2	9.77	54.1%	*15.01*	*14.77*	*14.62*	14.80	0.20	1.35%
.3	9.8	81.0%	*19.36*	*19.23*	*18.85*	19.15	0.27	1.41%
.4	10.14	90.5%	22.40	21.96	21.59	21.98	0.41	1.88%

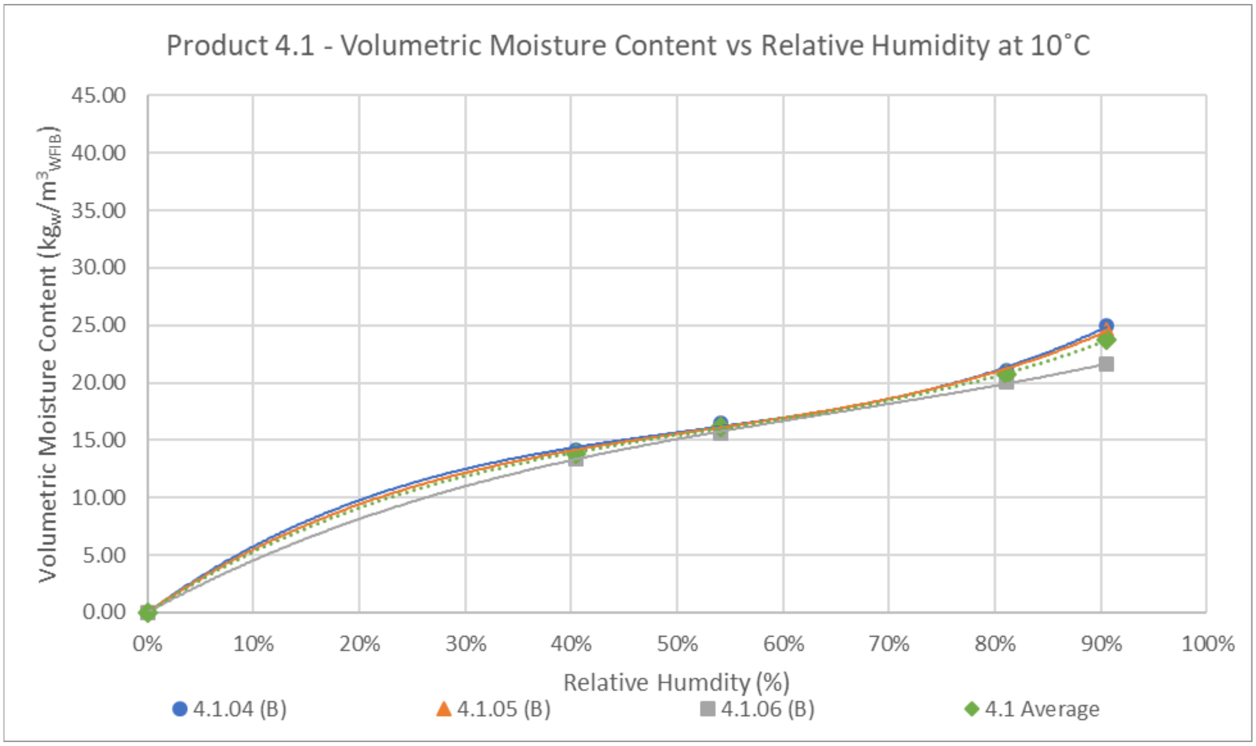


Figure C.15 – Product 4.1 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.21 – Volumetric Moisture Contents for Specimens 4.2.04, 4.2.05, 4.2.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen 4.2.04(*B*)	Specimen 4.2.05(*B*)	Specimen 4.2.06(*B*)	4.2 Average	VMC SD	VMC CV(%)
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	9.81	40.4%	*12.37*	*12.23*	*12.21*	12.27	0.09	0.71%
.2	9.77	54.1%	*15.01*	*14.77*	*14.62*	14.80	0.20	1.35%
.3	9.8	81.0%	*19.36*	*19.23*	*18.85*	19.15	0.27	1.41%
.4	10.14	90.5%	22.40	21.96	21.59	21.98	0.41	1.88%

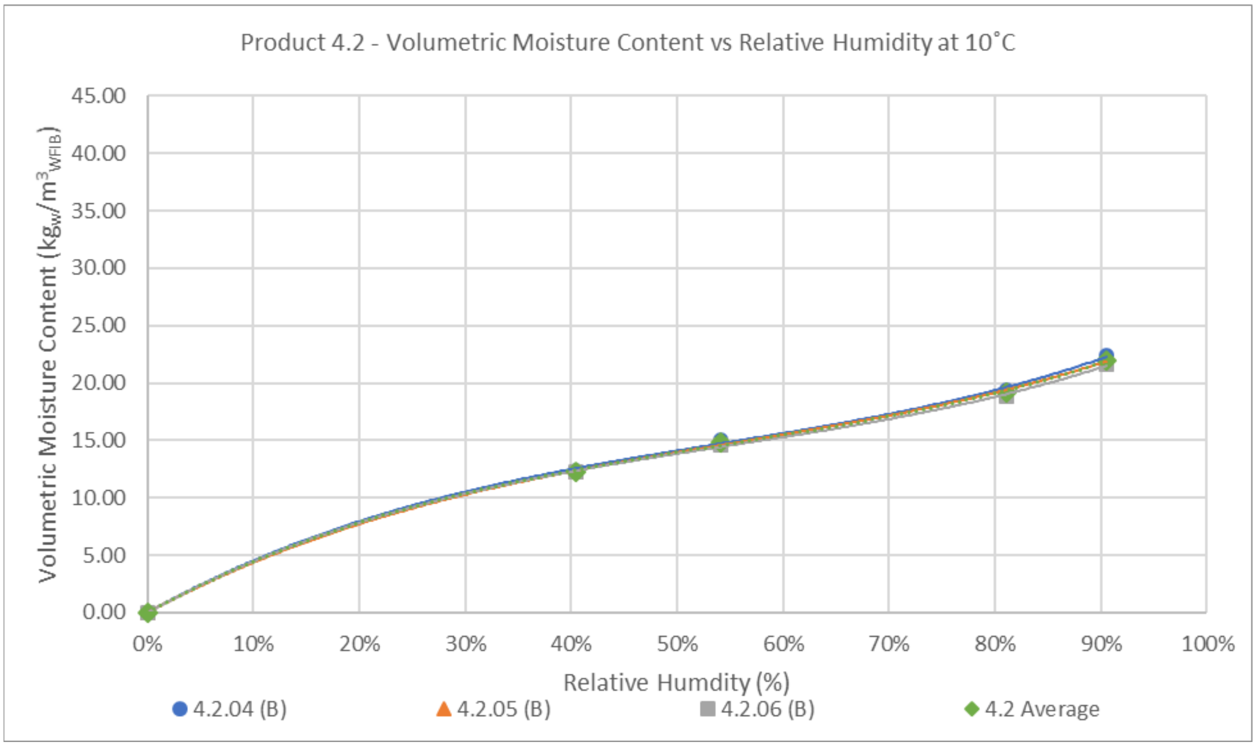


Figure C.16 – Product 4.2 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.22 – Volumetric Moisture Contents for Specimens 5.2.04, 5.2.05, 5.2.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen			5.2 Average	VMC SD	VMC CV(%)
			5.2.04(*B*)	5.2.05(*B*)	5.2.06(*B*)			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	9.81	40.4%	*10.14*	*10.32*	*10.17*	10.21	0.09	0.92%
.2	9.77	54.1%	*12.18*	*12.41*	*12.21*	12.27	0.13	1.05%
.3	9.8	81.0%	*15.74*	*16.08*	*15.75*	15.86	0.20	1.25%
.4	9.96	91.5%	18.09	18.52	18.02	18.21	0.27	1.50%

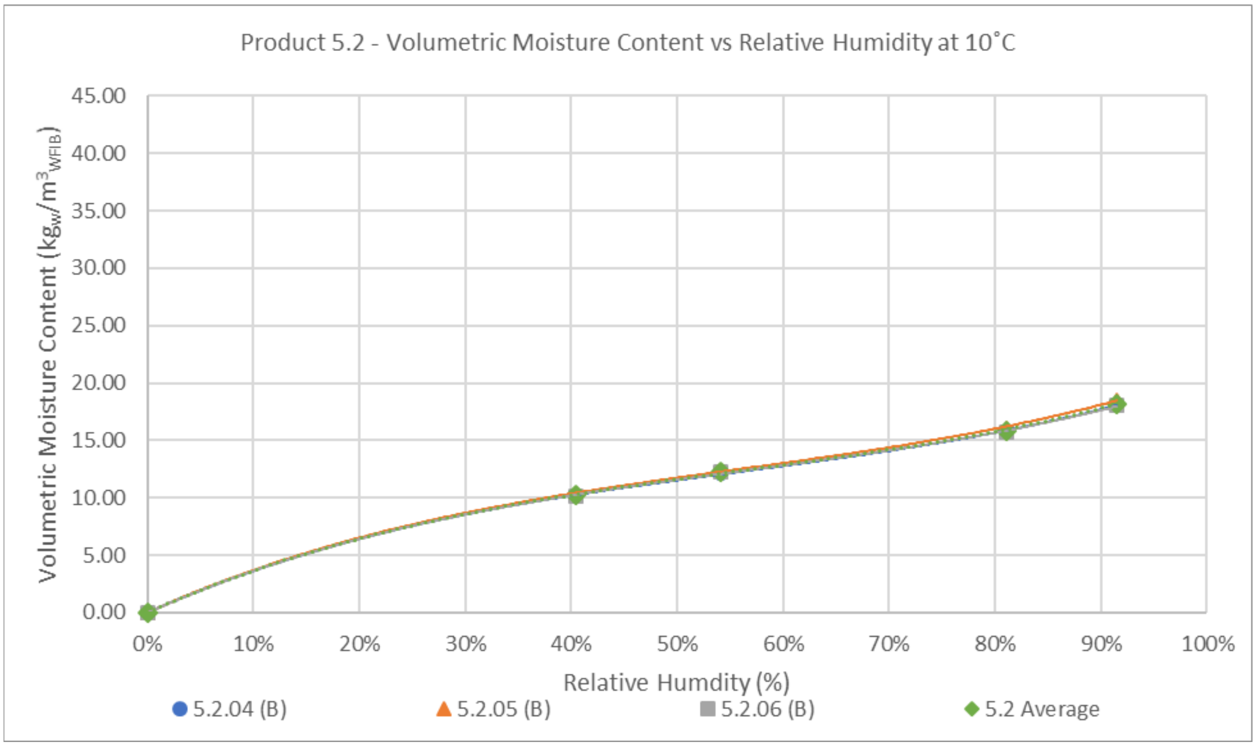


Figure C.17 – Product 5.2 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.23 – Volumetric Moisture Contents for Specimens 5.3.04, 5.3.05, 5.3.06, and Average over Full Relative Humidity Range at 10˚C

Test No.	Temp (˚C)	RH (%)	Specimen			5.3 Average	VMC SD	VMC CV(%)
			5.3.04(*B*)	5.3.05(*B*)	5.3.06(*B*)			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	9.81	40.4%	*14.27*	*14.55*	*14.61*	14.48	0.18	1.23%
.2	9.77	54.1%	*16.94*	*17.16*	*17.01*	17.03	0.11	0.66%
.3	9.8	81.0%	*22.24*	*22.48*	*22.26*	22.33	0.13	0.60%
.4	9.96	91.5%	26.64	27.04	26.10	26.59	0.47	1.79%

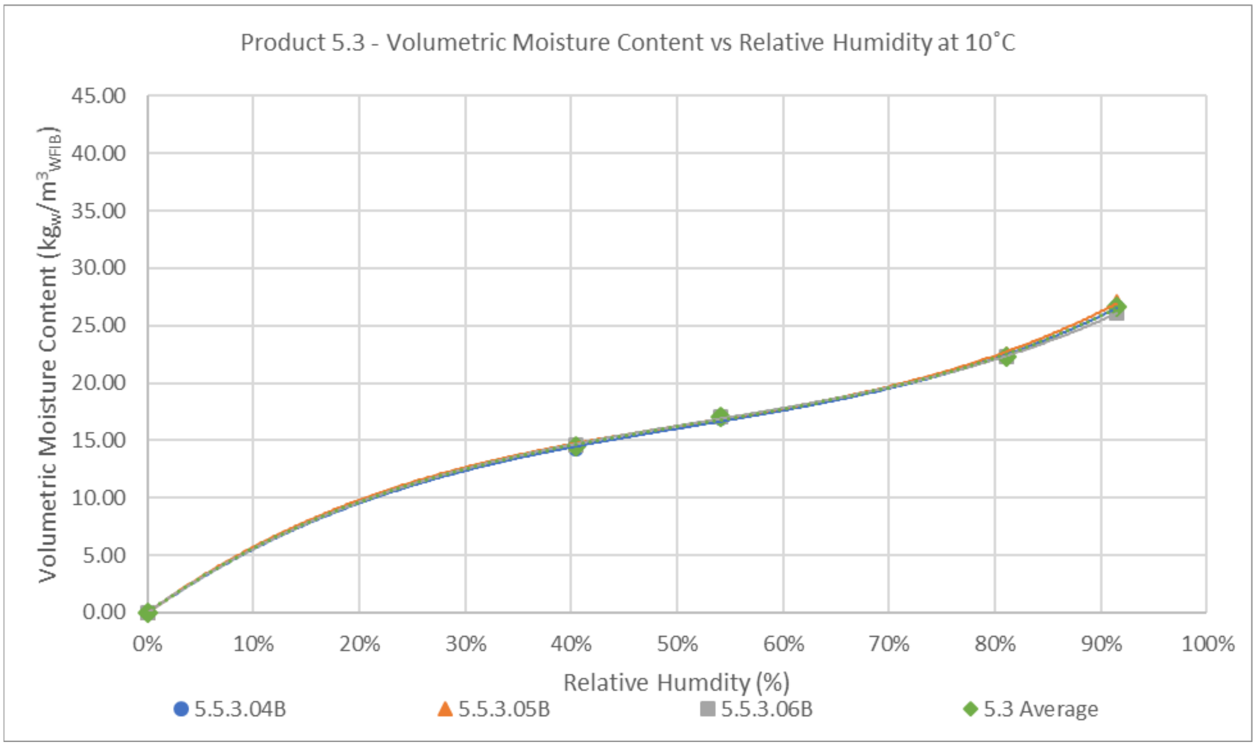


Figure C.18 – Product 5.3 Volumetric Moisture Content versus Relative Humidity at 10˚C.

Table C.24 – Volumetric Moisture Contents for Specimens 6.2.01, 6.2.02, 6.2.03, and Average over Full Relative Humidity Range at 25˚C

Test No.	Temp (˚C)	RH (%)	Specimen			6.2 Average	VMC SD	VMC CV(%)
			6.2.01	6.2.02	6.2.03			
			Volumetric MC (kg_w/m^3_{WFIB})					
.1	10.07	35.2%	12.65	12.44	12.25	12.45	0.20	1.65%
.2	10.05	50.6%	14.45	14.19	14.03	14.22	0.21	1.50%
.3	9.96	80.0%	19.22	19.00	18.43	18.88	0.41	2.22%
.4	10.14	90.5%	22.59	22.23	21.30	22.04	0.67	3.14%

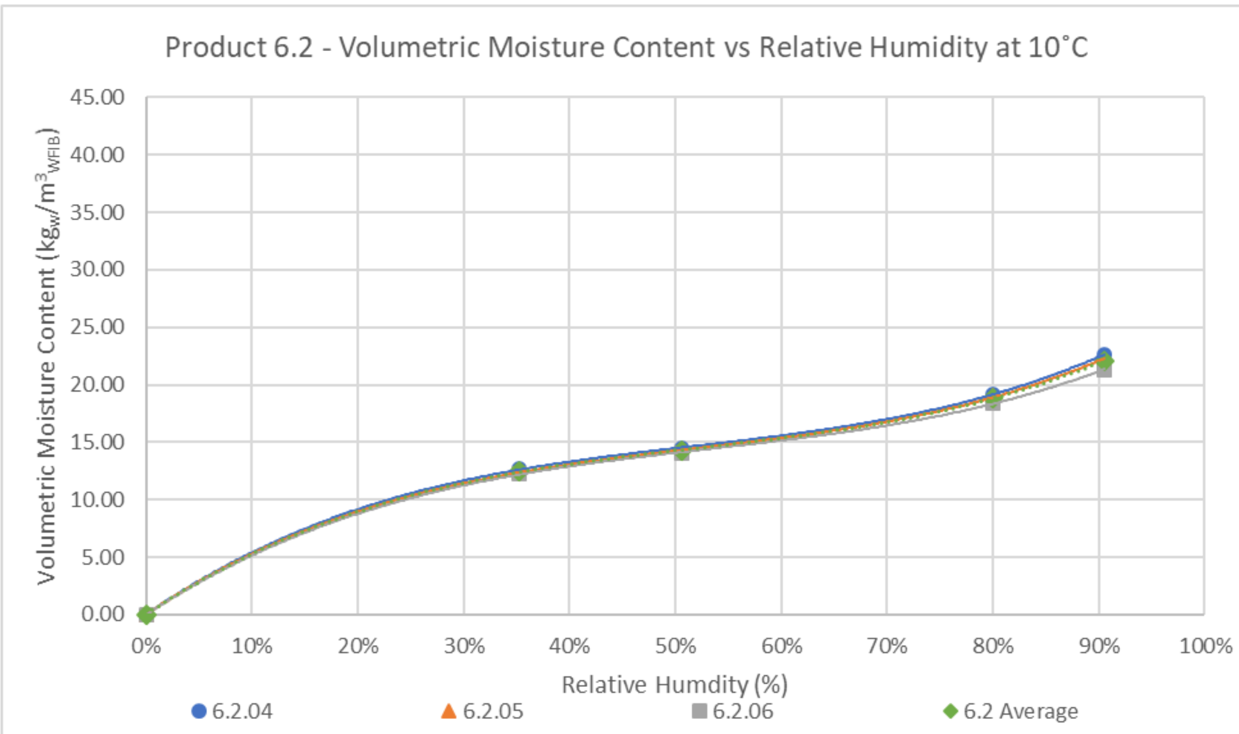


Figure C.19 – Product 5.3 Volumetric Moisture Content versus Relative Humidity at 10˚C.

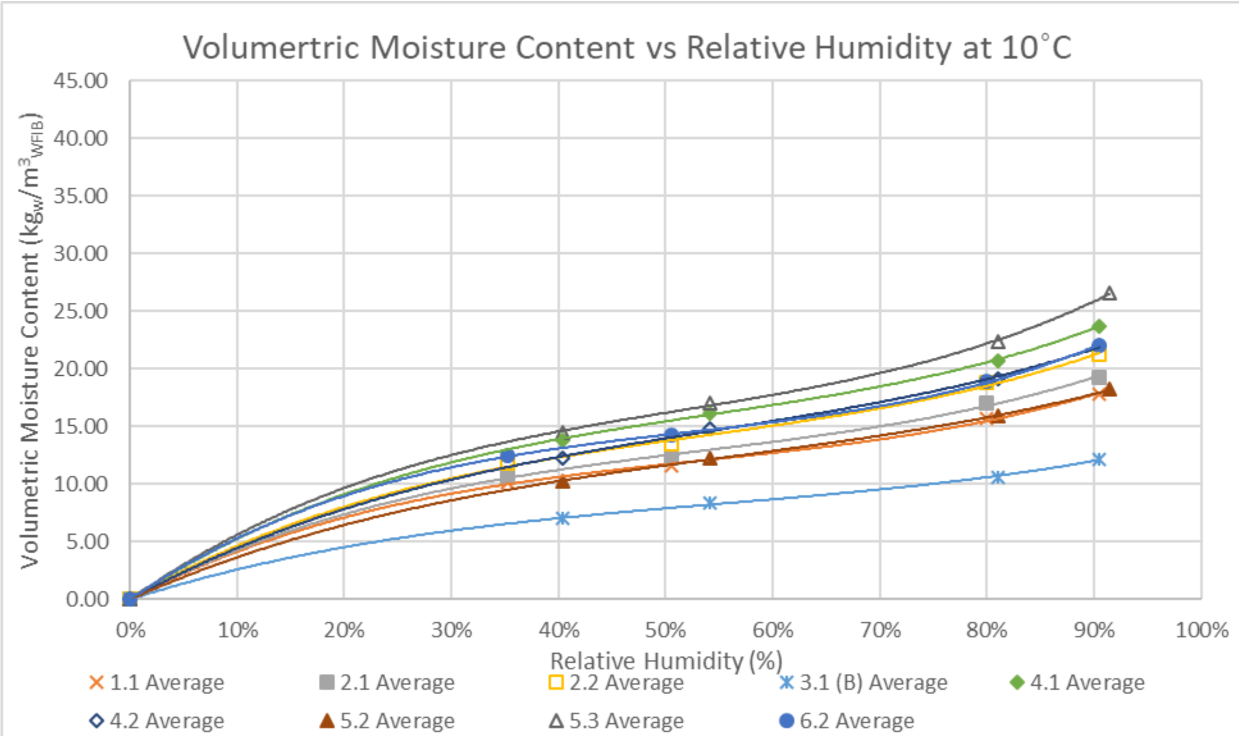


Figure C.20 – All Products Volumetric Moisture Content versus Relative Humidity at 10˚C.

Appendix E - Moisture Sorption Test Results at 10˚C and 25˚C

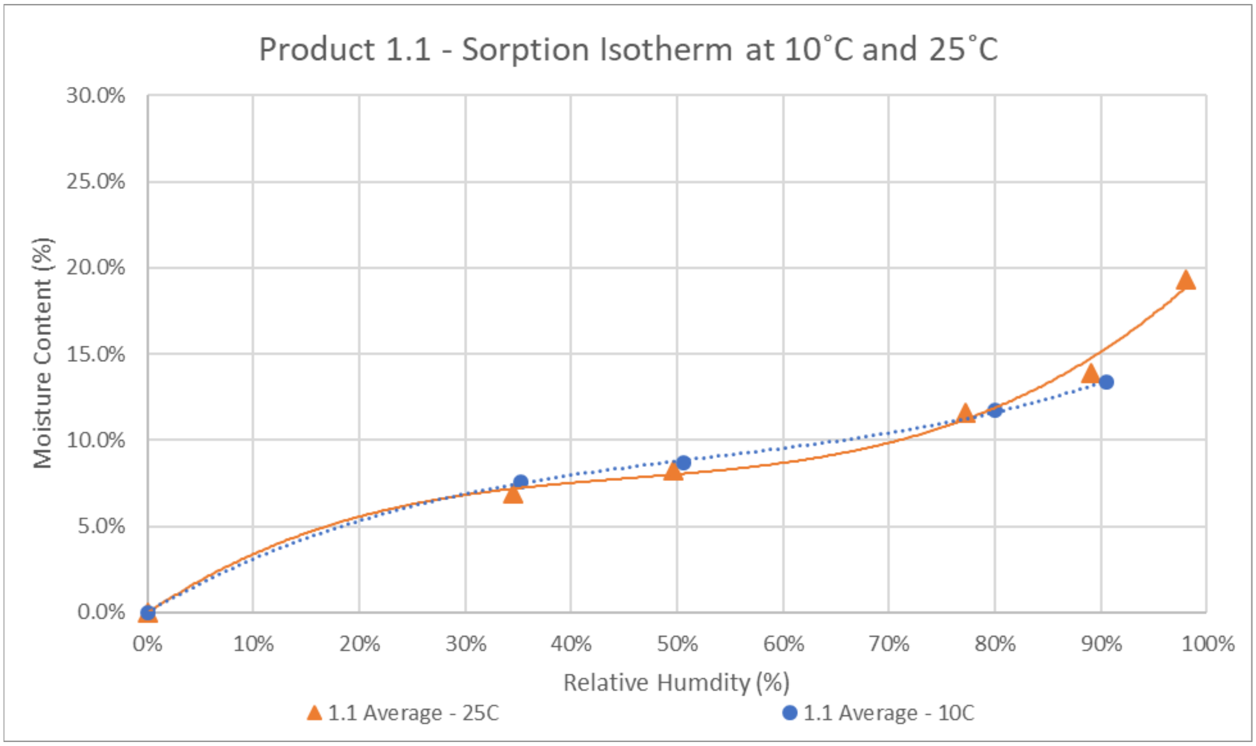


Figure D.1 – Average Sorption Isotherms for Product 1.1 over Full Relative Humidity Range at 10˚C and 25 ˚C.

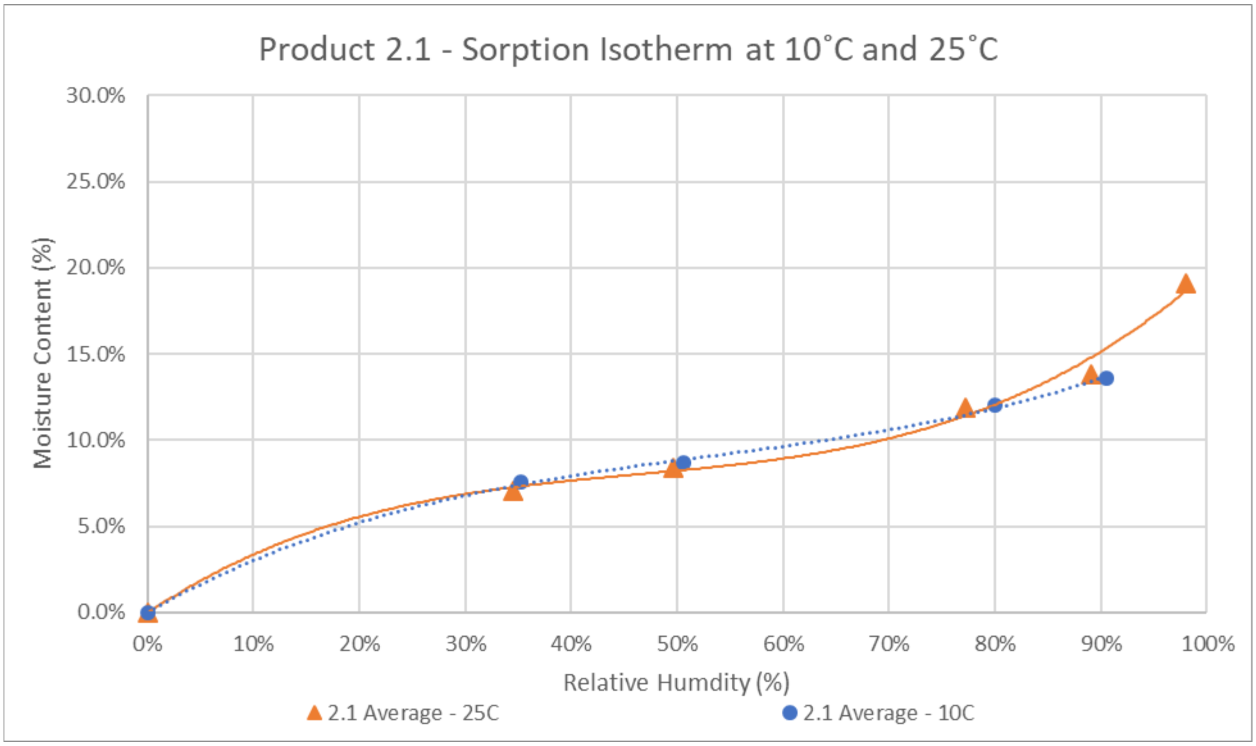


Figure D.2 – Average Sorption Isotherms for Product 2.1 over Full Relative Humidity Range at 10˚C and 25 ˚C.

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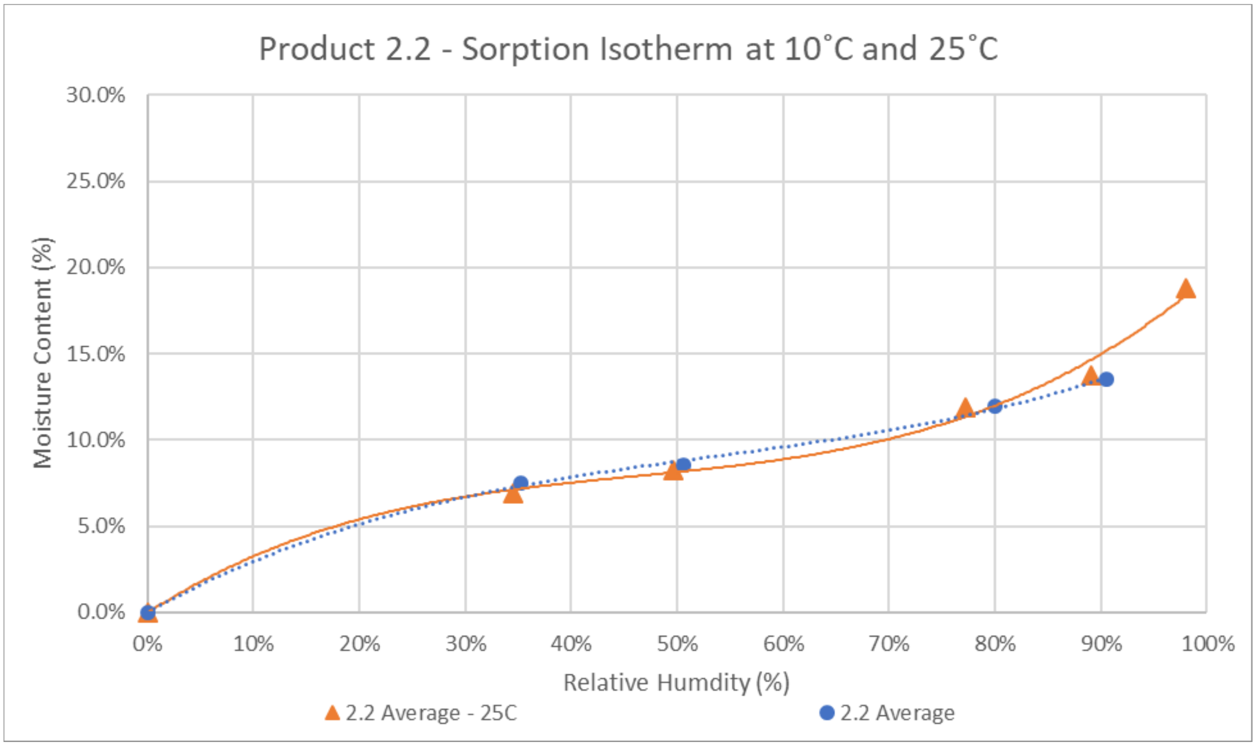


Figure D.3 – Average Sorption Isotherms for Product 2.2 over Full Relative Humidity Range at 10˚C and 25 ˚C.

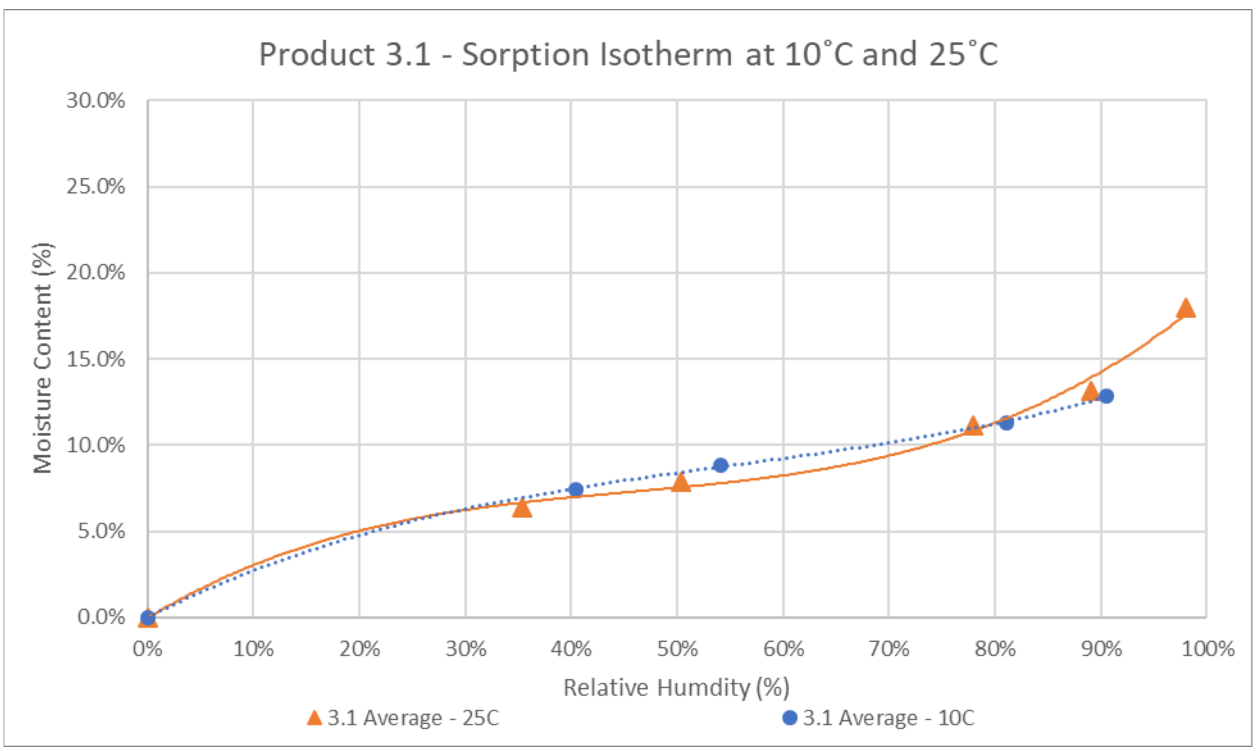


Figure D.4 – Average Sorption Isotherms for Product 3.1 over Full Relative Humidity Range at 10˚C and 25 ˚C.

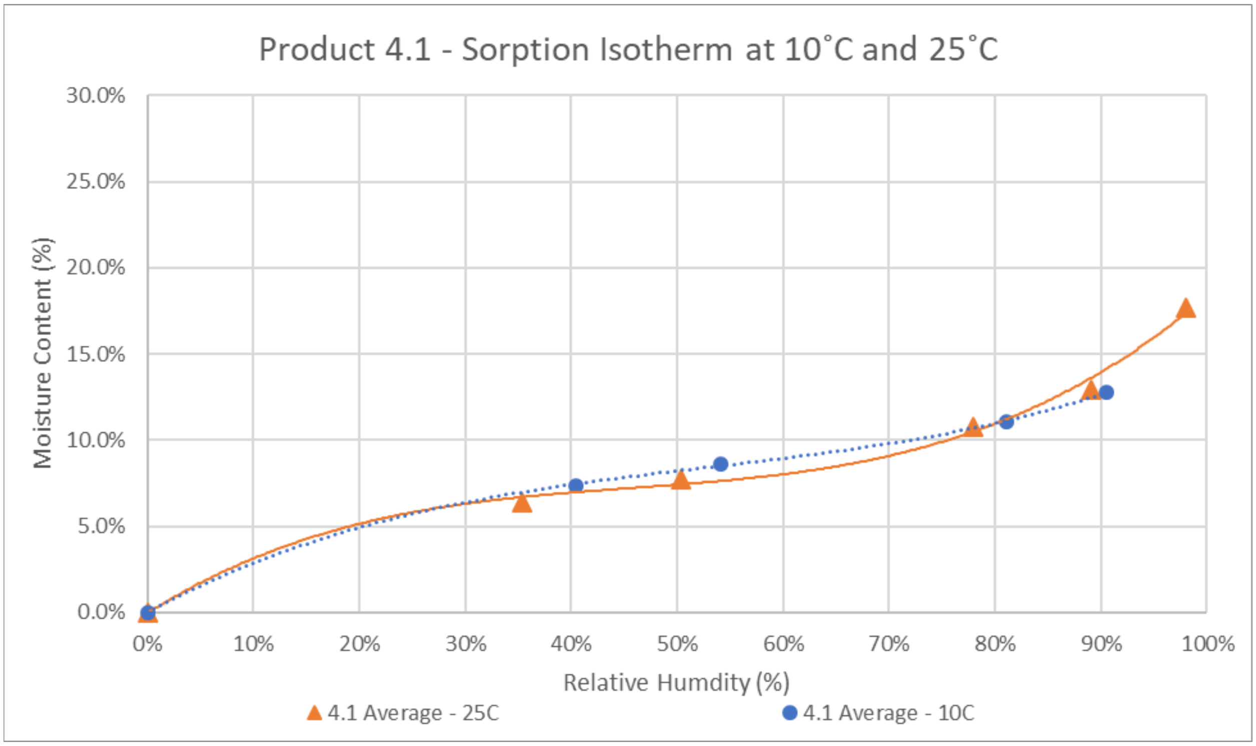


Figure D.5 – Average Sorption Isotherms for Product 4.1 over Full Relative Humidity Range at 10˚C and 25 ˚C.

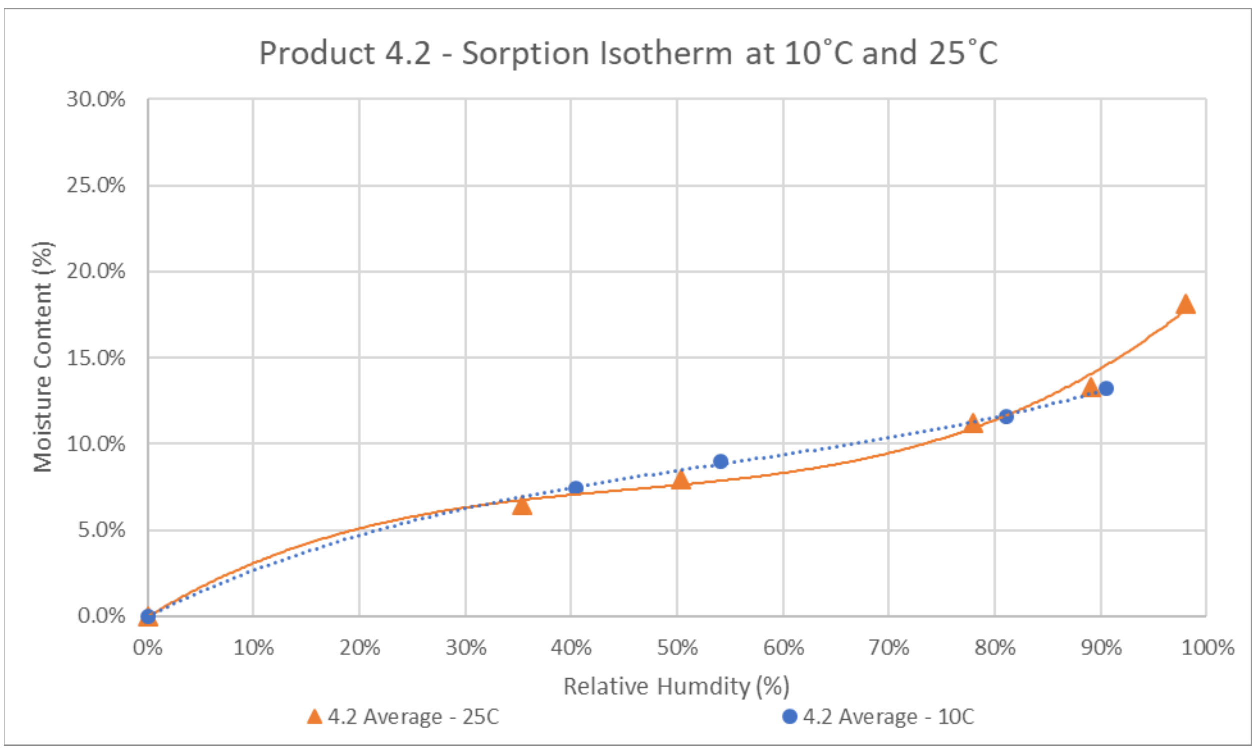


Figure D.6 – Average Sorption Isotherms for Product 4.2 over Full Relative Humidity Range at 10˚C and 25 ˚C.

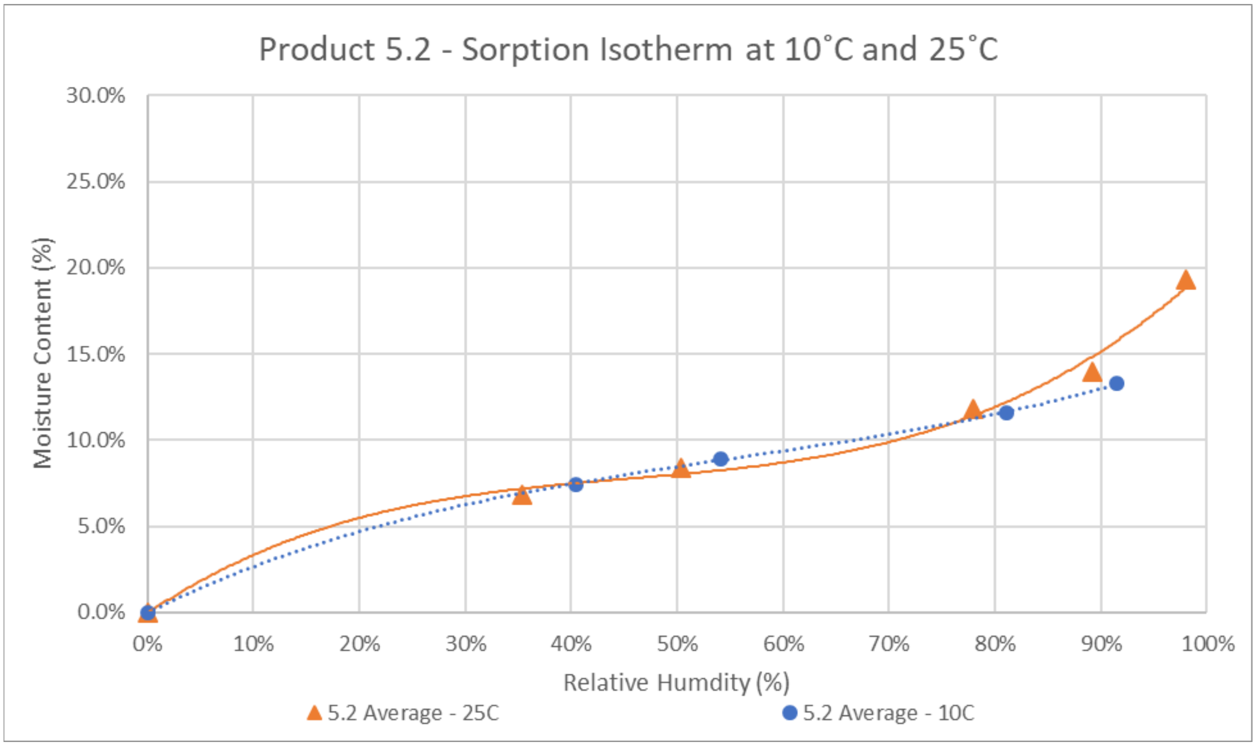


Figure D.7 – Average Sorption Isotherms for Product 5.2 over Full Relative Humidity Range at 10˚C and 25 ˚C.

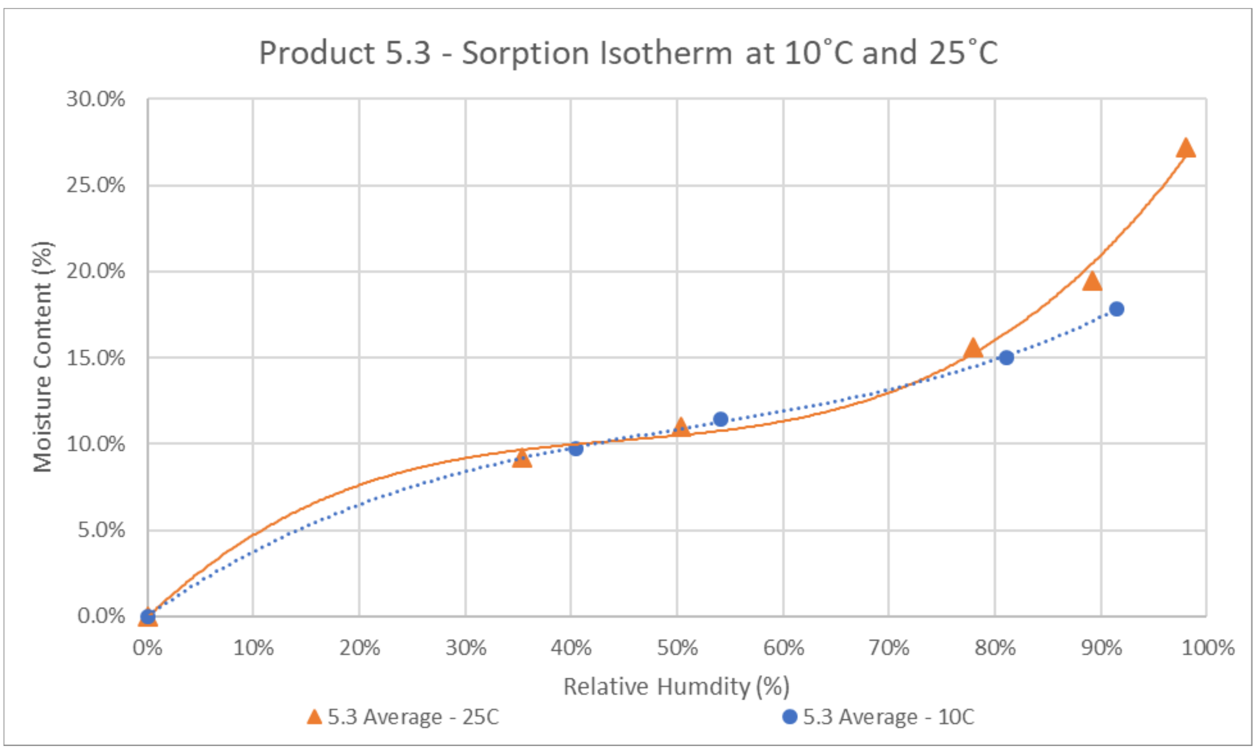


Figure D.8 – Average Sorption Isotherms for Product 5.3 over Full Relative Humidity Range at 10˚C and 25 ˚C.

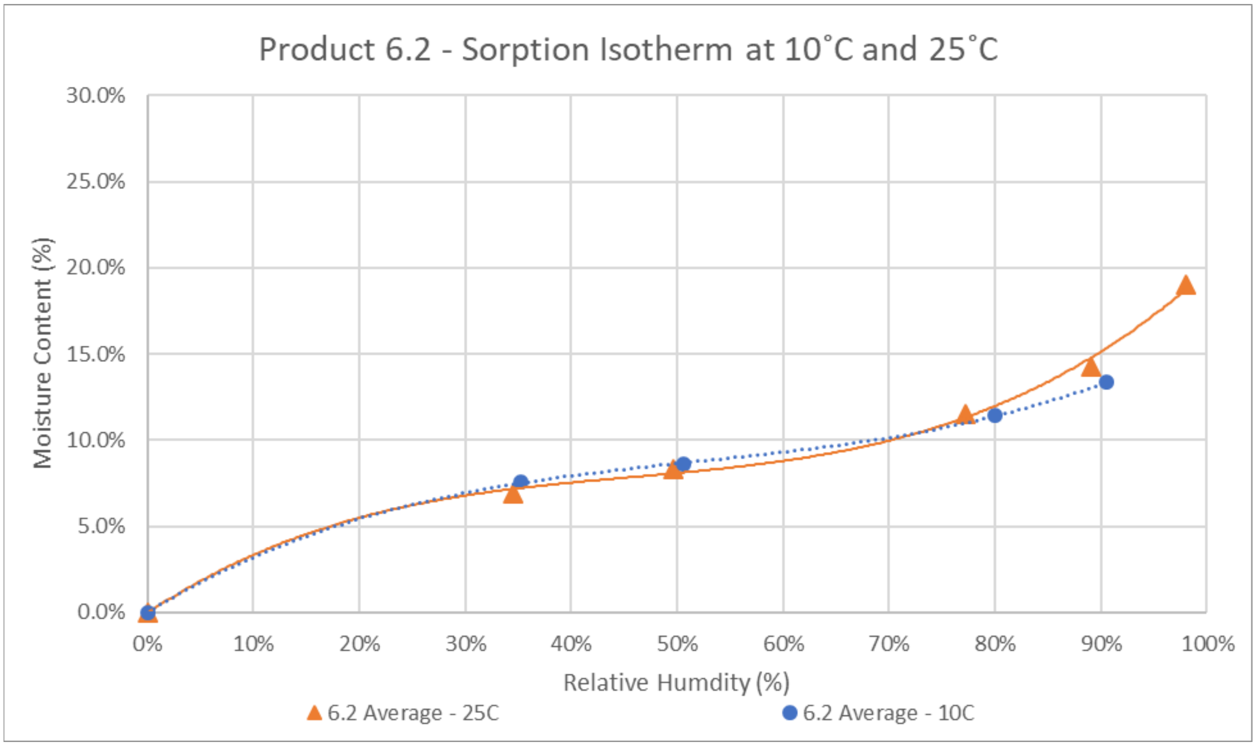


Figure D.9 – Average Sorption Isotherms for Product 6.2 over Full Relative Humidity Range at 10˚C and 25 ˚C.

Appendix F - Vapour Permeability Test Results at 25˚C

Table E.1 - Permeabilities of Specimens 1.1.0.1, 1.1.02.1, 1.1.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	34.4%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	0.44%, 1.29%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	18%	42%	66%	82%
Pressure Differential (Pa)	983	516	730	451
1.1.03.1	55.28	72.93	68.52	47.14
1.1.02.1	55.53	73.43	70.11	46.53
1.1.01.1	55.25	79.41	67.45	48.94
1.1 Average	55.35	75.26	68.69	47.54
Standard Deviation	0.15	3.60	1.34	1.25
Coefficient of variation	0.28%	4.79%	1.95%	2.63%

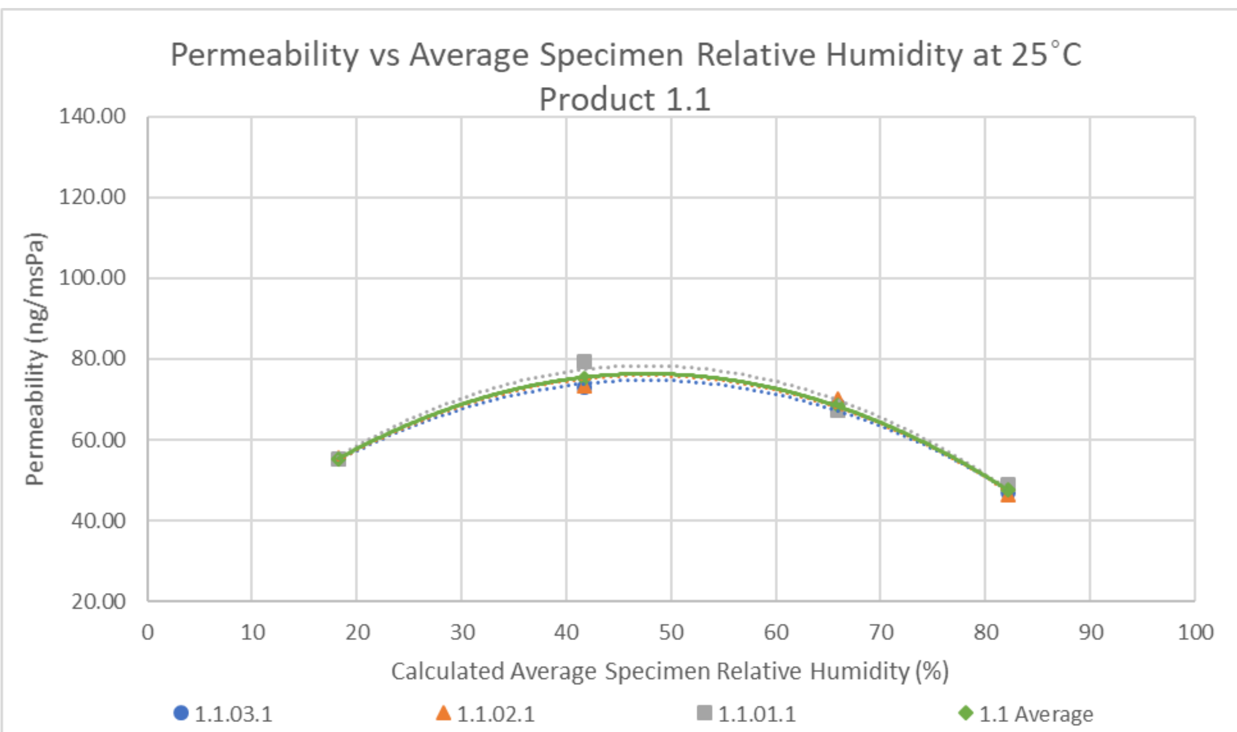


Figure E.1 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.2 - Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
1.1.03.1	98.00	45.28
1.1.02.1	98.61	50.08
1.1.01.1	104.84	38.64
1.1 Average	100.48	44.67
Standard Deviation	3.78	5.74
Coefficient of variation	3.76%	12.86%

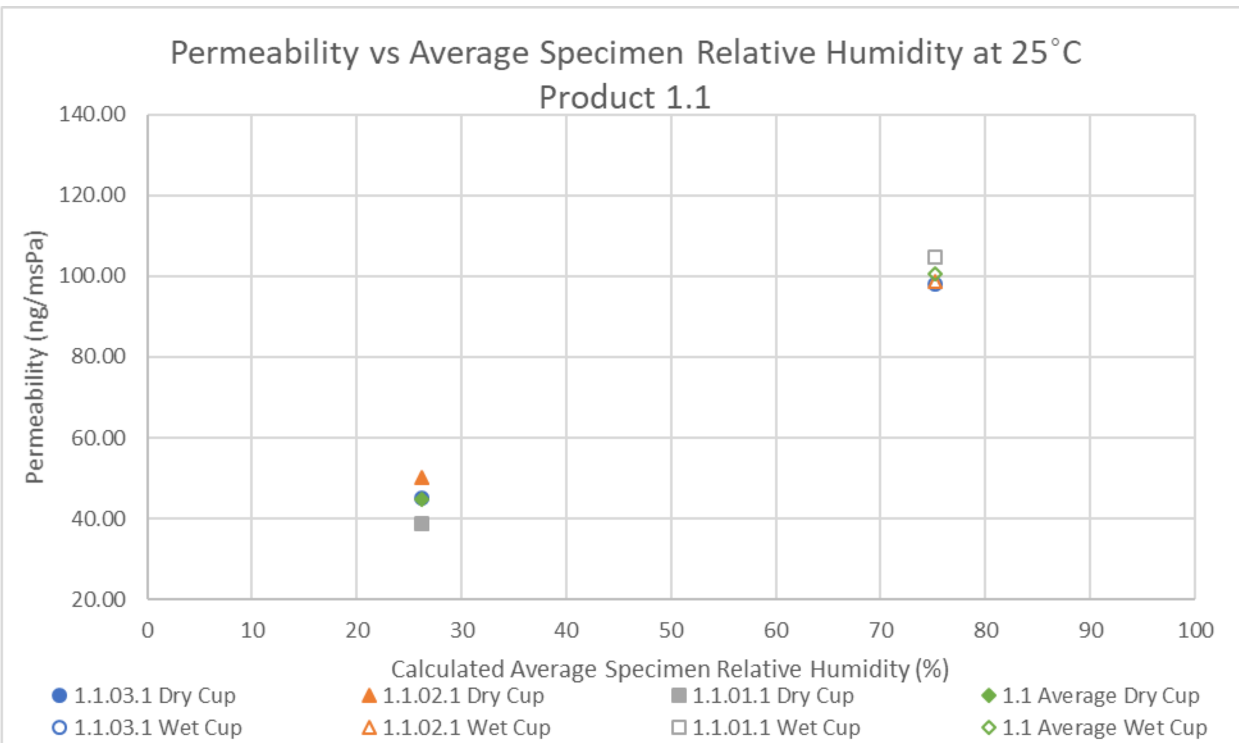


Figure E.2 – Permeabilities of Specimens 1.1.01, 1.1.02, 1.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.3 - Permeabilities of Specimens 2.1.0.1, 2.1.02.1, 2.1.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	34.4%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	0.44%, 1.29%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	18%	42%	66%	82%
Pressure Differential (Pa)	983	516	730	451
2.1.03.1	55.28	72.93	68.52	47.14
2.1.02.1	55.53	73.43	70.11	46.53
2.1.01.1	55.25	79.41	67.45	48.94
2.1 Average	55.35	75.26	68.69	47.54
Standard Deviation	0.15	3.60	1.34	1.25
Coefficient of variation	0.28%	4.79%	1.95%	2.63%

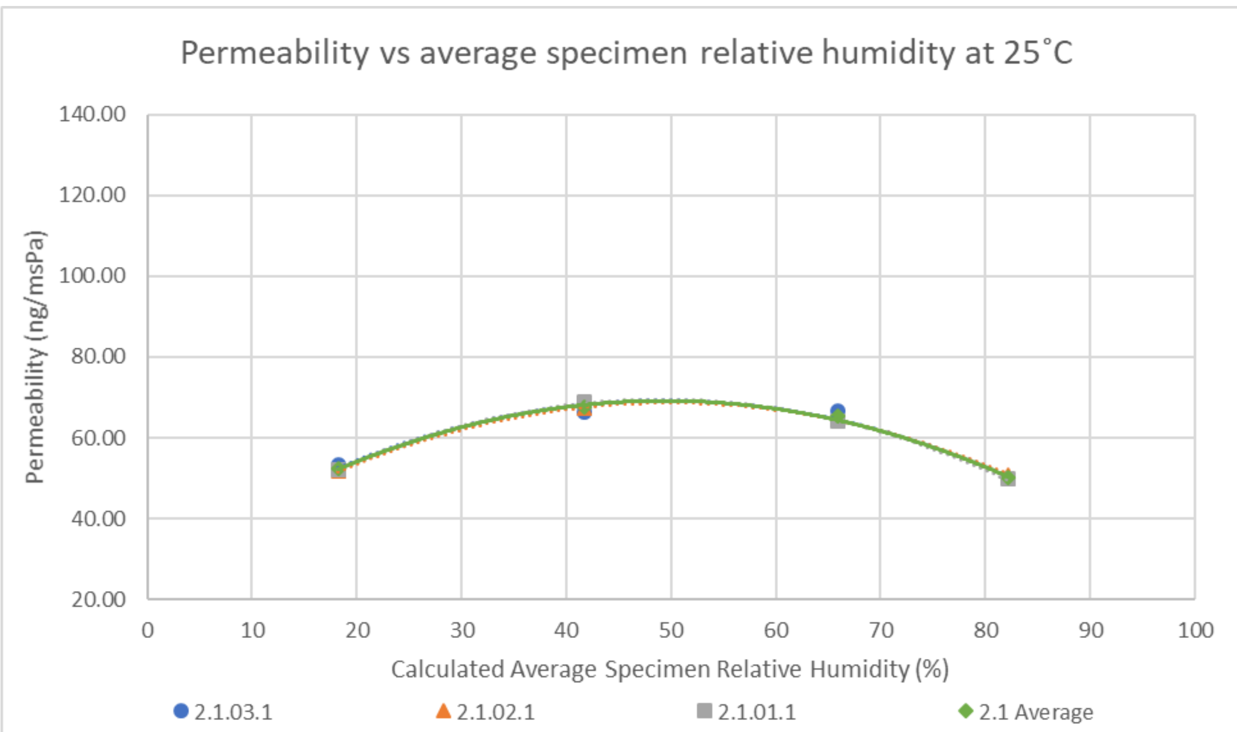


Figure E.3 – Permeabilities of Specimens 2.1.01, 2.1.02, 2.1.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.4 - Permeabilities of Specimens 2.1.01, 2.1.02, 2.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
2.1.03.1	98.00	45.28
2.1.02.1	98.61	50.08
2.1.01.1	104.84	38.64
2.1 Average	100.48	44.67
Standard Deviation	3.78	5.74
Coefficient of variation	3.76%	12.86%

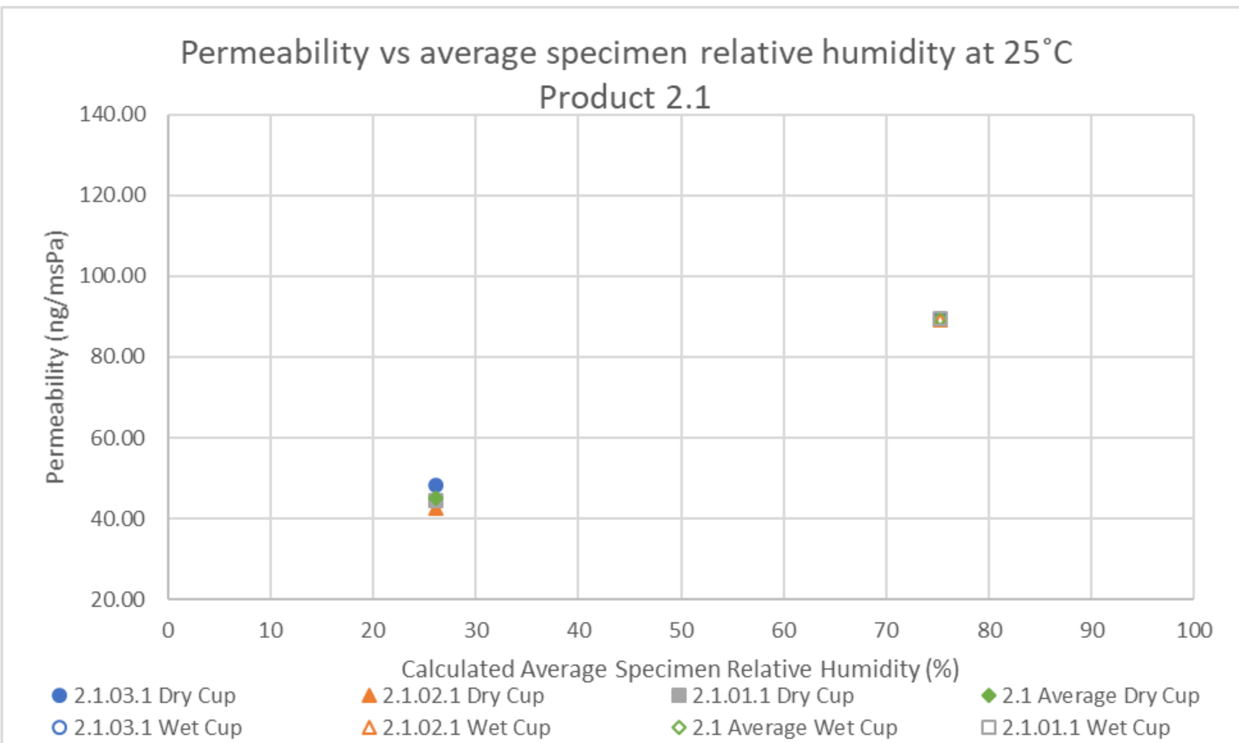


Figure E.4 – Permeabilities of Specimens 2.1.01, 2.1.02, 2.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.5 - Permeabilities of Specimens 2.2.0.1, 2.2.02.1, 2.2.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	34.4%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	0.44%, 1.29%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	18%	42%	66%	82%
Pressure Differential (Pa)	983	516	730	451
2.2.03.1	75.46	77.14	73.84	60.58
2.2.02.1	72.71	72.53	68.83	60.31
2.2.01.1	71.53	67.26	68.92	59.34
2.2 Average	73.23	72.31	70.53	60.08
Standard Deviation	2.02	4.94	2.87	0.65
Coefficient of variation	2.76%	6.84%	4.06%	1.08%

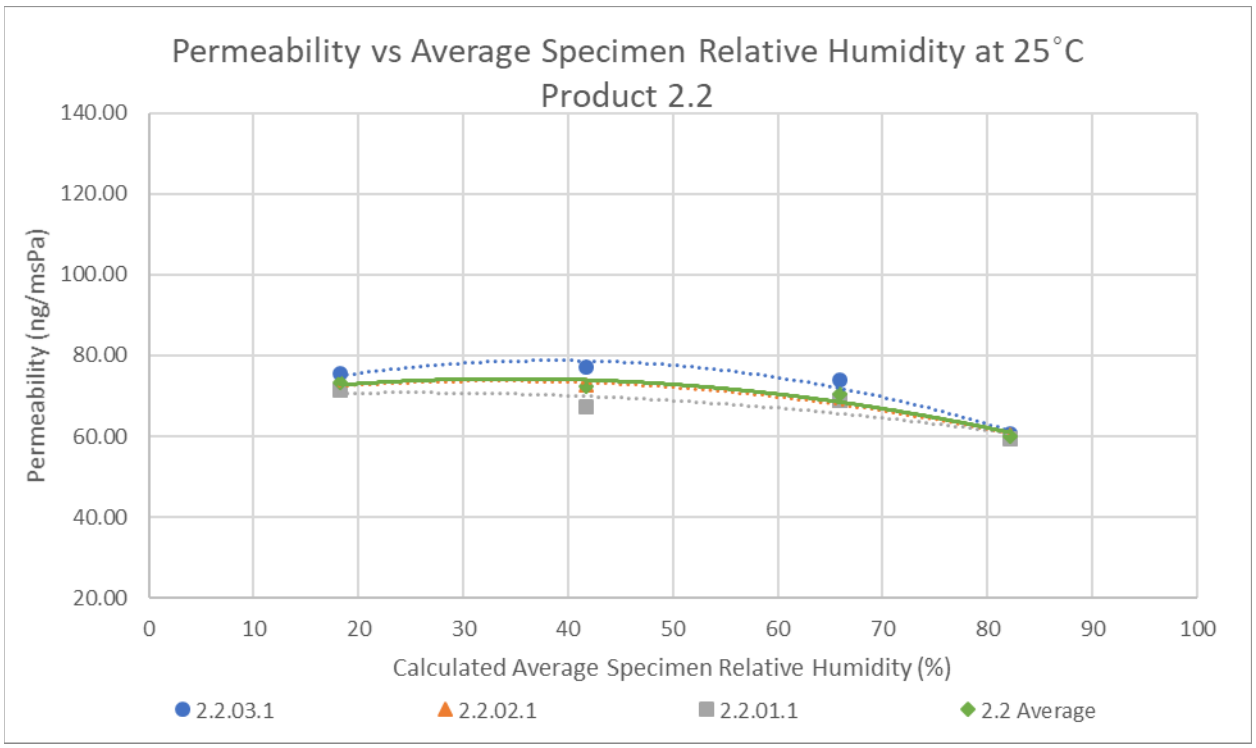


Figure E.5 – Permeabilities of Specimens 2.2.01, 2.2.02, 2.2.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.6 - Permeabilities of Specimens 2.2.01, 2.2.02, 2.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
2.2.03.1	95.51	67.93
2.2.02.1	86.85	60.75
2.2.01.1	87.88	62.24
2.2 Average	90.08	63.64
Standard Deviation	4.73	3.79
Coefficient of variation	5.25%	5.96%

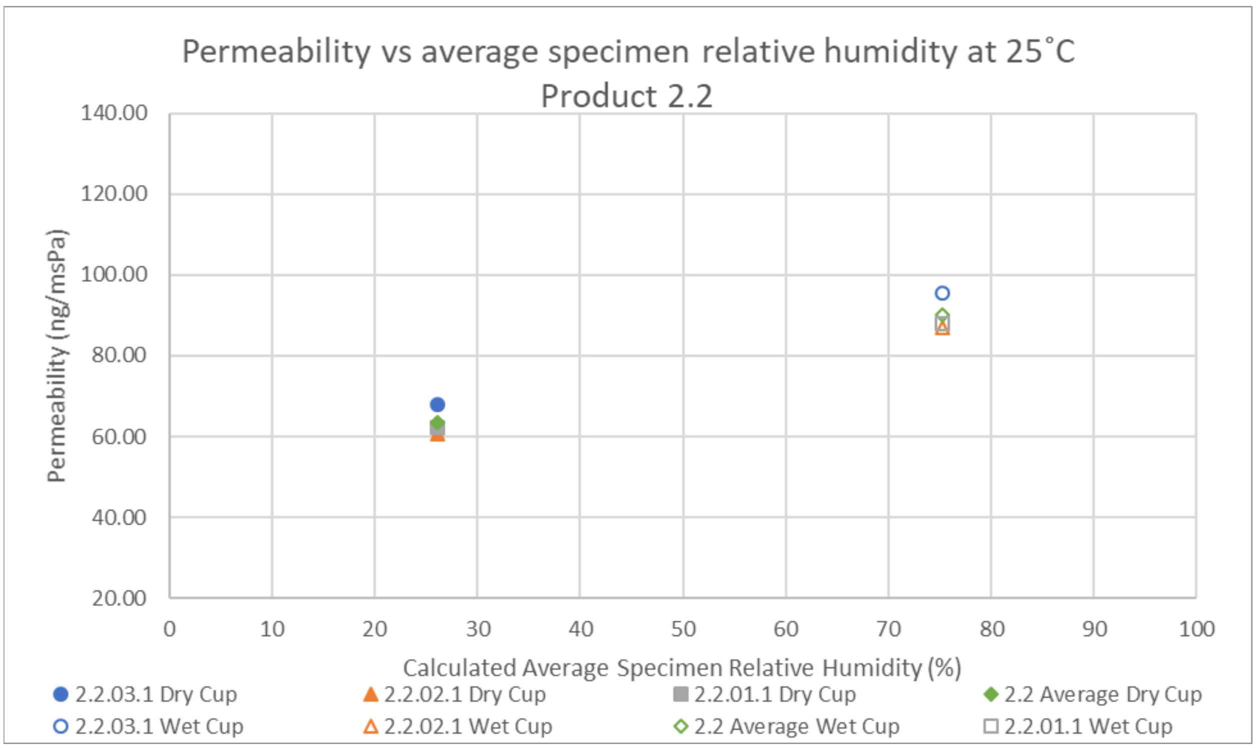


Figure E.6 – Permeabilities of Specimens 2.2.01, 2.2.02, 2.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.7 - Permeabilities of Specimens 3.1.0.1, 3.1.02.1, 3.1.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	35.3%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	1.46%, 4.13%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	19%	42%	66%	82%
Pressure Differential (Pa)	1010	516	730	408
3.1.03.1	45.06	87.42	80.46	61.65
3.1.02.1	44.99	87.81	81.46	62.25
3.1.01.1	43.98	86.41	82.41	62.86
3.1 Average	44.67	87.21	81.44	62.26
Standard Deviation	0.61	0.72	0.98	0.61
Coefficient of variation	1.36%	0.83%	1.20%	0.97%

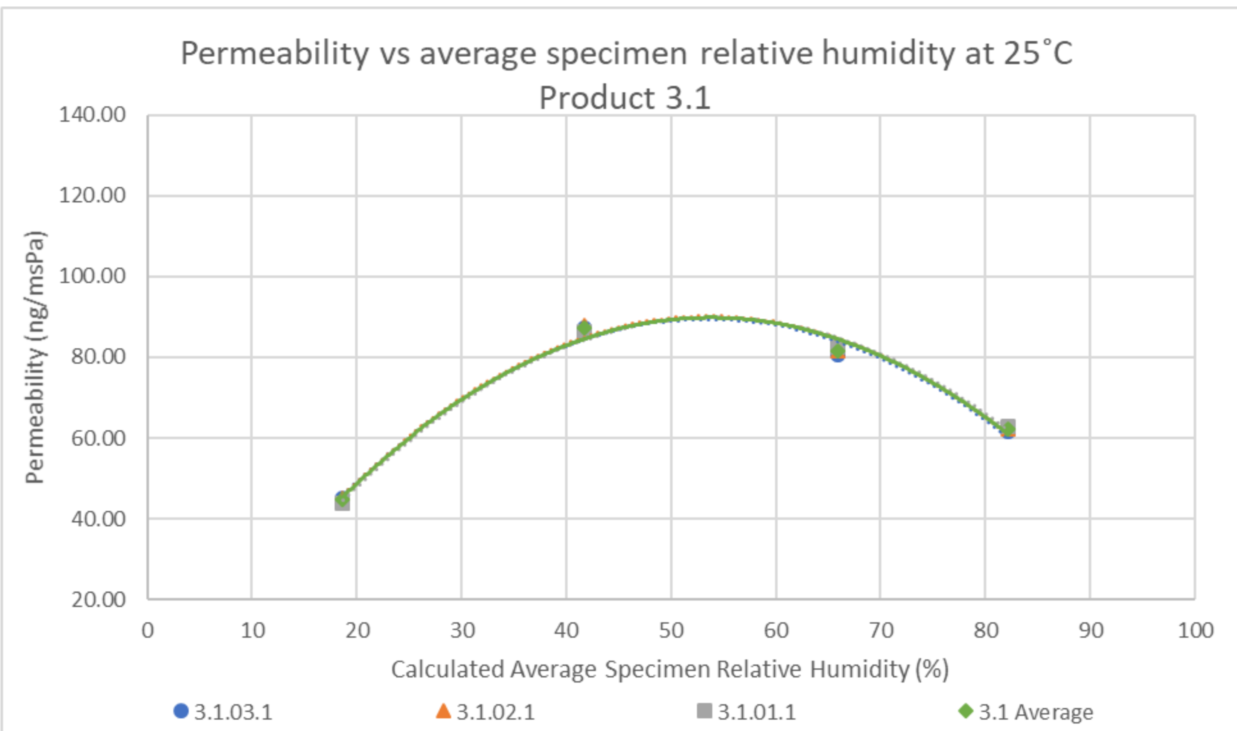


Figure E.7 – Permeabilities of Specimens 3.1.01, 3.1.02, 3.1.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.8 - Permeabilities of Specimens 3.1.01, 3.1.02, 3.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
3.1.03.1	118.14	52.54
3.1.02.1	114.79	49.76
3.1.01.1	114.30	52.66
3.1 Average	115.74	51.65
Standard Deviation	2.09	1.64
Coefficient of variation	1.80%	3.17%

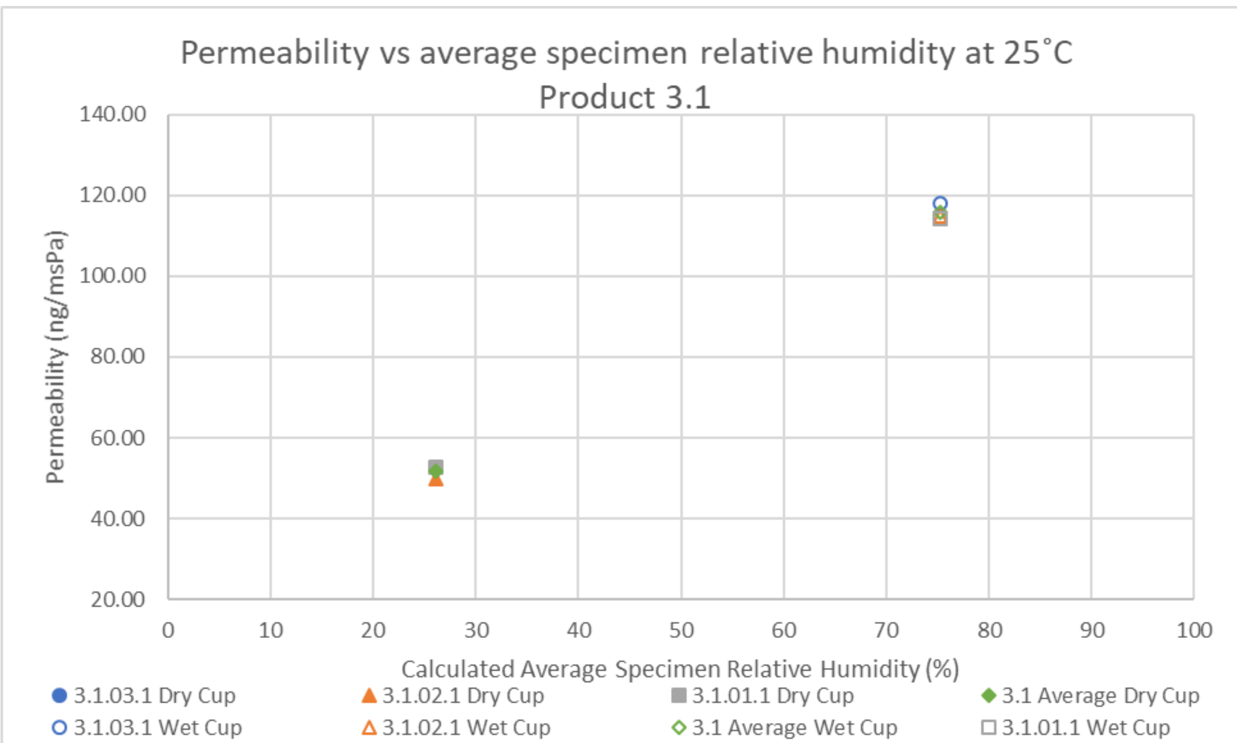


Figure E.8 – Permeabilities of Specimens 3.1.01, 3.1.02, 3.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.9 - Permeabilities of Specimens 4.1.0.1, 4.1.02.1, 4.1.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	35.3%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	1.46%, 4.13%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	19%	42%	66%	82%
Pressure Differential (Pa)	1010	516	730	408
4.1.03.1	44.62	69.30	65.60	46.32
4.1.02.1	44.27	67.28	64.64	45.64
4.1.01.1	42.77	65.75	63.94	45.20
4.1 Average	43.89	67.44	64.73	45.72
Standard Deviation	0.98	1.78	0.84	0.57
Coefficient of variation	2.23%	2.64%	1.29%	1.24%

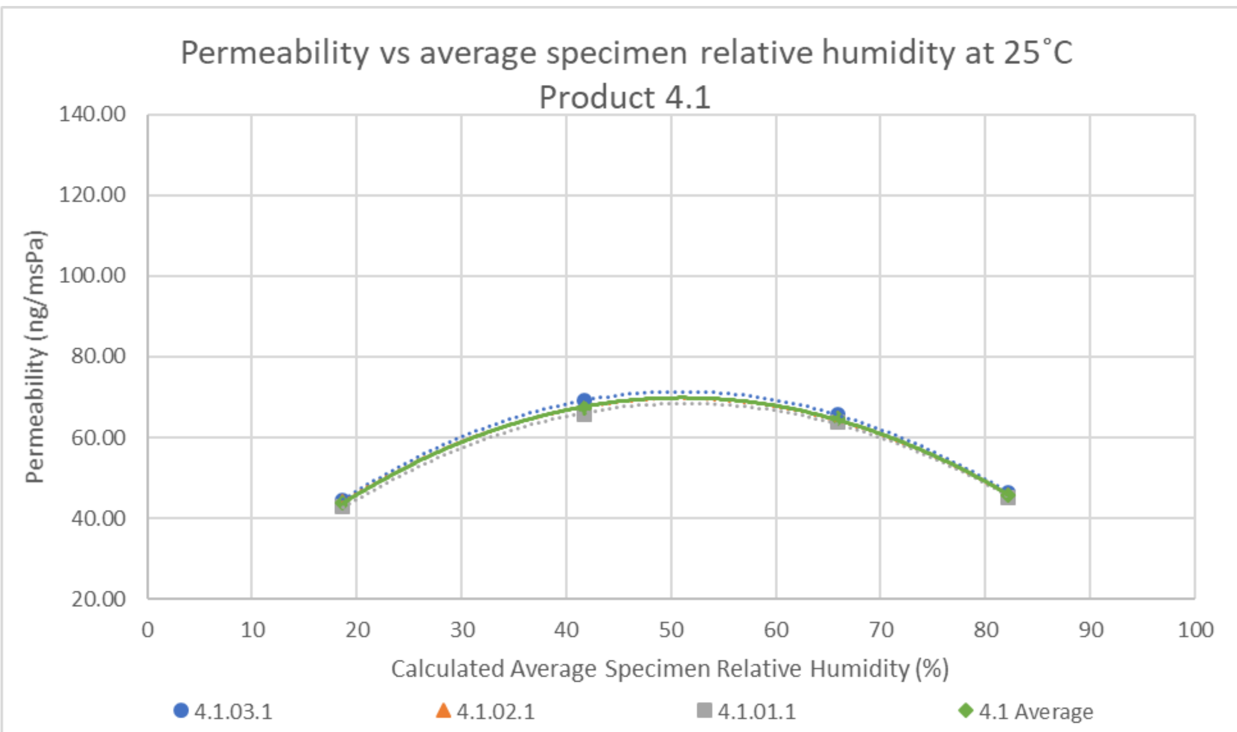


Figure E.9 – Permeabilities of Specimens 4.1.01, 4.1.02, 4.1.03, and Average for Modified Cup Test Conditions at 25 ˚C

Table E.10 - Permeabilities of Specimens 4.1.01, 4.1.02, 4.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
4.1.03.1	94.09	49.79
4.1.02.1	88.86	49.52
4.1.01.1	89.54	49.65
4.1 Average	90.83	49.65
Standard Deviation	2.84	0.14
Coefficient of variation	3.13%	0.28%

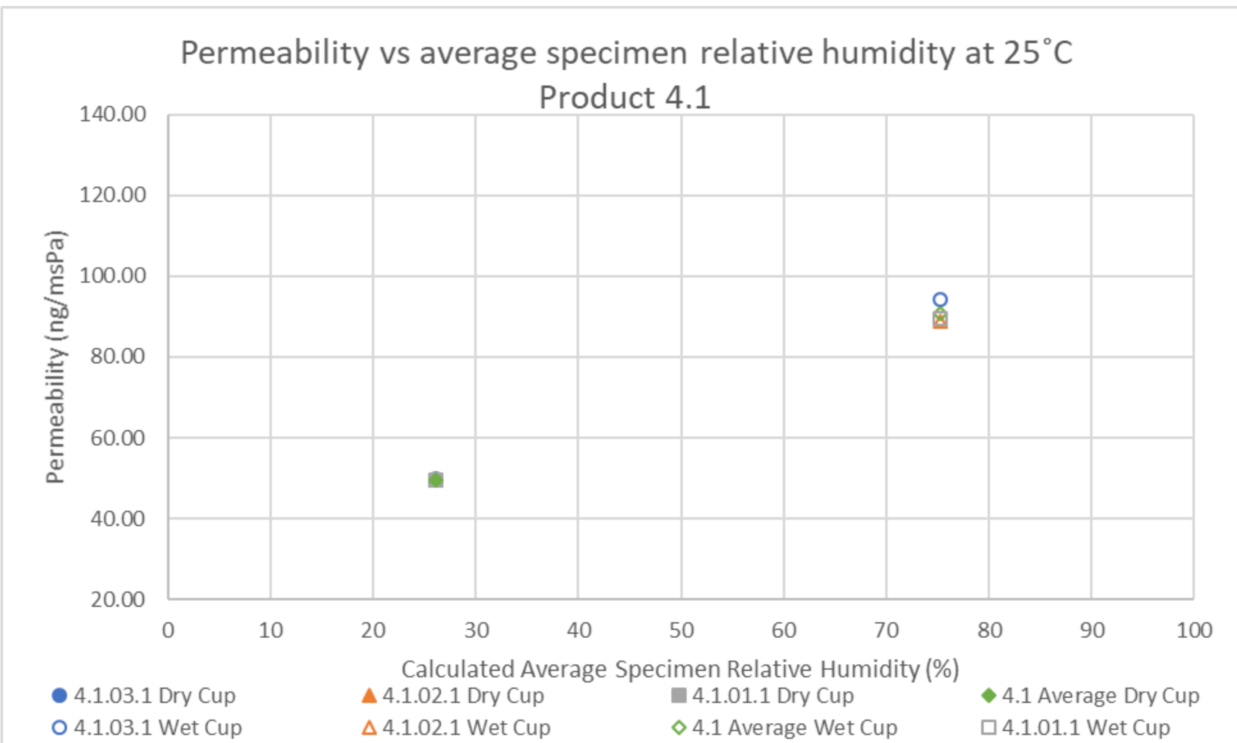


Figure E.10 – Permeabilities of Specimens 4.1.01, 4.1.02, 4.1.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.11 - Permeabilities of Specimens 4.2.0.1, 4.2.02.1, 4.2.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	35.3%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	1.46%, 4.13%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	19%	42%	66%	82%
Pressure Differential (Pa)	1010	516	730	408
4.2.03.1	57.88	76.63	74.75	52.84
4.2.02.1	56.68	77.35	75.79	53.27
4.2.01.1	55.17	76.85	74.91	54.04
4.2 Average	56.58	76.94	75.15	53.38
Standard Deviation	1.36	0.37	0.56	0.61
Coefficient of variation	2.40%	0.48%	0.75%	1.15%

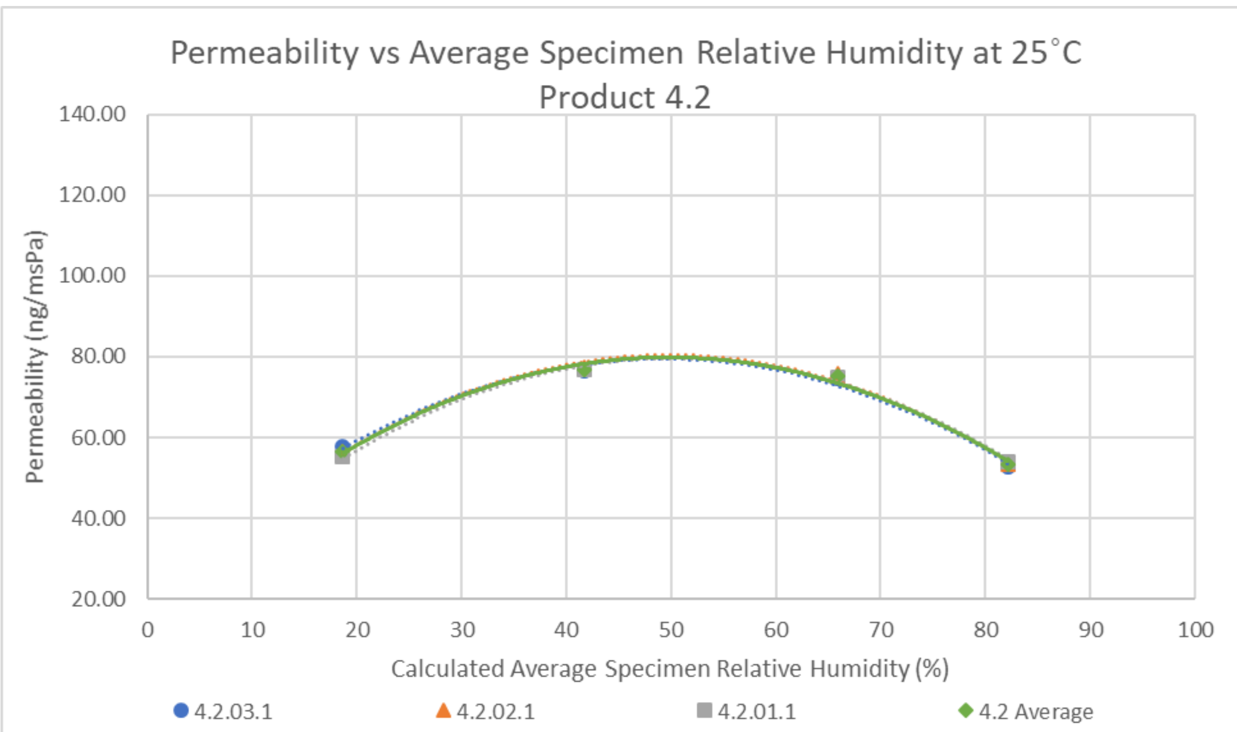


Figure E.11 – Permeabilities of Specimens 4.2.01, 4.2.02, 4.2.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.12 - Permeabilities of Specimens 4.2.01, 4.2.02, 4.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
4.2.03.1	98.63	66.05
4.2.02.1	99.05	64.32
4.2.01.1	96.47	64.54
4.2 Average	98.05	64.97
Standard Deviation	1.39	0.94
Coefficient of variation	1.41%	1.45%

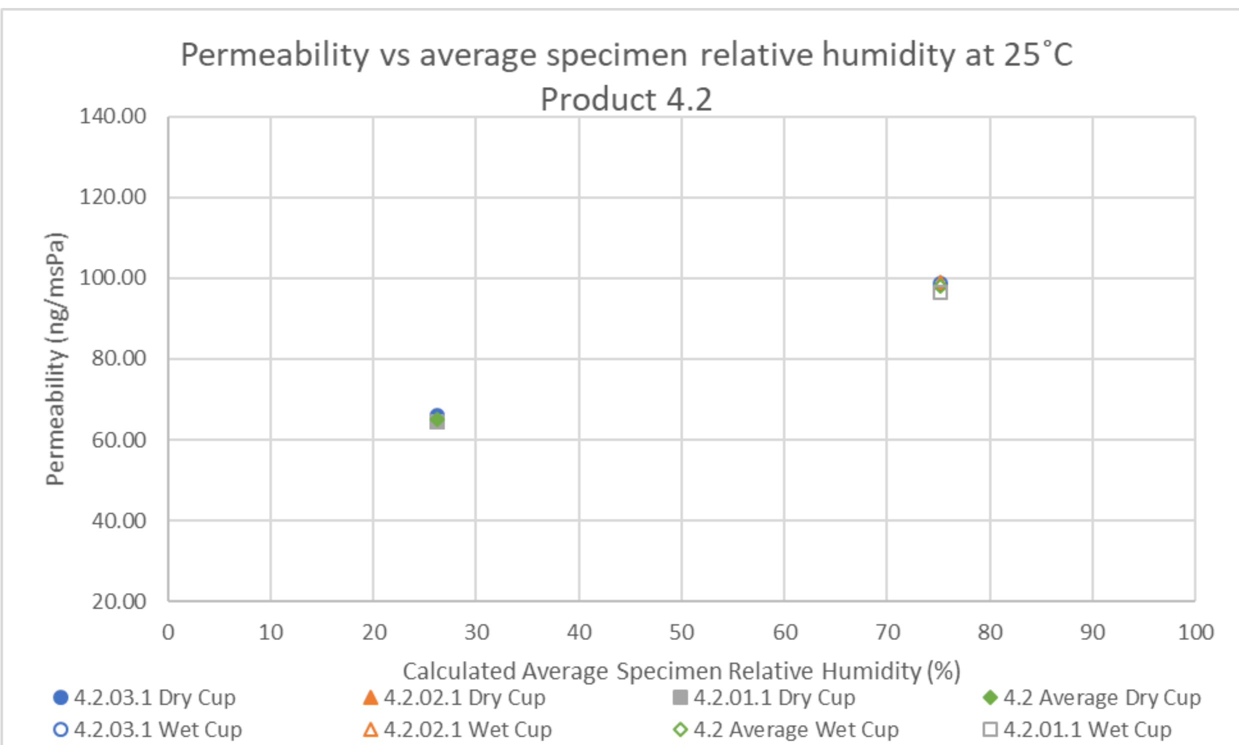


Figure E.12 – Permeabilities of Specimens 4.2.01, 4.2.02, 4.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.13 - Permeabilities of Specimens 5.2.0.1, 5.2.02.1, 5.2.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	*.1*	*.2*	*.3*	*.4*
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.07, 0.27%
Chamber RH (%)	35.3%	50.2%	77.8%	89.4%
Chamber RH - SD, CV (%)	1.46%, 4.13%	0.35, 0.70%	2.16, 2.78%	1.67%, 1.86%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	19%	42%	66%	82%
Pressure Differential (Pa)	1010	516	730	422
5.2.03.1	65.36	89.64	82.42	62.59
5.2.02.1	61.25	90.98	85.78	66.56
5.2.01.1	61.06	90.61	86.15	67.63
5.2 Average	62.56	90.41	84.78	65.59
Standard Deviation	2.43	0.69	2.05	2.66
Coefficient of variation	3.89%	0.76%	2.42%	4.05%

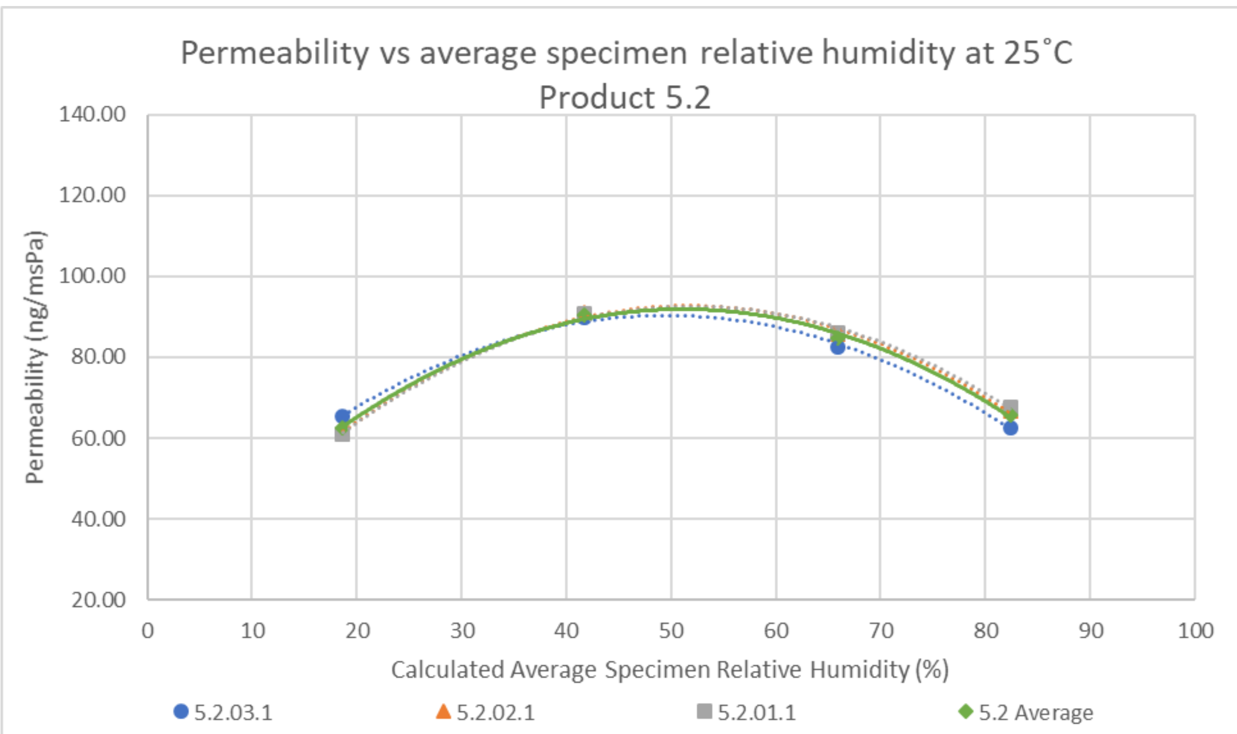


Figure E.13 – Permeabilities of Specimens 5.2.01, 5.2.02, 5.2.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.14 - Permeabilities of Specimens 5.2.01, 5.2.02, 5.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
5.2.03.1	110.47	72.62
5.2.02.1	110.80	69.93
5.2.01.1	111.05	70.23
5.2 Average	110.77	70.93
Standard Deviation	0.29	1.47
Coefficient of variation	0.27%	2.08%

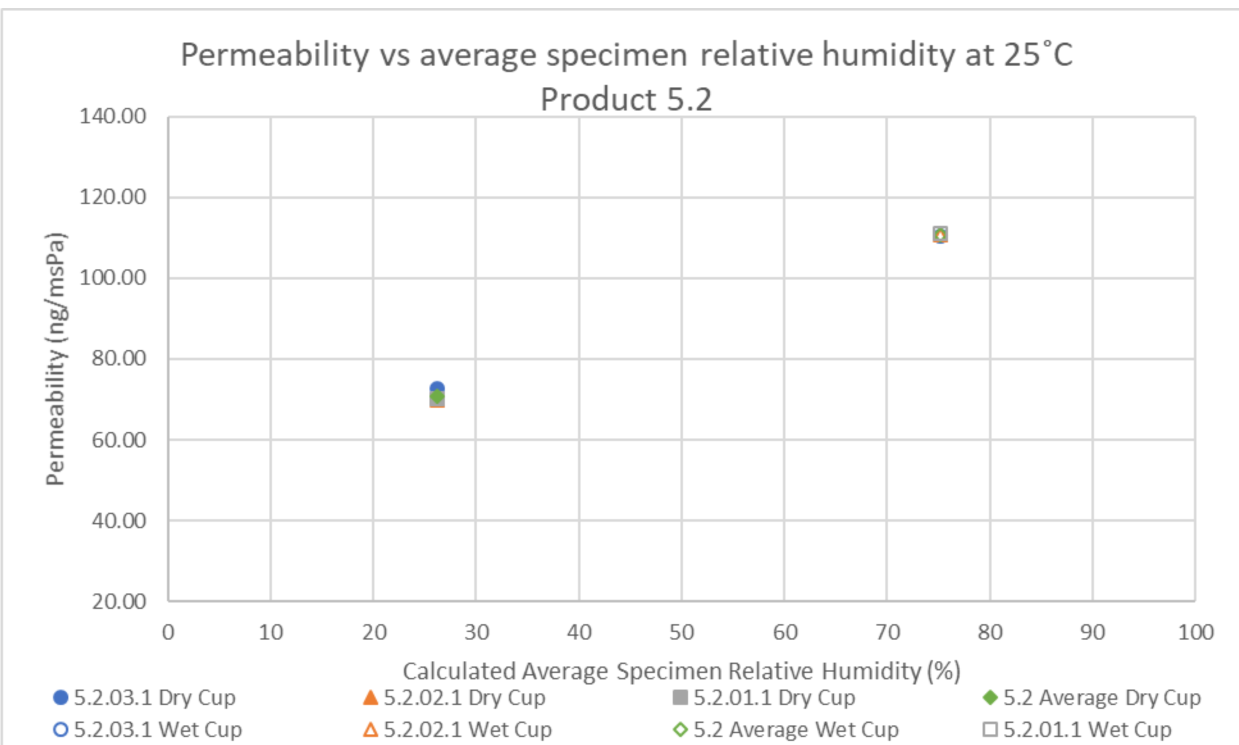


Figure E.14 – Permeabilities of Specimens 5.2.01, 5.2.02, 5.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.15 - Permeabilities of Specimens 5.3.02.1, 5.3.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.07, 0.27%
Chamber RH (%)	35.3%	50.2%	77.8%	89.4%
Chamber RH - SD, CV (%)	1.46%, 4.13%	0.35, 0.70%	2.16, 2.78%	1.67%, 1.86%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	19%	42%	66%	82%
Pressure Differential (Pa)	1010	516	730	422
5.3.02.1	59.94	87.96	92.67	78.71
5.3.01.1	65.07	92.51	94.14	80.96
5.3 Average	62.50	90.23	93.40	79.83
Standard Deviation	3.63	3.22	1.04	1.59
Coefficient of variation	5.80%	3.57%	1.11%	1.99%

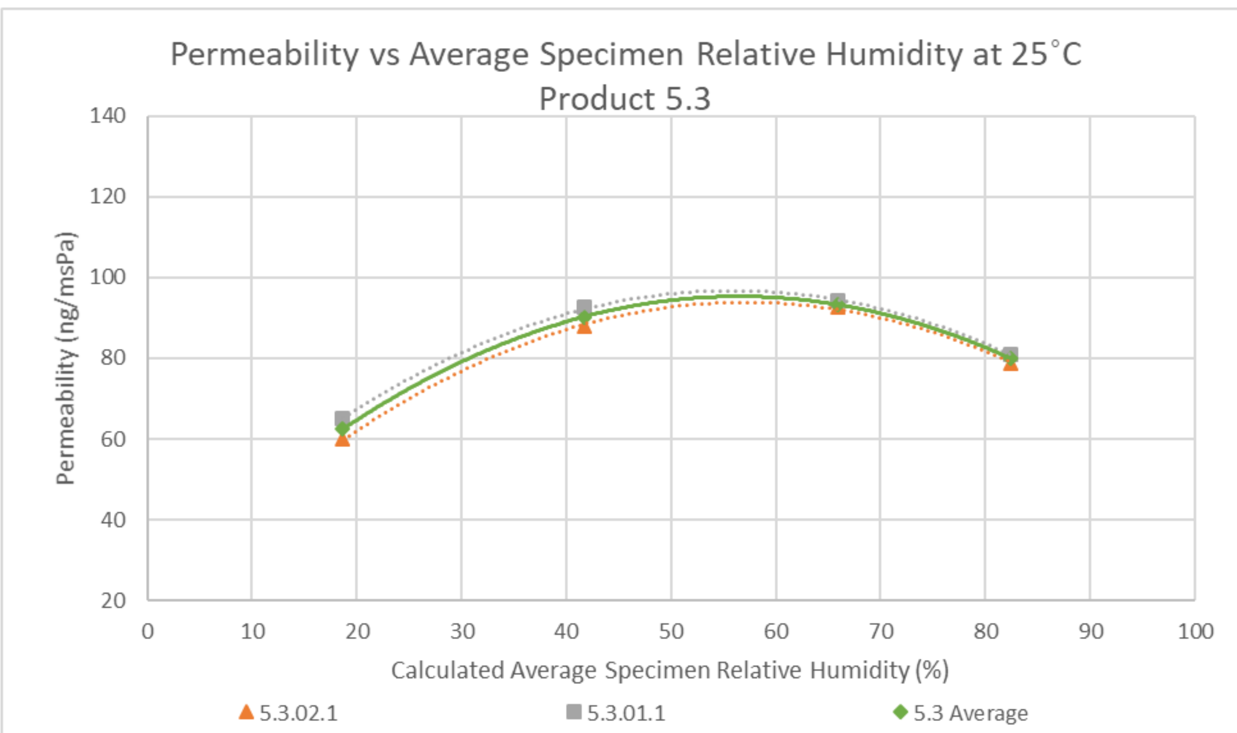


Figure E.15 – Permeabilities of Specimens 5.3.01, 5.3.02, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.16 - Permeabilities of Specimens 5.3.01, 5.3.02, 5.3.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
5.3.02.1	102.65	76.29
5.3.01.1	106.28	82.22
5.3 Average	104.47	79.25
Standard Deviation	2.57	4.19
Coefficient of variation	2.46%	5.29%

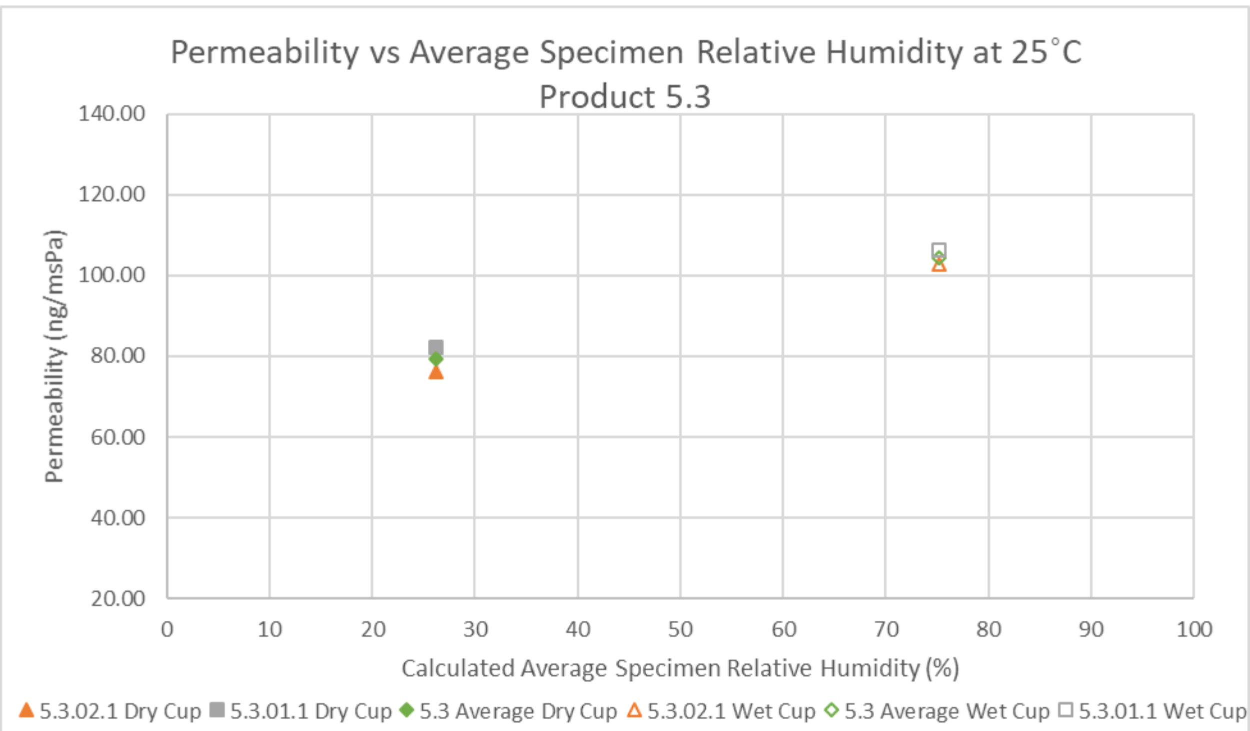


Figure E.16 – Permeabilities of Specimens 5.3.01, 5.3.02, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Table E.17 - Permeabilities of Specimens 6.2.0.1, 6.2.02.1, 6.2.01.1, and Average for Modified Cup Test Conditions at 25˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	24.2	24.3	24.4	24.4
Chamber Temp – SD, CV (%)	0.11, 0.44%	0.04, 0.17%	0.1, 0.43%	0.16, 0.67%
Chamber RH (%)	34.4%	50.2%	77.8%	88.8%
Chamber RH - SD, CV (%)	0.44%, 1.29%	0.35, 0.70%	2.16, 2.78%	2.66, 2.99%
Cup RH	2%	33%	54%	76%
Calc. Avg. Specimen RH	18%	42%	66%	82%
Pressure Differential (Pa)	983	516	730	451
6.2.03.1	73.64	71.05	70.94	57.29
6.2.02.1	71.84	71.61	71.92	57.54
6.2.01.1	72.47	72.84	72.73	57.29
6.2 Average	72.65	71.83	71.86	57.38
Standard Deviation	0.92	0.91	0.89	0.14
Coefficient of variation	1.26%	1.27%	1.24%	0.25%

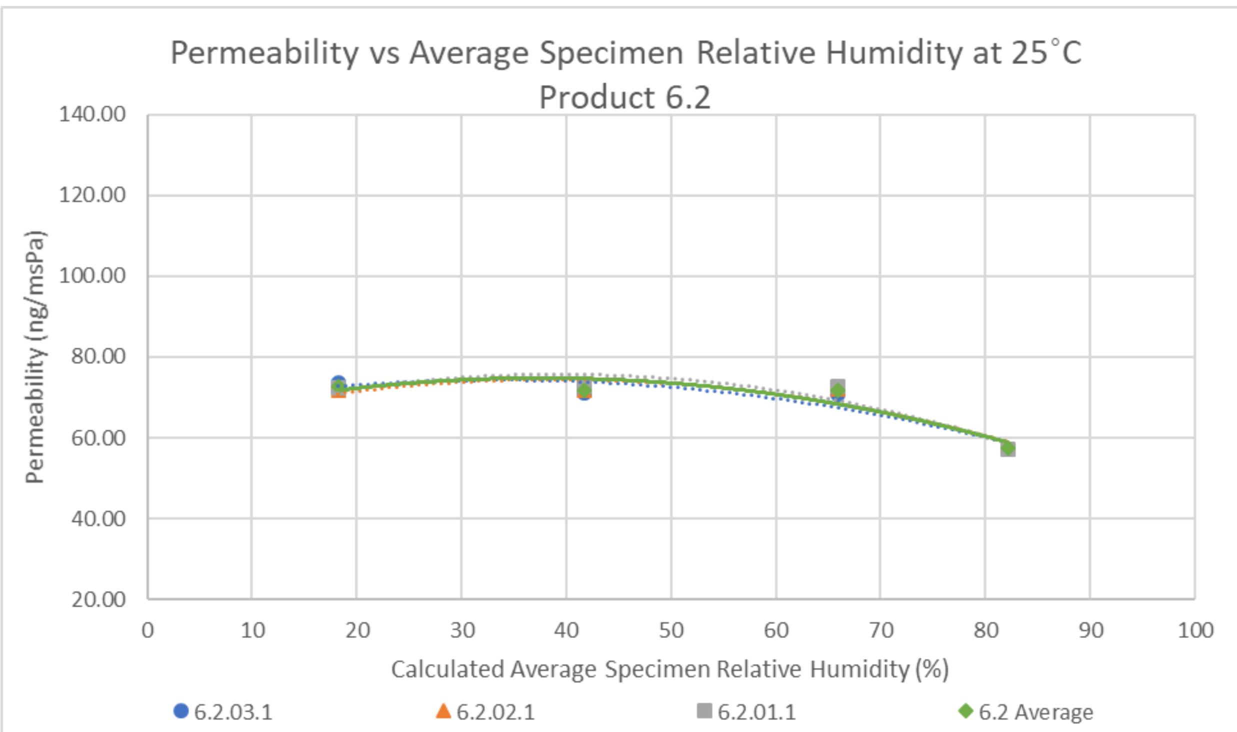


Figure E.17 – Permeabilities of Specimens 6.2.01, 6.2.02, 6.2.03, and Average for Modified Cup Test Conditions at 25 ˚C.

Table E.18 - Permeabilities of Specimens 6.2.01, 6.2.02, 6.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25˚C.

Test No.	.6	.7
Chamber Temp (˚C)	24.3	24.3
Chamber Temp – SD, CV (%)	0.06, 0.26%	0.03, 0.14%
Chamber RH (%)	50.4%	50.3%
Chamber RH - SD, CV (%)	0.96%, 1.91%	0.10%, 0.20%
Cup RH	100%	2%
Calc. Avg. Specimen RH	75.2%	26.2%
Pressure Differential (Pa)	-1512	1474
6.2.03.1	92.01	59.21
6.2.02.1	90.32	63.95
6.2.01.1	89.55	63.56
6.2 Average	90.63	62.24
Standard Deviation	1.26	2.63
Coefficient of variation	1.39%	4.22%

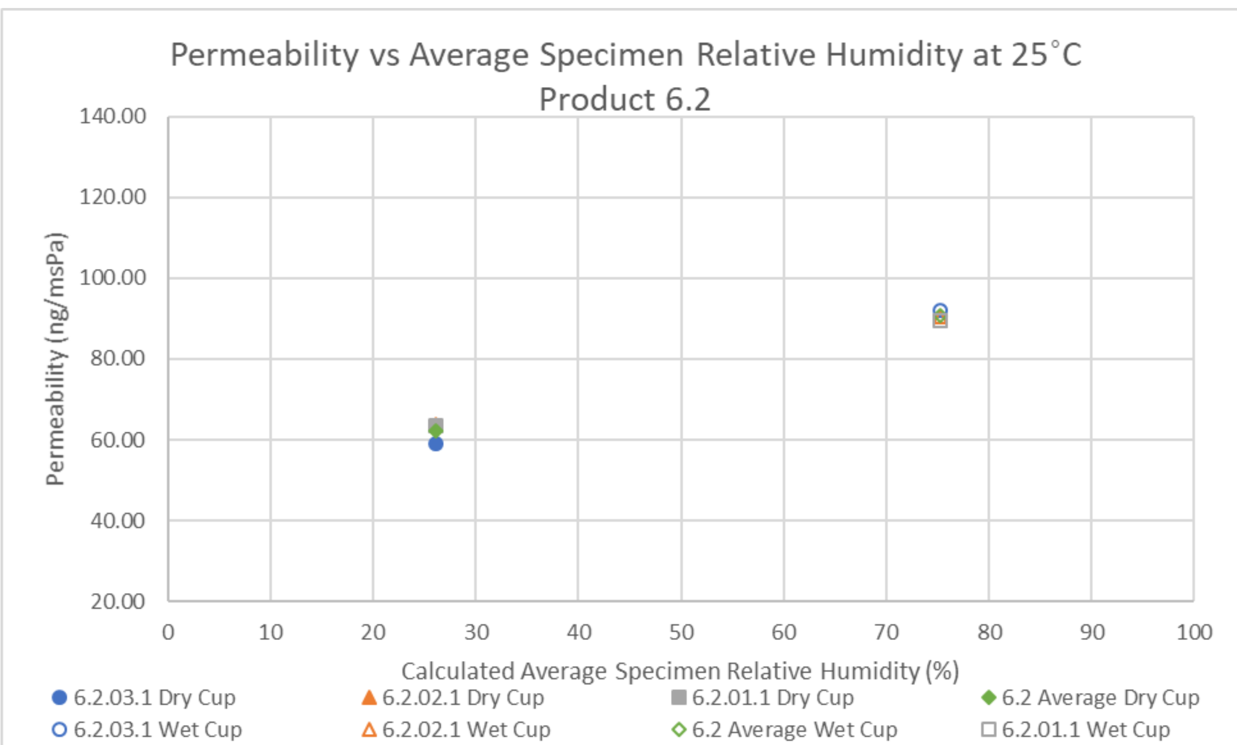


Figure E.18 – Permeabilities of Specimens 6.2.01, 6.2.02, 6.2.03, and Average for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

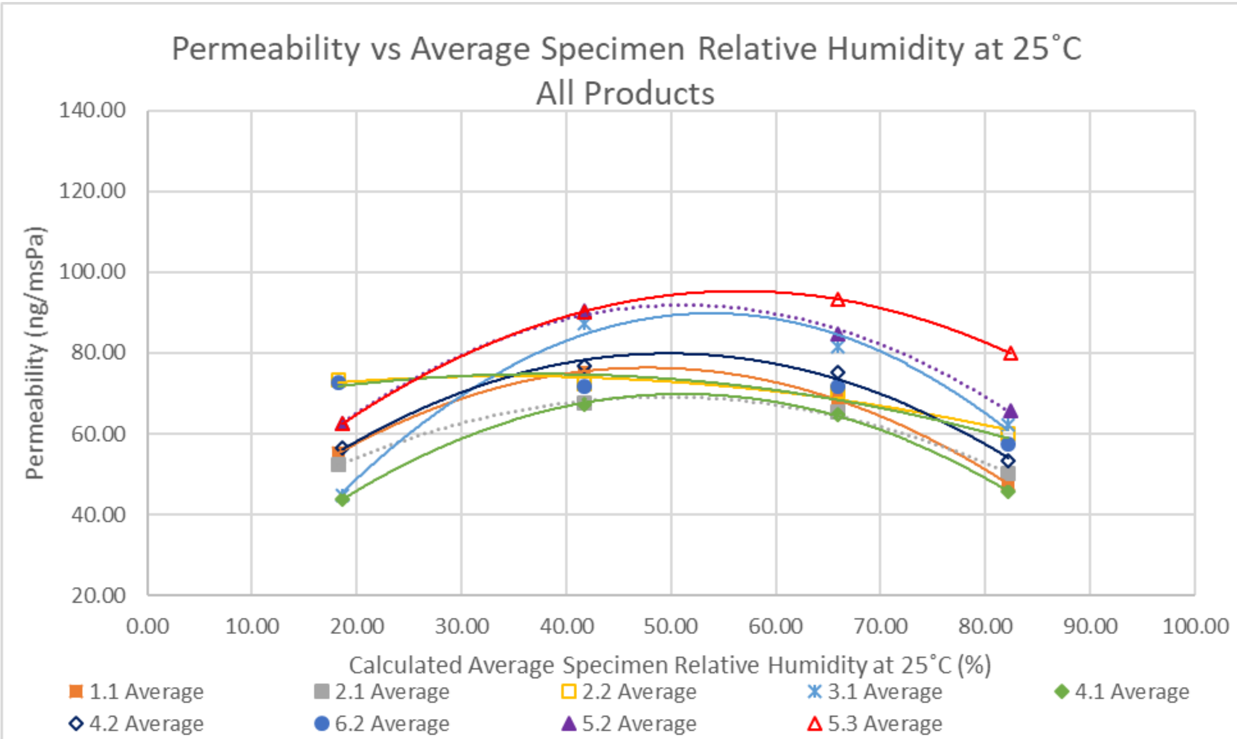


Figure E.19 – Average Permeabilities for all Products for Modified Cup Test Conditions at 25 ˚C.

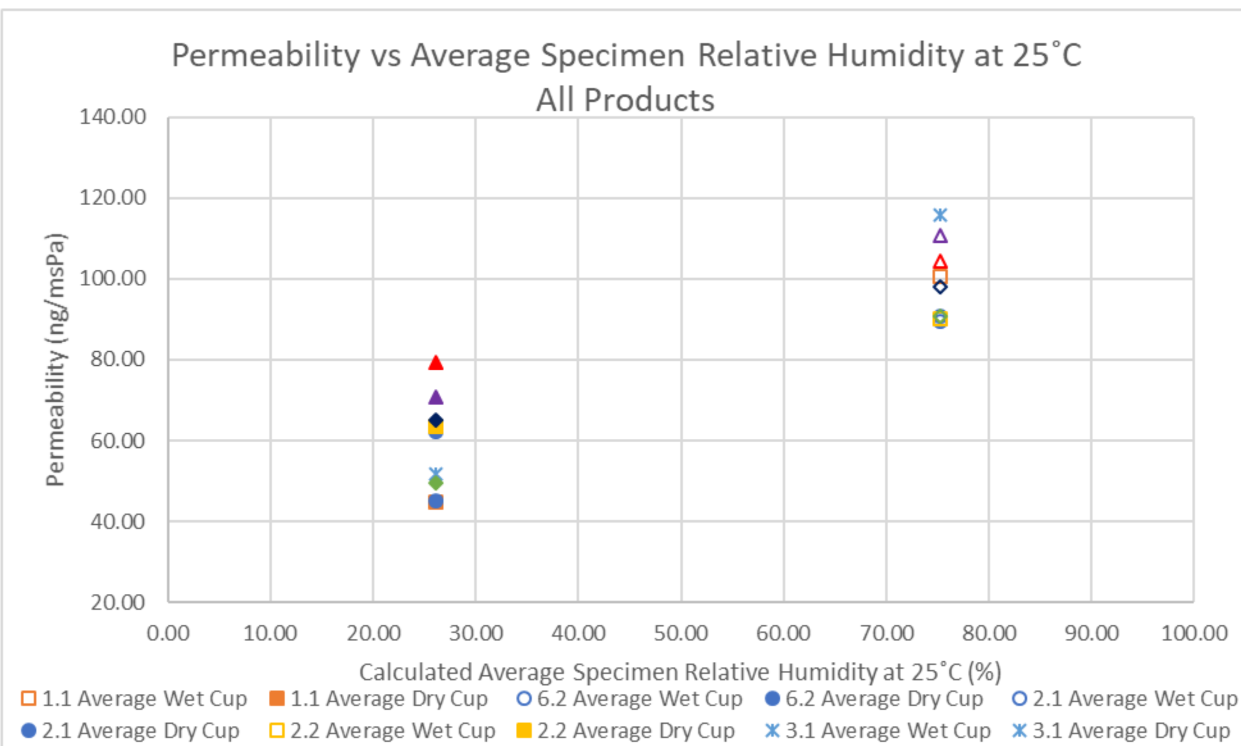


Figure E.20 – Average Permeabilities for All Products for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

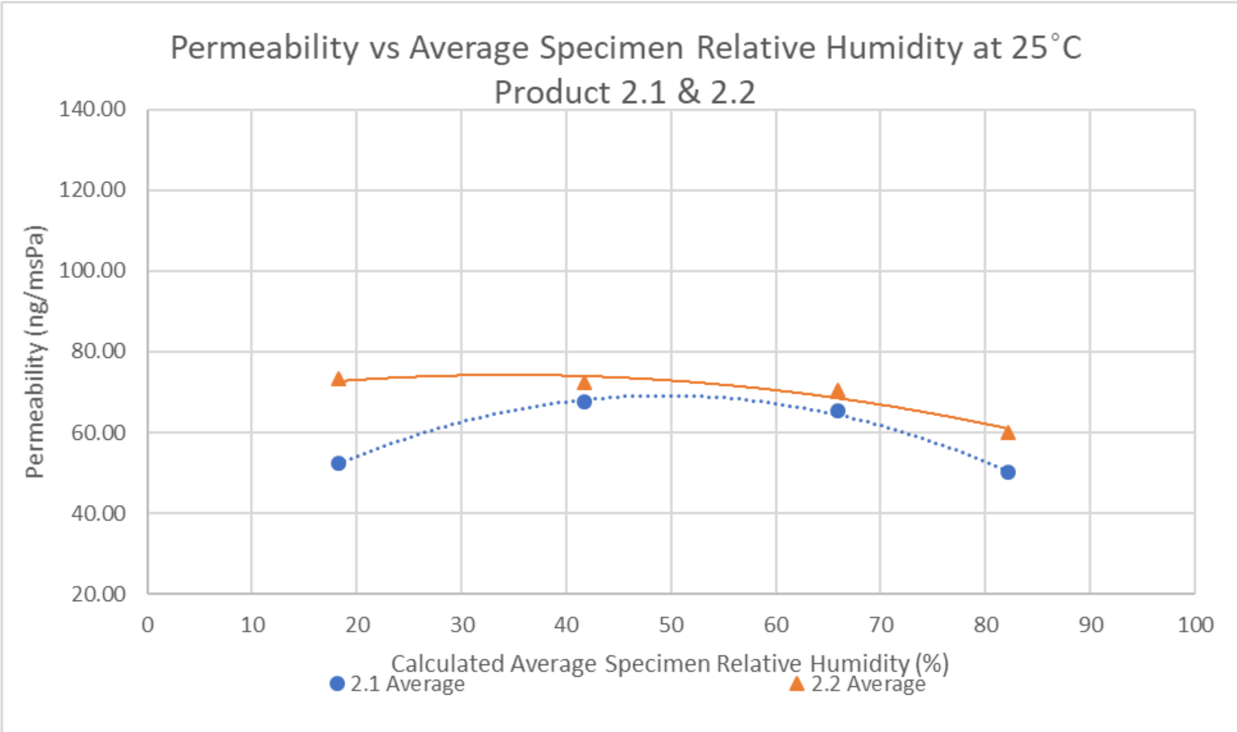


Figure E.21 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) for Modified Cup Test Conditions at 25˚C.

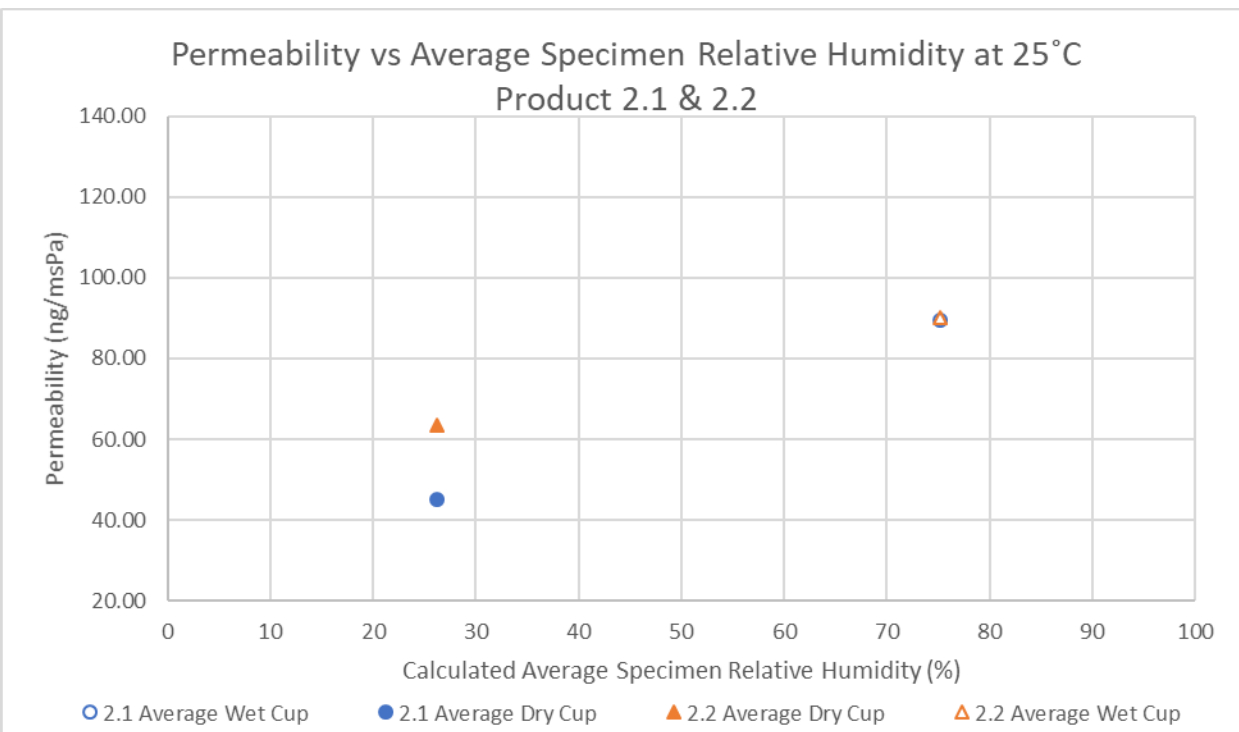


Figure E.22 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) for Wet Cup and Dry Cup Test Conditions at 25˚C.

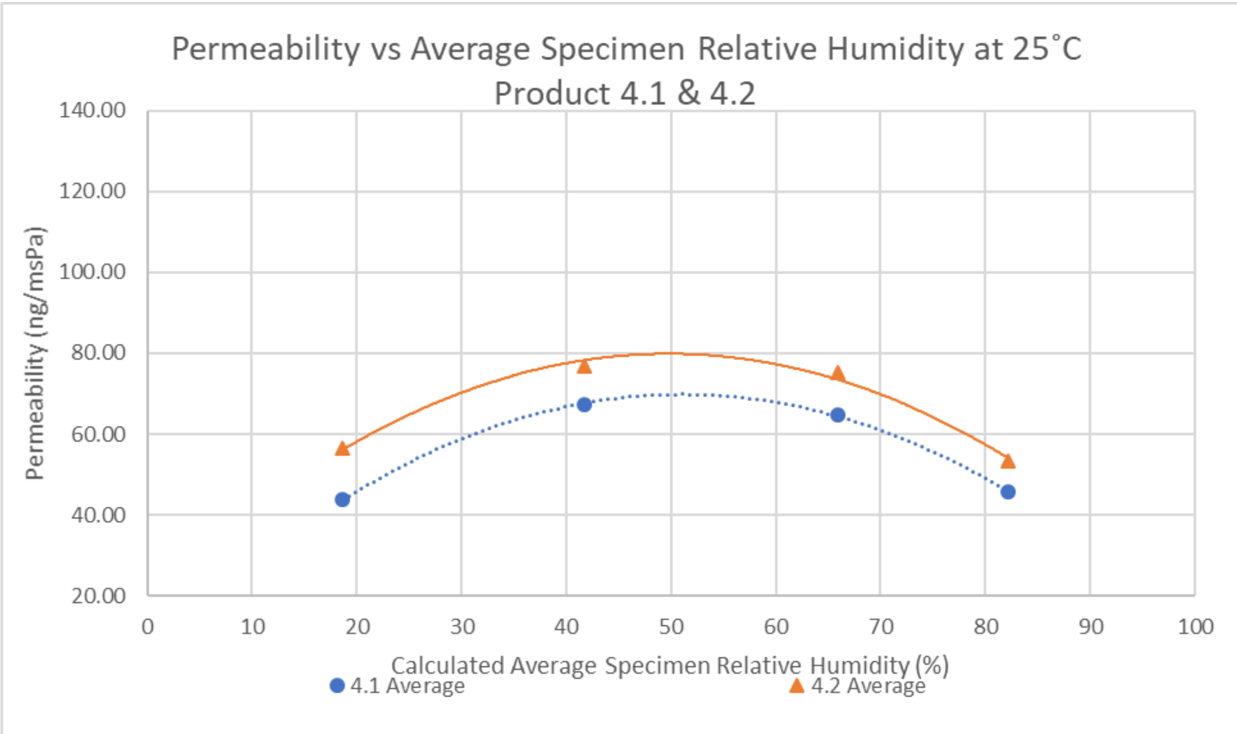


Figure E.23 – Average Permeabilities for Products 4.1 (40mm) and 4.2 (60mm) for Modified Cup Test Conditions at 25˚C.

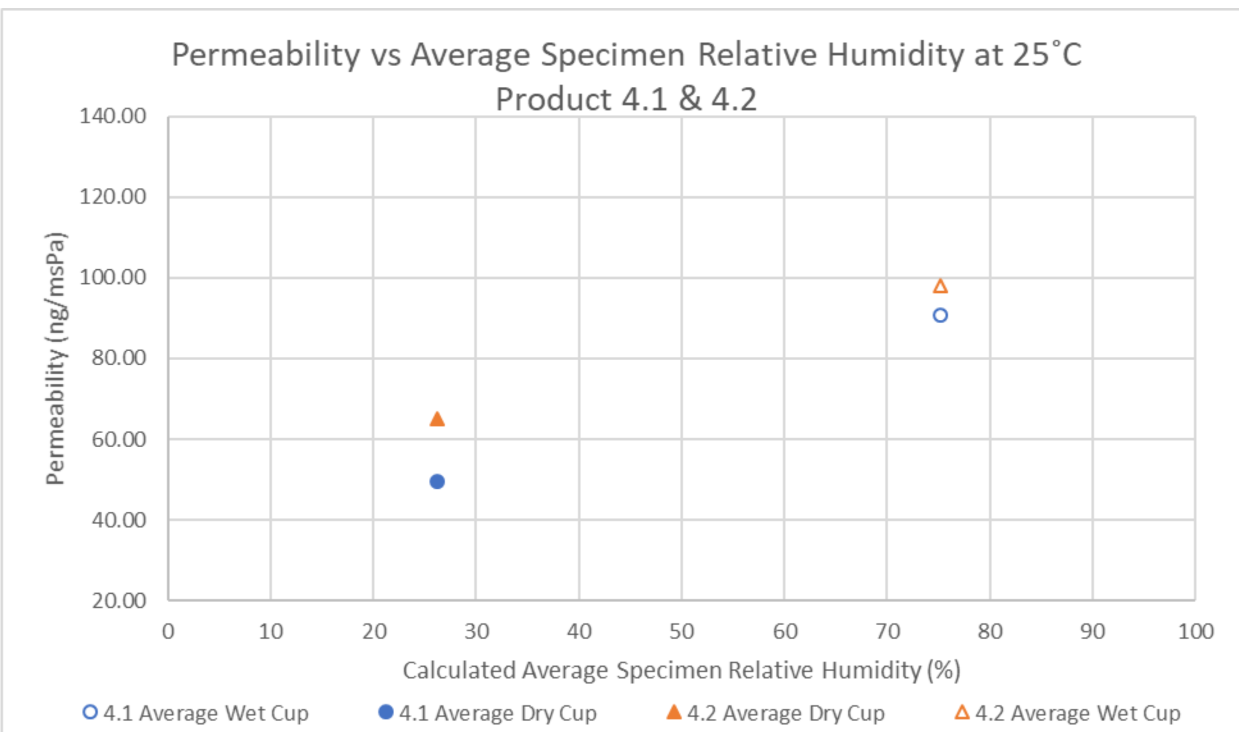


Figure E.24 – Average Permeabilities for Products 4.1 (40mm) and 4.2 (60mm) for Wet Cup and Dry Cup Test Conditions at 25˚C.

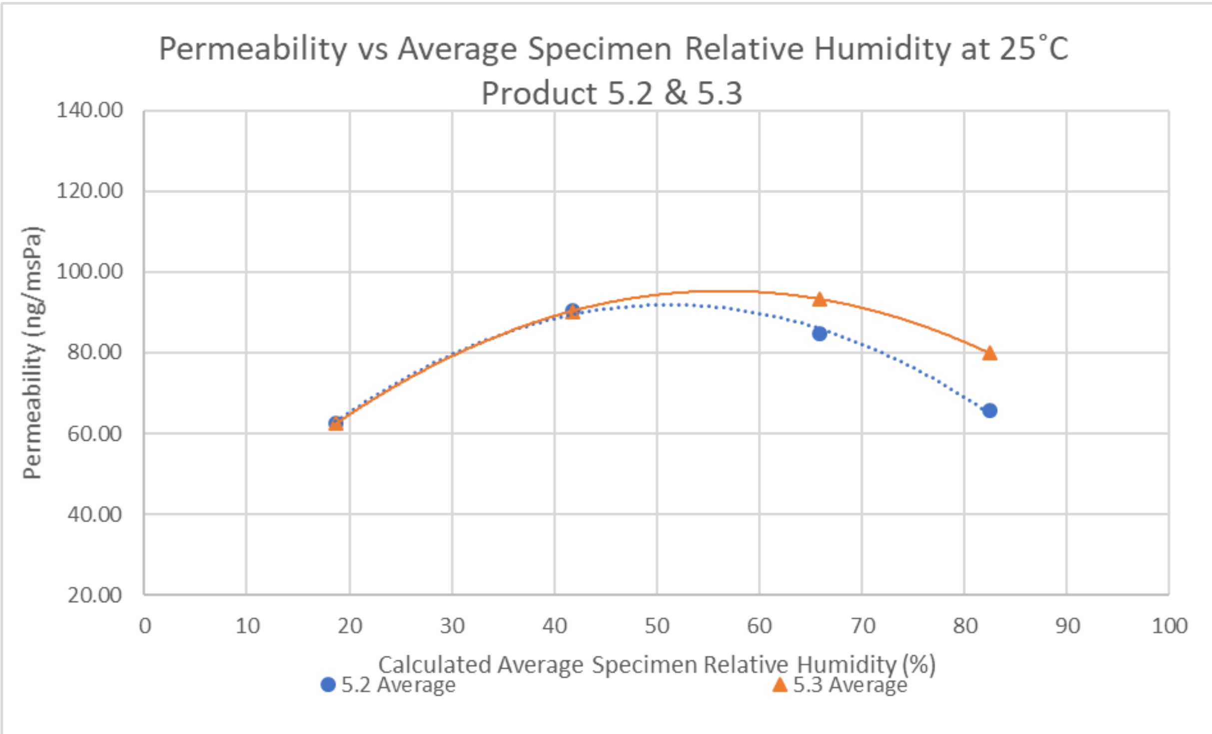


Figure E.25 – Average Permeabilities for Products 5.2 (60mm) and 5.3 (80mm) for Modified Cup Test Conditions at 25˚C.

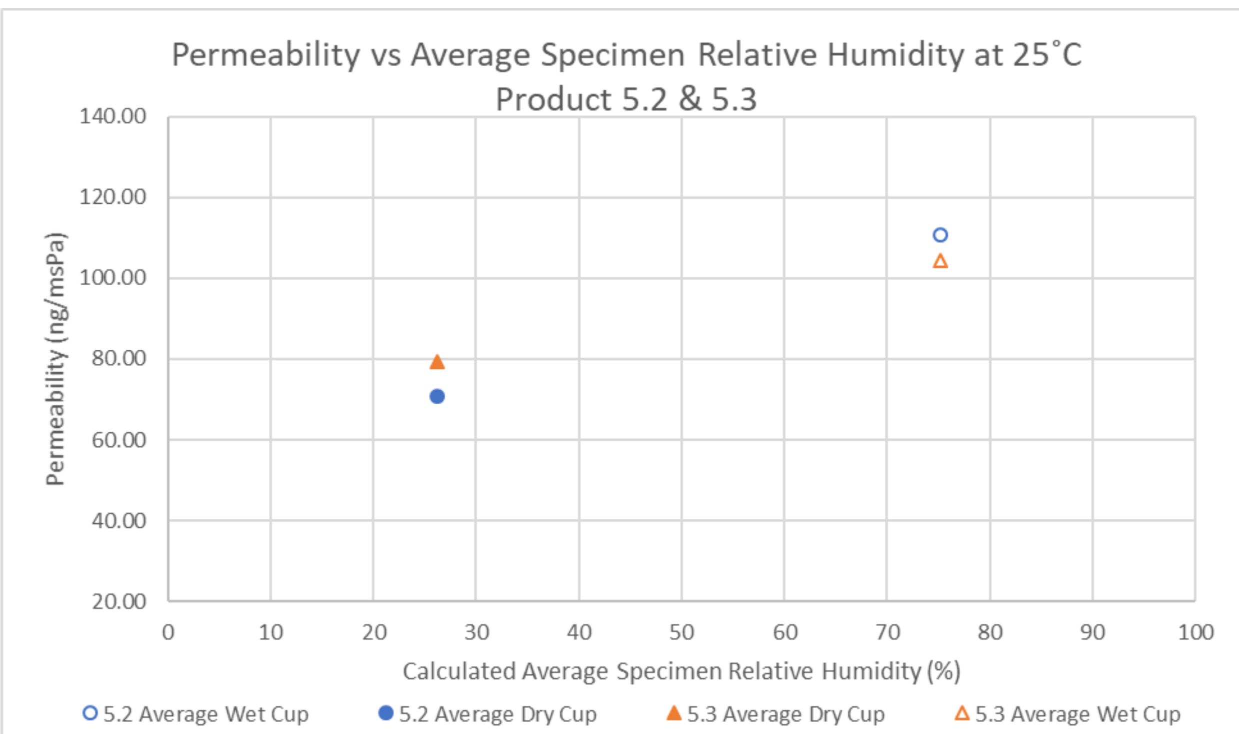


Figure E.26 – Average Permeabilities for Products 5.2 (60mm) and 5.3 (80mm) for Wet Cup and Dry Cup Test Conditions at 25˚C.

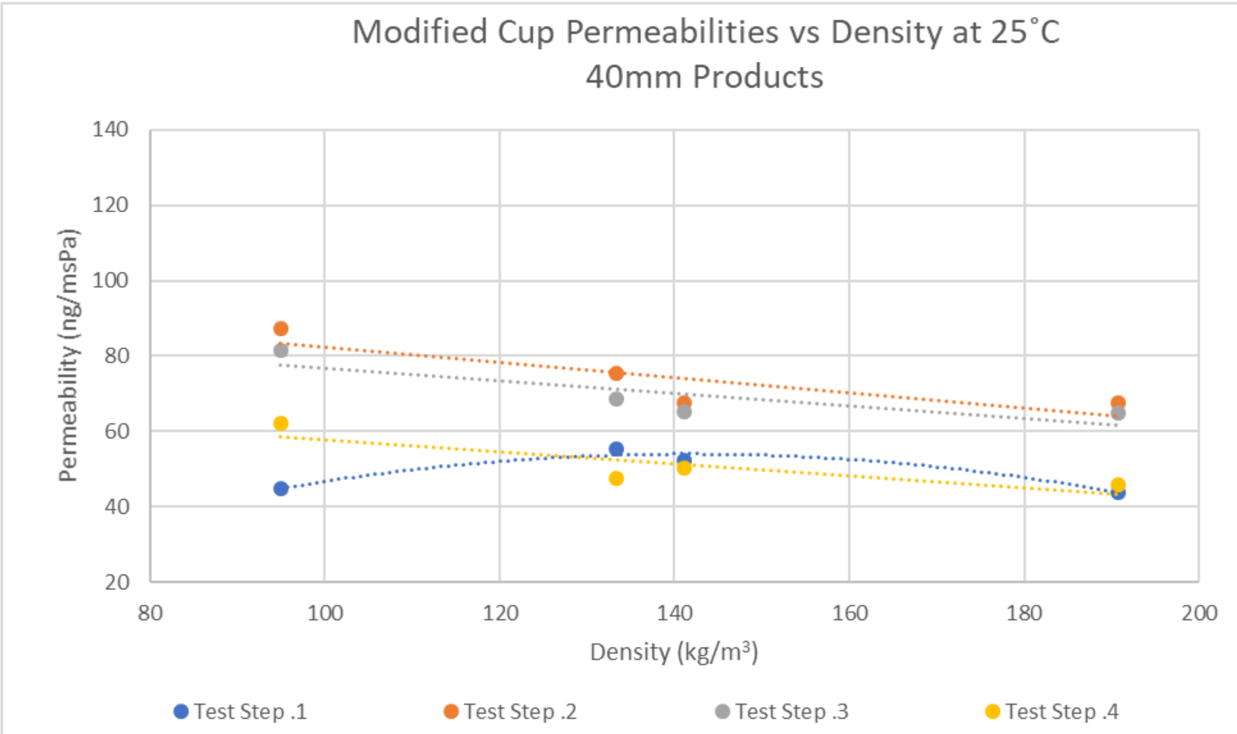


Figure E.27 – Permeability vs Density for 40mm Products for Modified Cup Test Conditions at 25 ˚C.

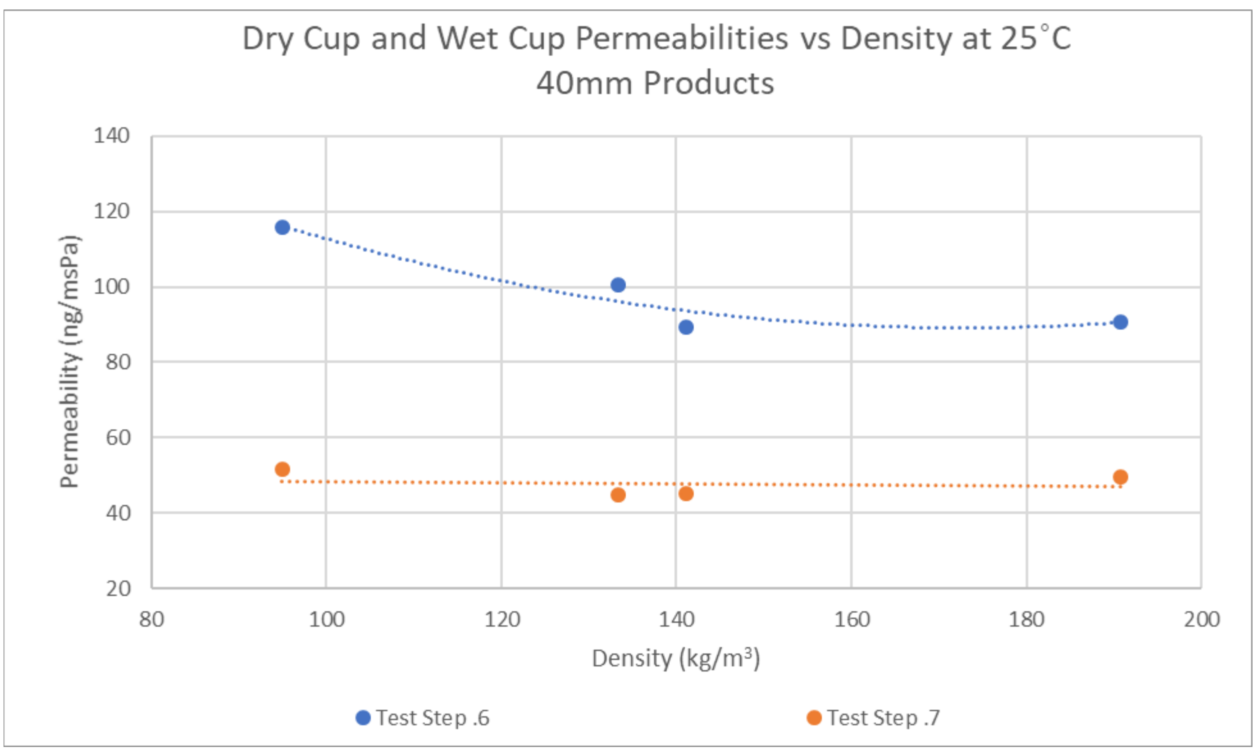


Figure E.28 – Permeability vs Density for 40mm Products for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

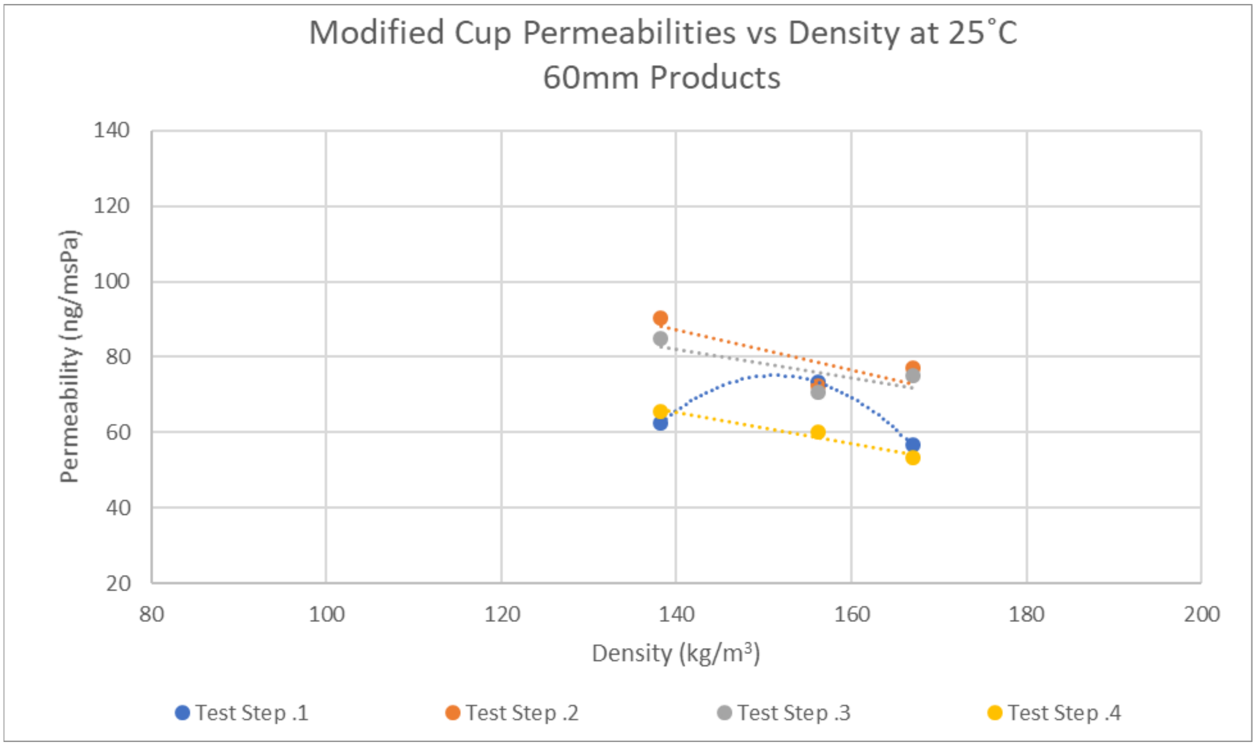


Figure E.29 – Permeability vs Density for 60mm Products for Modified Cup Test Conditions at 25 ˚C

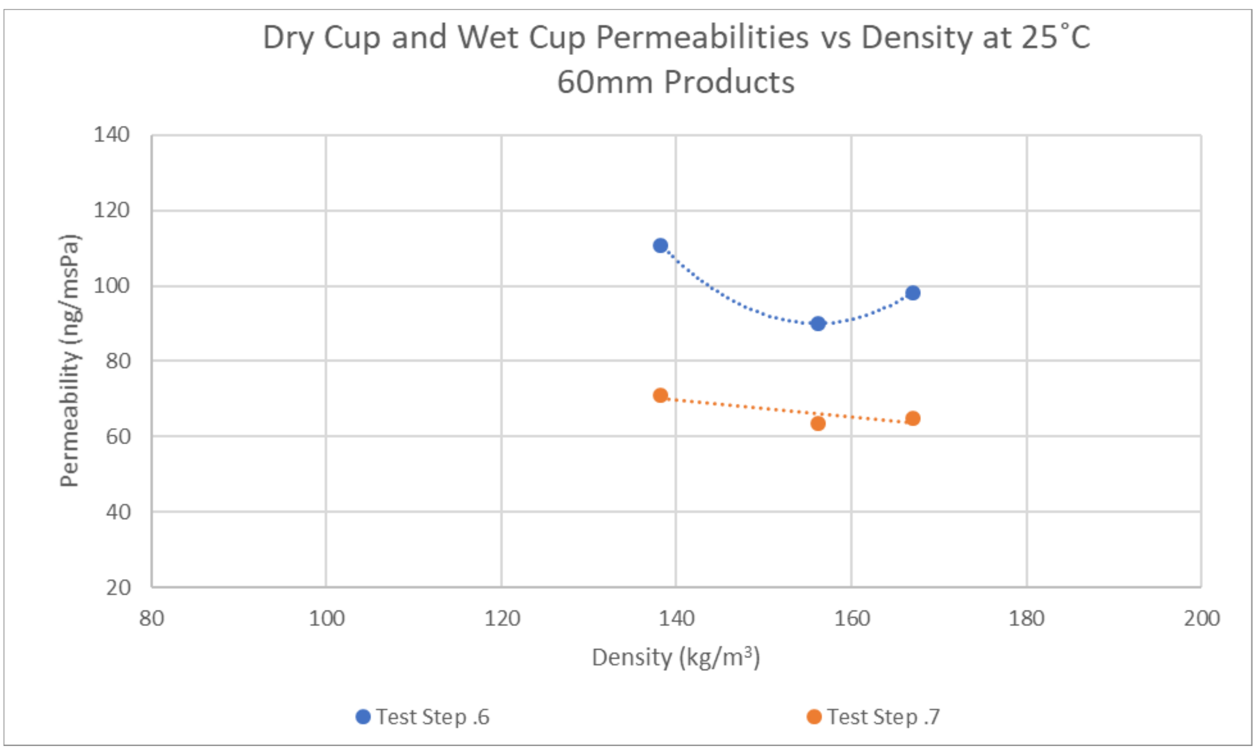


Figure E.30 – Permeability vs Density for 60mm Products for Wet Cup and Dry Cup Test Conditions at 25 ˚C.

Appendix G - Vapour Permeability Test Results at 10˚C

Table F.1 - Permeabilities of Specimens 1.1.0.4, 1.1.05.1, 1.1.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.1	10.02	9.99	10.14
Chamber Temp – SD, CV (%)	0.10, 1.04%	0.11, 1.13%	0.08, 0.85%	0.09, 0.84%
Chamber RH (%)	35%	51%	81%	90%
Chamber RH - SD, CV (%)	1.03%, 2.90%	1.11%, 2.19%	0.89%, 1.11%	1.54%, 1.71%
Cup RH	2%	34%	57%	75%
Calc. Avg. Specimen RH	19%	42%	69%	83%
Pressure Differential (Pa)	413	205	273	186
1.1.06.1	62.46	57.16	56.20	23.96
1.1.05.1	61.93	58.73	58.37	29.76
1.1.04.1	64.83	60.68	62.39	31.88
1.1 Average	63.07	58.86	58.99	28.53
Standard Deviation	1.54	1.76	3.14	4.10
Coefficient of variation	2.45%	3.00%	5.32%	14.38%

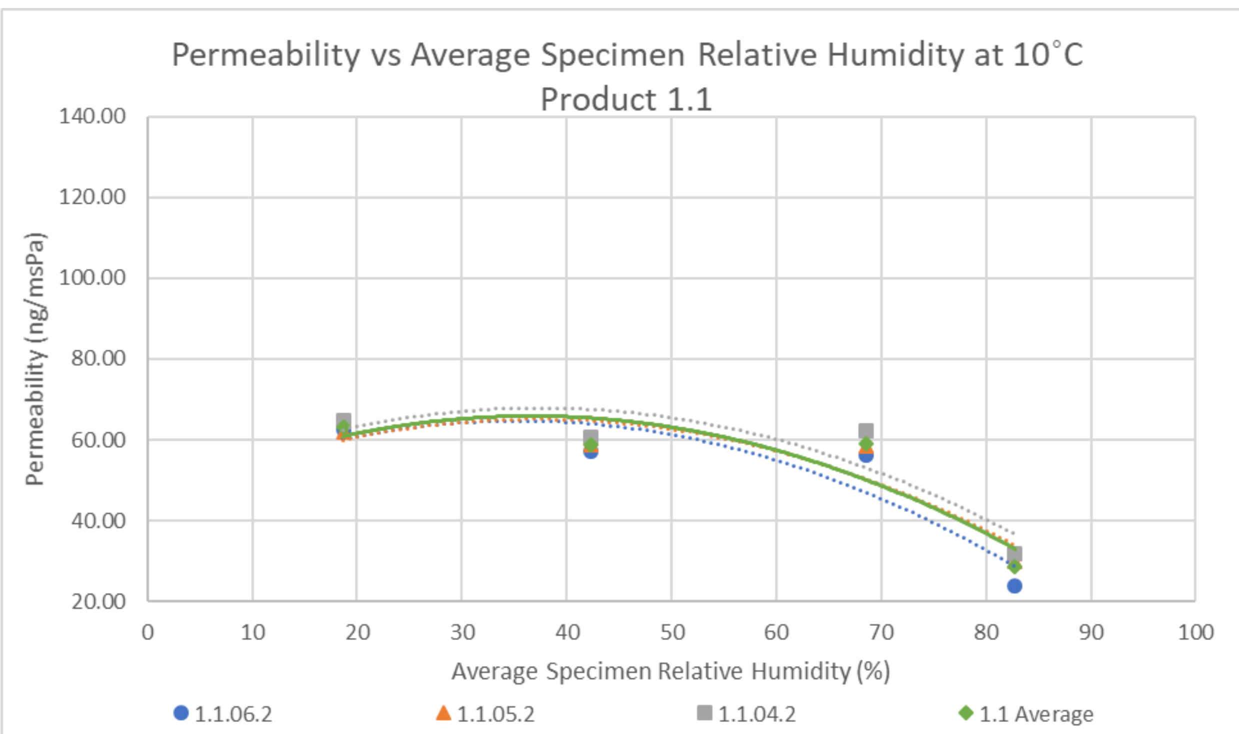


Figure F.1 – Permeabilities of Specimens 1.1.04, 1.1.05, 1.1.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.2 - Permeabilities of Specimens 1.1.04, 1.1.05, 1.1.06, and Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
1.1.06.1	111.22	69.19
1.1.05.1	104.87	68.93
1.1.04.1	104.68	71.02
1.1 Average	106.93	69.71
Standard Deviation	3.72	1.14
Coefficient of variation	3.48%	1.63%

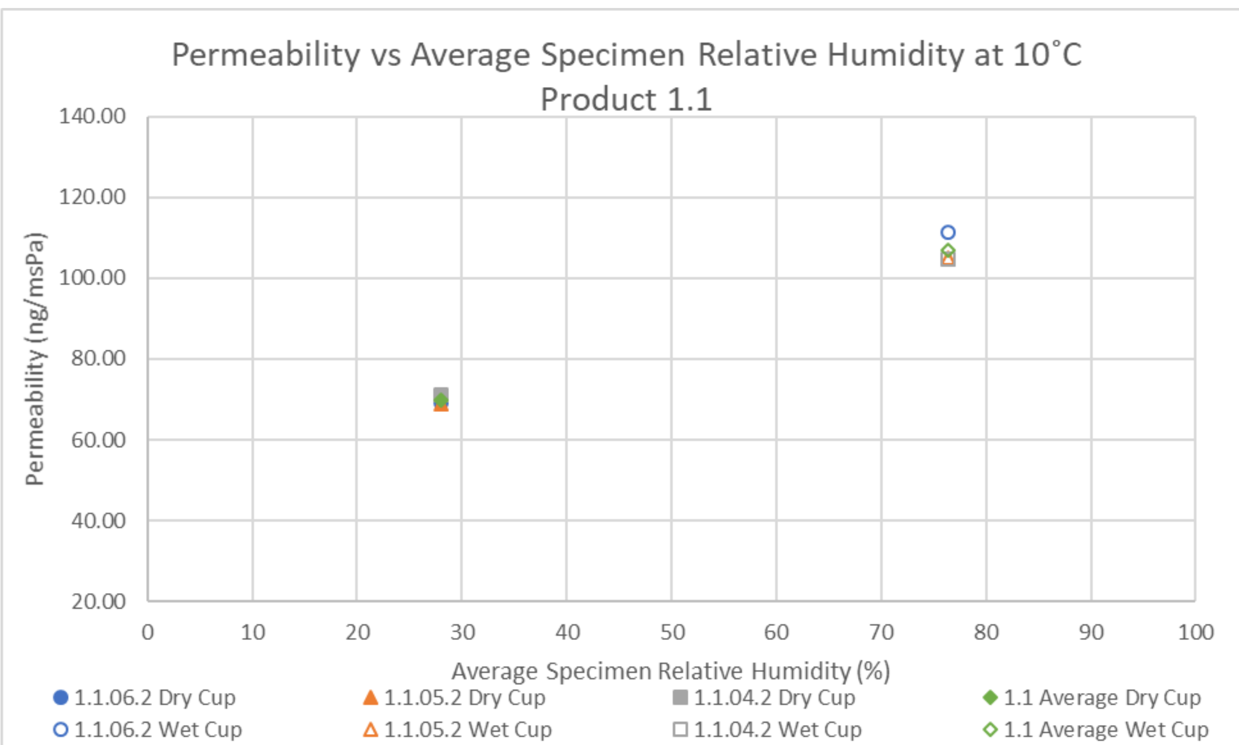


Figure F.2 – Permeabilities of Specimens 1.1.04, 1.1.05, 1.1.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.3 - Permeabilities of Specimens 2.1.0.4, 2.1.05.1, 2.1.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.1	10.02	9.99	10.14
Chamber Temp – SD, CV (%)	0.10, 1.04%	0.11, 1.13%	0.08, 0.85%	0.09, 0.84%
Chamber RH (%)	35%	51%	81%	90%
Chamber RH - SD, CV (%)	1.03%, 2.90%	1.11%, 2.19%	0.89%, 1.11%	1.54%, 1.71%
Cup RH	2%	34%	57%	75%
Calc. Avg. Specimen RH	19%	42%	69%	83%
Pressure Differential (Pa)	413	205	273	186
2.1.06.1	67.37	62.08	54.17	30.13
2.1.05.1	69.86	64.80	57.16	32.68
2.1.04.1	67.10	62.71	55.94	33.91
2.1 Average	68.11	63.20	55.76	32.24
Standard Deviation	1.52	1.43	1.50	1.93
Coefficient of variation	2.23%	2.26%	2.69%	5.98%

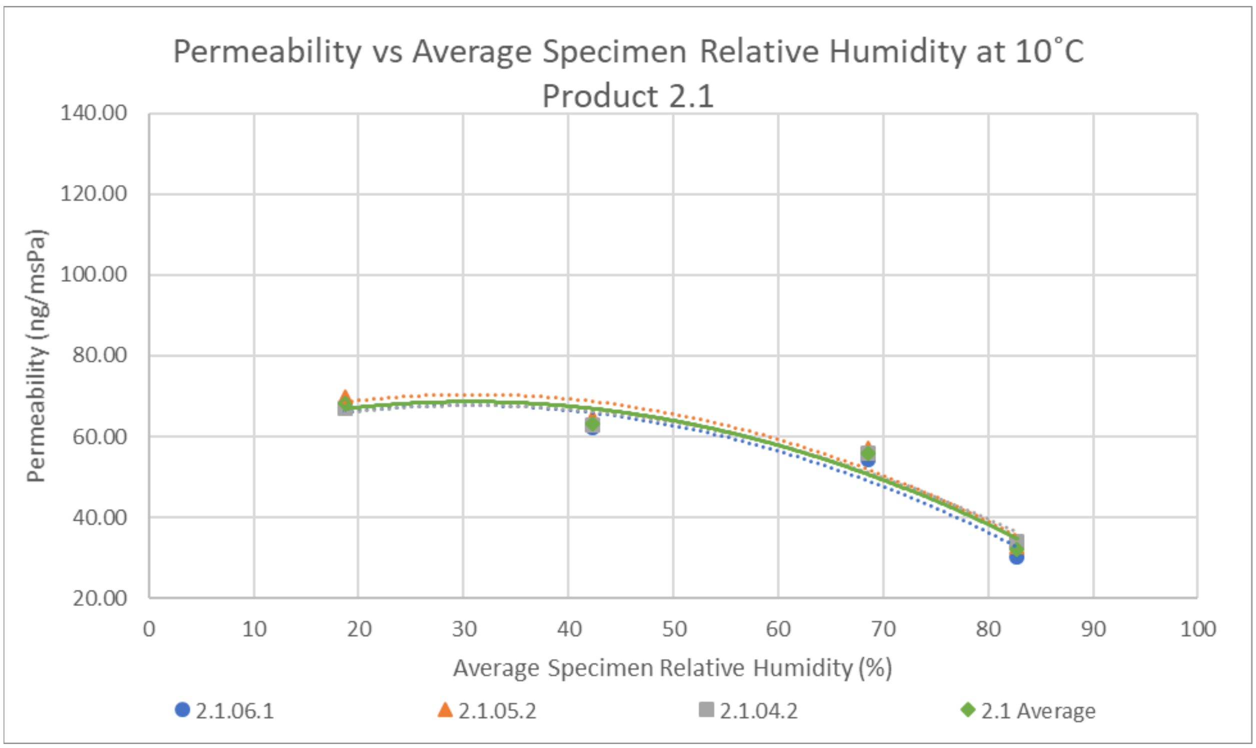


Figure F.3 – Permeabilities of Specimens 2.1.04, 2.1.05, 2.1.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.4 - Permeabilities of Specimens 2.1.04, 2.1.05, 2.1.06, and Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
2.1.06.1	97.68	63.46
2.1.05.1	91.92	63.11
2.1.04.1	91.95	66.79
2.1 Average	93.85	64.45
Standard Deviation	3.32	2.03
Coefficient of variation	3.53%	3.15%

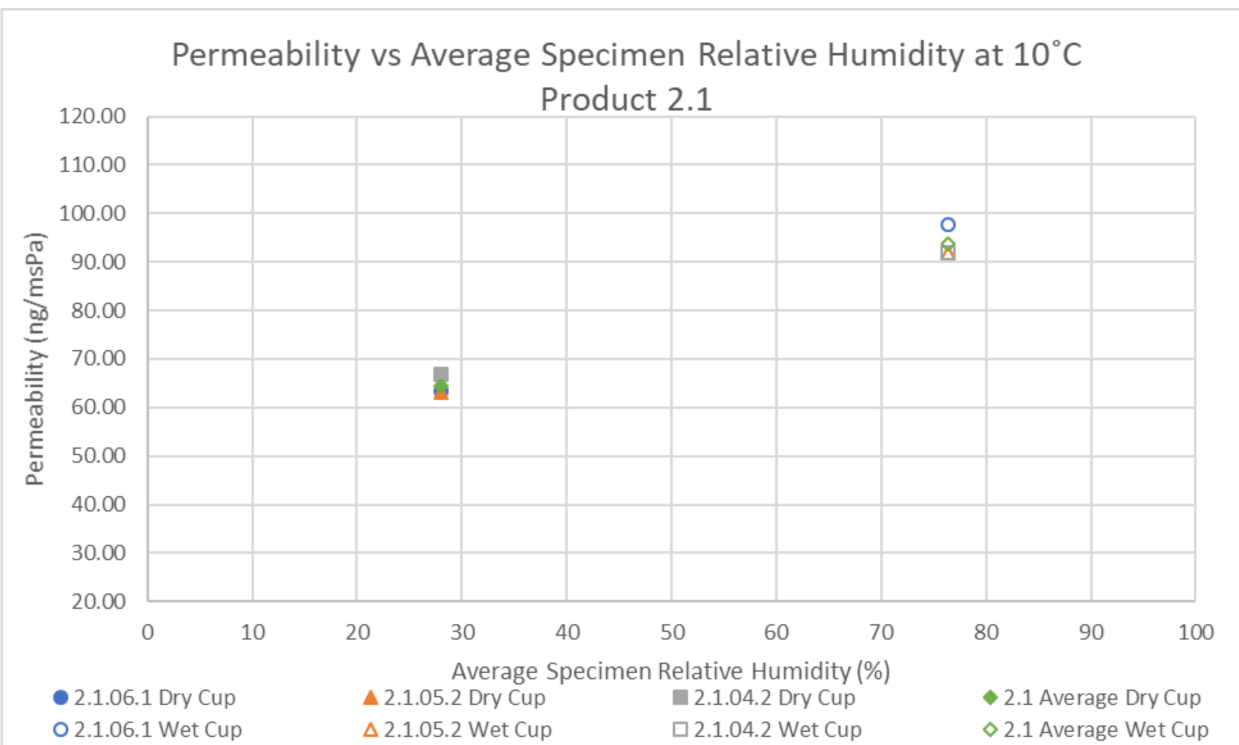


Figure F.4 – Permeabilities of Specimens 2.1.04, 2.1.05, 2.1.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.5 - Permeabilities of Specimens 2.2.0.4, 2.2.05.1, 2.2.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.1	10.02	9.99	10.14
Chamber Temp – SD, CV (%)	0.10, 1.04%	0.11, 1.13%	0.08, 0.85%	0.09, 0.84%
Chamber RH (%)	35%	51%	81%	90%
Chamber RH - SD, CV (%)	1.03%, 2.90%	1.11%, 2.19%	0.89%, 1.11%	1.54%, 1.71%
Cup RH	2%	34%	57%	75%
Calc. Avg. Specimen RH	19%	42%	69%	83%
Pressure Differential (Pa)	413	205	273	186
2.2.06.1	87.42	68.90	71.25	41.87
2.2.05.1	81.35	68.83	78.56	47.70
2.2.04.1	81.48	70.07	81.12	50.04
2.2 Average	83.41	69.27	76.97	46.54
Standard Deviation	3.47	0.69	5.12	4.21
Coefficient of variation	4.16%	1.00%	6.66%	9.04%

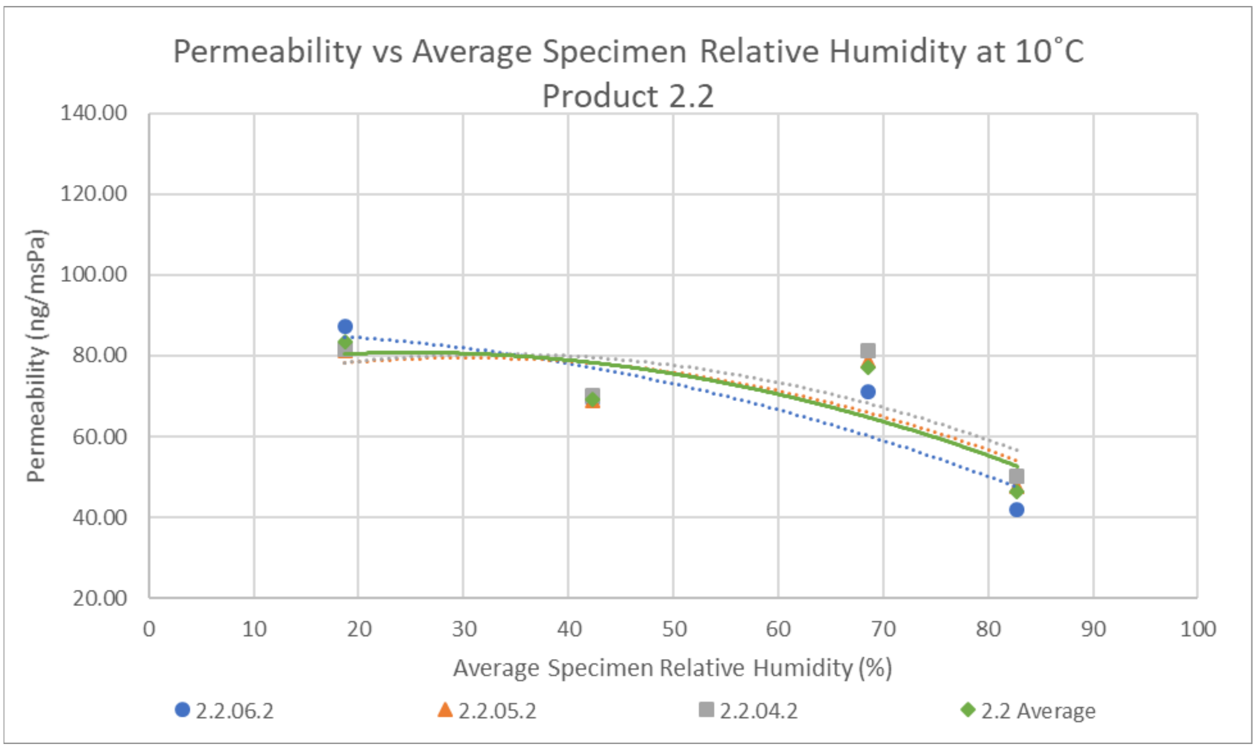


Figure F.5 – Permeabilities of Specimens 2.2.04, 2.2.05, 2.2.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.6 - Permeabilities of Specimens 2.2.04, 2.2.05, 2.2.06, and Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
2.2.06.1	103.63	82.17
2.2.05.1	89.19	74.38
2.2.04.1	90.32	74.69
2.2 Average	94.38	77.08
Standard Deviation	8.03	4.41
Coefficient of variation	8.51%	5.72%

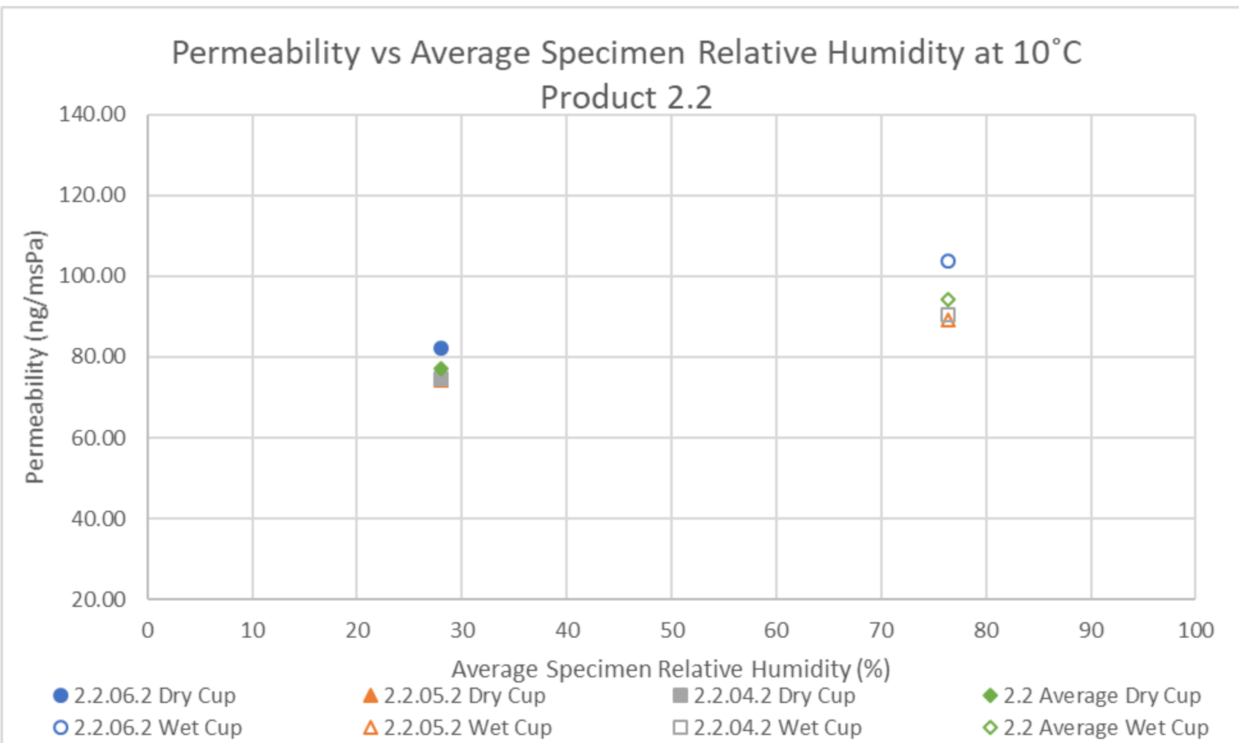


Figure F.6 – Permeabilities of Specimens 2.2.04, 2.2.05, 2.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.7 - Permeabilities of Specimens 3.1.0.4, 3.1.05.1, 3.1.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.06	9.83	9.79	10.14
Chamber Temp – SD, CV (%)	1.21, 12.01%	0.12, 1.19%	0.12, 1.20%	0.09, 0.84%
Chamber RH (%)	41%	53%	81%	90%
Chamber RH - SD, CV (%)	4.94%, 12.08%	3.63%, 6.88%	0.60%, 0.73%	1.54%, 1.71%
Cup RH	2%	34%	58%	75%
Calc. Avg. Specimen RH	21%	43%	69%	83%
Pressure Differential (Pa)	482	228	286	186
3.1.06.1	80.99	71.99	58.24	25.15
3.1.05.1	84.40	73.44	60.38	32.65
3.1.04.1	85.08	72.77	62.34	34.61
3.1 Average	83.49	72.73	60.32	30.81
Standard Deviation	2.19	0.73	2.05	4.99
Coefficient of variation	2.63%	1.00%	3.40%	16.20%

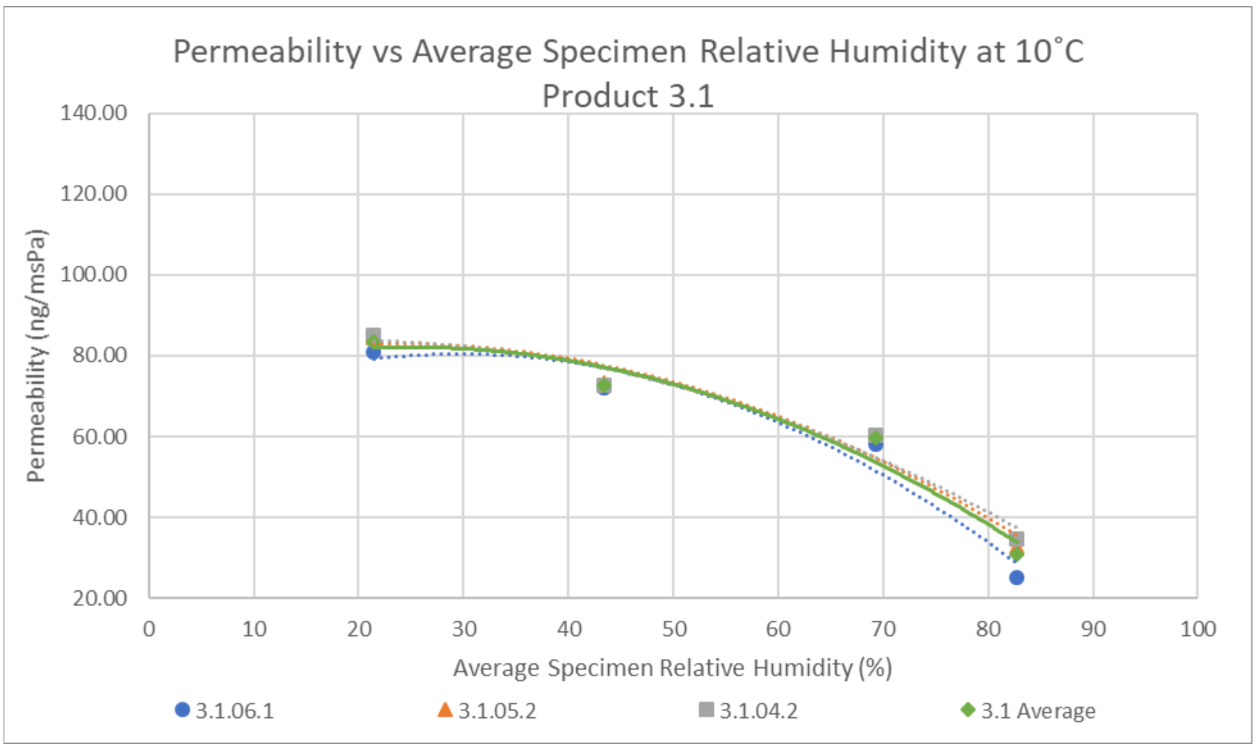


Figure F.7 – Permeabilities of Specimens 3.1.04, 3.1.05, 3.1.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.8 - Permeabilities of Specimens 3.1.04, 3.1.05, 3.1.06, and Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
3.1.06.1	137.93	78.34
3.1.05.1	135.97	75.99
3.1.04.1	129.31	72.78
3.1 Average	134.41	75.70
Standard Deviation	4.52	2.79
Coefficient of variation	3.36%	3.69%

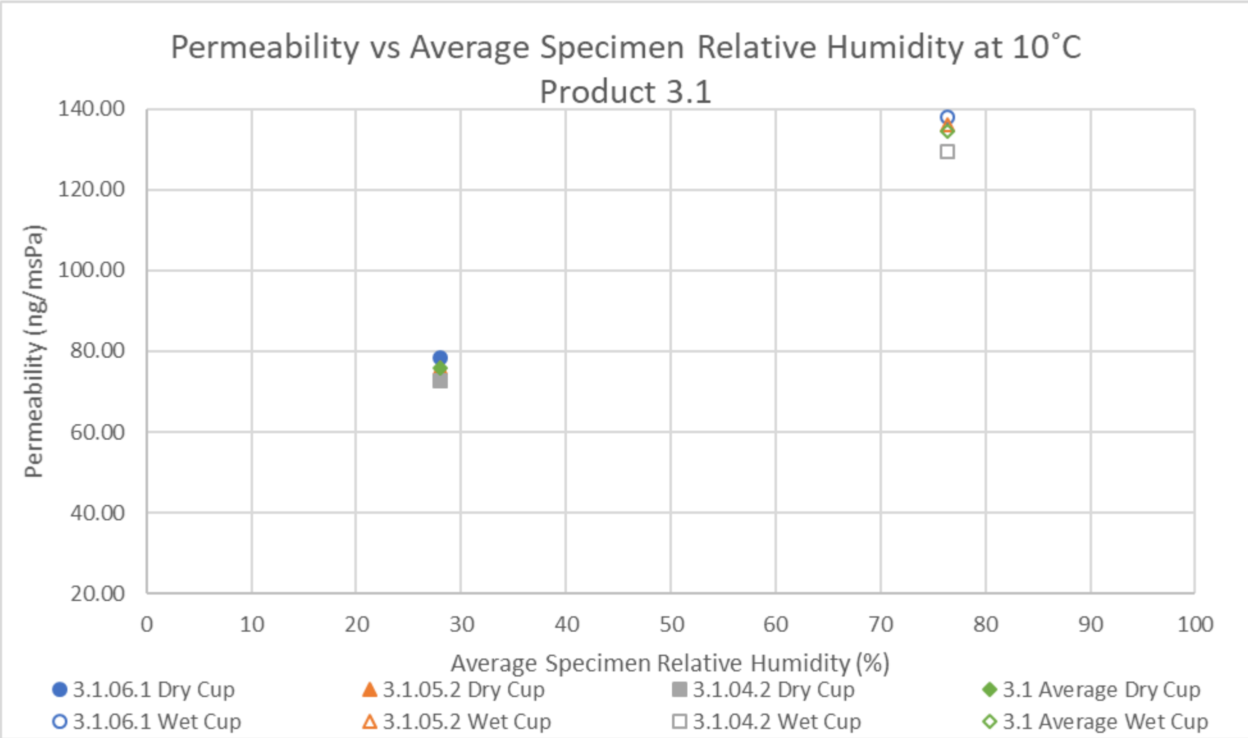


Figure F.8 – Permeabilities of Specimens 3.1.04, 3.1.05, 3.1.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.9 - Permeabilities of Specimens 4.1.0.4, 4.1.05.1, 4.1.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.06	9.83	9.79	10.14
Chamber Temp – SD, CV (%)	1.21, 12.01%	0.12, 1.19%	0.12, 1.20%	0.09, 0.84%
Chamber RH (%)	41%	53%	81%	90%
Chamber RH - SD, CV (%)	4.94%, 12.08%	3.63%, 6.88%	0.60%, 0.73%	1.54%, 1.71%
Cup RH	2%	34%	58%	75%
Calc. Avg. Specimen RH	21%	43%	69%	83%
Pressure Differential (Pa)	482	228	286	186
4.1.06.1	77.13	64.66	53.57	24.74
4.1.05.1	72.31	58.62	55.32	31.39
4.1.04.1	69.93	62.17	55.67	38.60
4.1 Average	73.12	61.82	54.85	31.58
Standard Deviation	3.67	3.03	1.12	6.93
Coefficient of variation	5.02%	4.91%	2.05%	21.94%

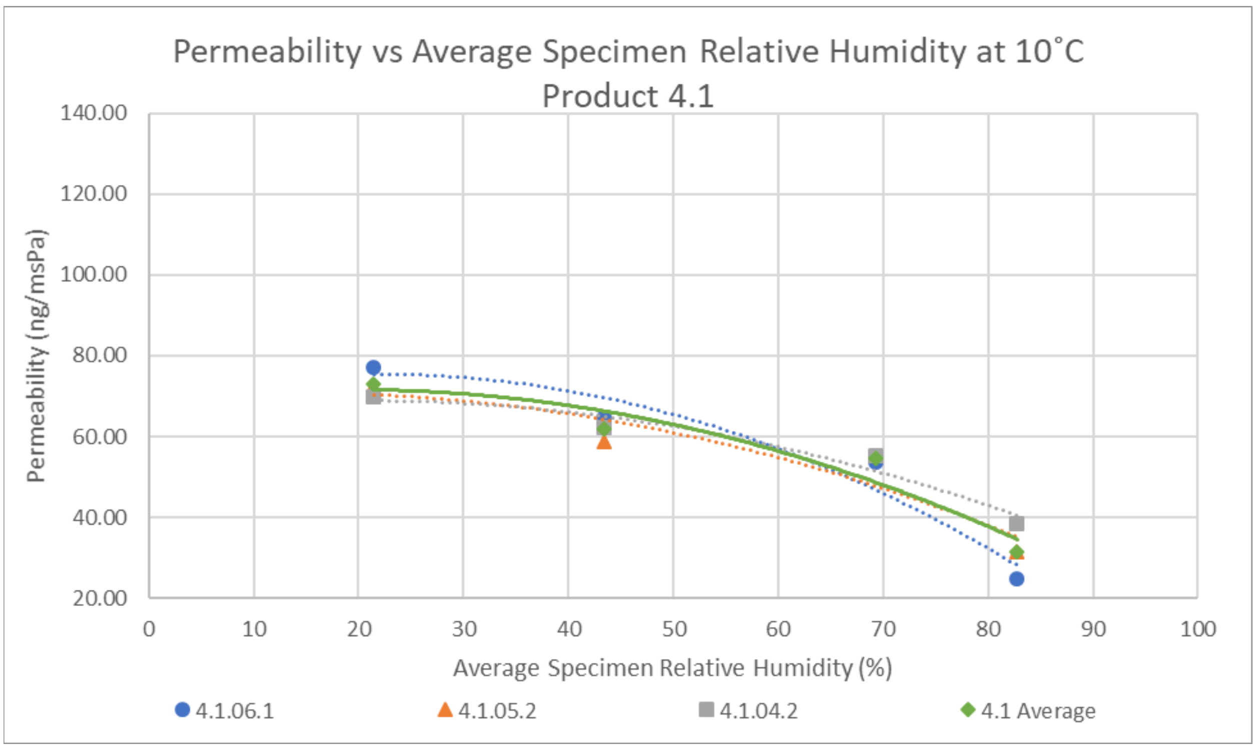


Figure F.9 – Permeabilities of Specimens 4.1.04, 4.1.05, 4.1.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.10 - Permeabilities of Specimens 4.1.04, 4.1.05, 4.1.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
4.1.06.1	97.97	68.37
4.1.05.1	90.56	66.76
4.1.04.1	85.22	66.66
4.1 Average	91.25	67.26
Standard Deviation	6.40	0.96
Coefficient of variation	7.01%	1.43%

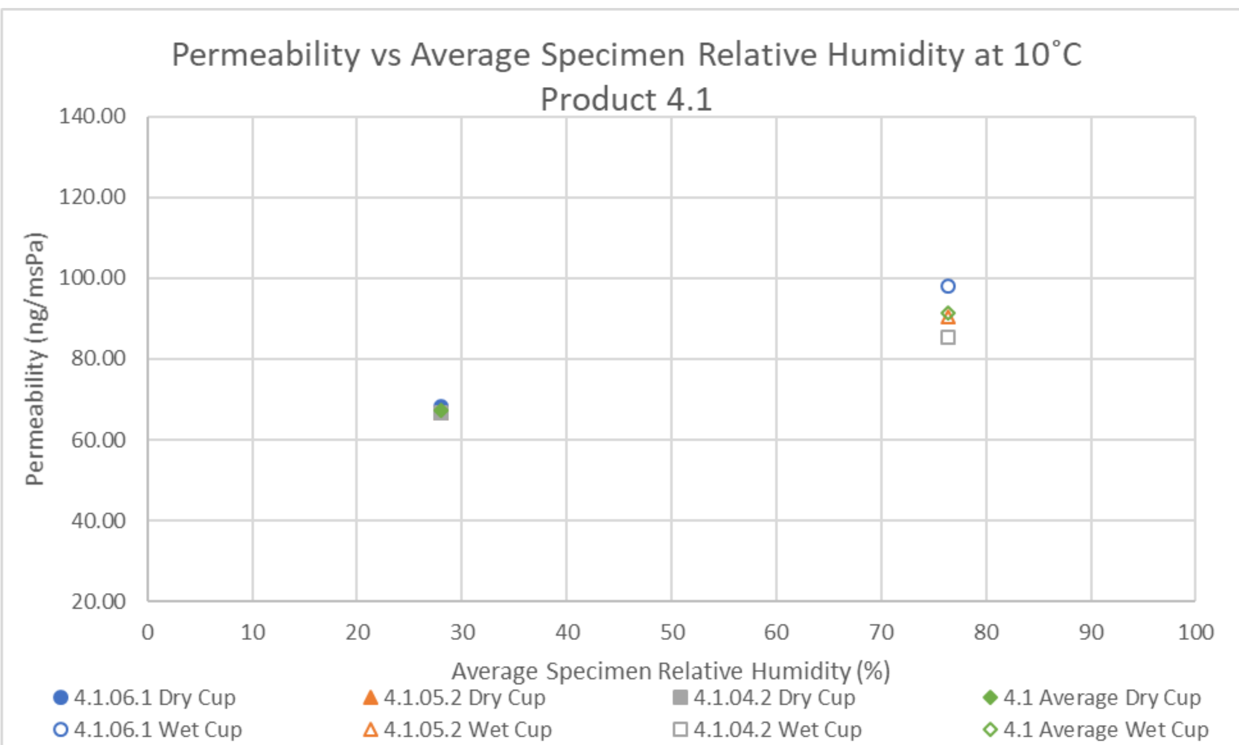


Figure F.10 – Permeabilities of Specimens 4.1.04, 4.1.05, 4.1.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.11 - Permeabilities of Specimens 4.2.0.4, 4.2.05.1, 4.2.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.06	9.83	9.79	10.14
Chamber Temp – SD, CV (%)	1.21, 12.01%	0.12, 1.19%	0.12, 1.20%	0.09, 0.84%
Chamber RH (%)	41%	53%	81%	90%
Chamber RH - SD, CV (%)	4.94%, 12.08%	3.63%, 6.88%	0.60%, 0.73%	1.54%, 1.71%
Cup RH	2%	34%	58%	75%
Calc. Avg. Specimen RH	21%	43%	69%	83%
Pressure Differential (Pa)	482	228	286	186
4.2.06.1	87.35	76.66	93.82	40.24
4.2.05.1	86.52	75.33	90.62	45.44
4.2.04.1	85.46	74.37	90.54	51.22
4.2 Average	86.44	75.45	91.66	45.63
Standard Deviation	0.94	1.15	1.87	5.49
Coefficient of variation	1.09%	1.52%	2.04%	12.03%

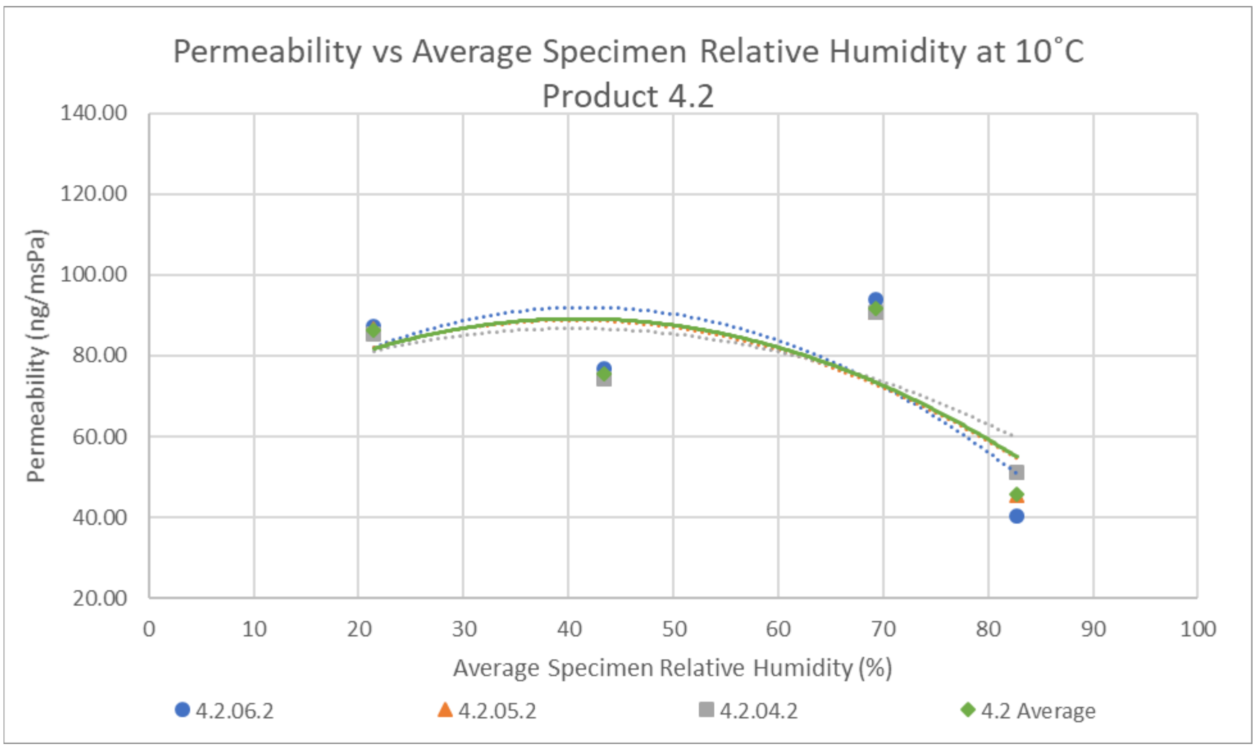


Figure F.11 – Permeabilities of Specimens 4.2.04, 4.2.05, 4.2.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.12 - Permeabilities of Specimens 4.2.04, 4.2.05, 4.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
4.2.06.1	102.29	80.91
4.2.05.1	95.25	79.71
4.2.04.1	93.23	79.63
4.2 Average	96.92	80.08
Standard Deviation	4.75	0.72
Coefficient of variation	4.90%	0.89%

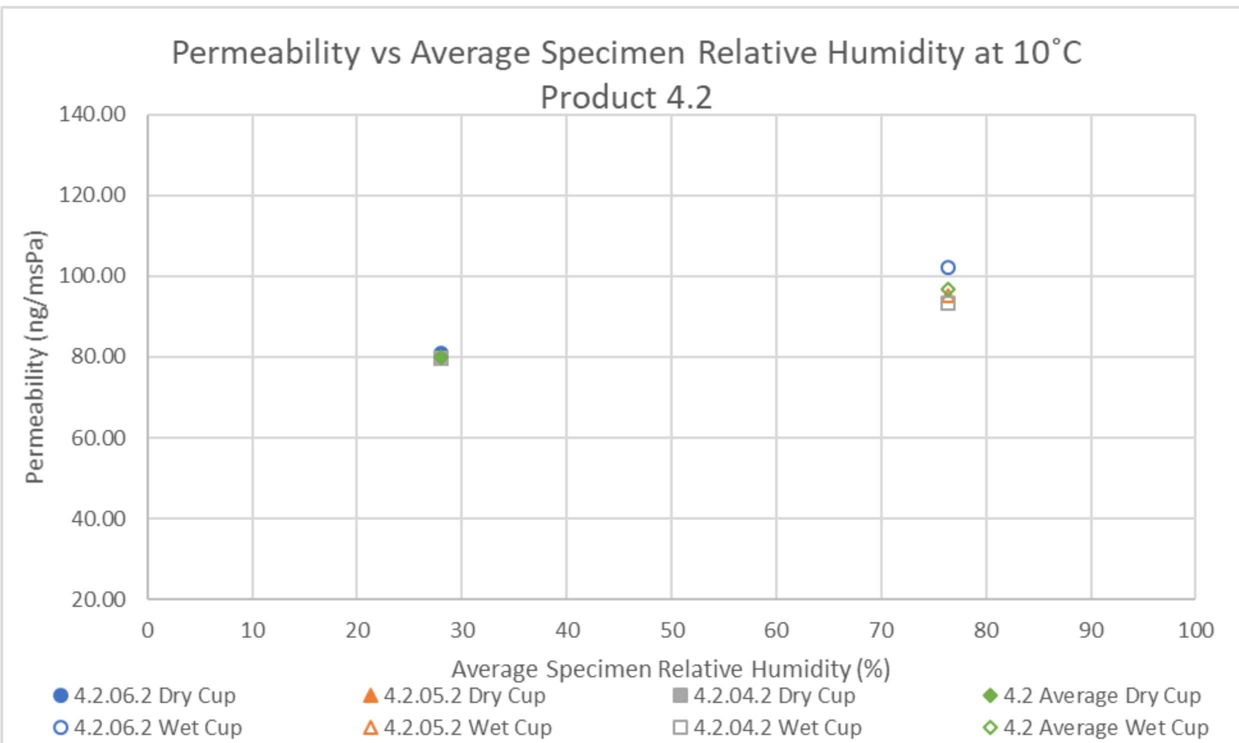


Figure F.12 – Permeabilities of Specimens 4.2.04, 4.2.05, 4.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.13 - Permeabilities of Specimens 5.2.0.4, 5.2.05.1, 5.2.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.06	9.83	9.79	9.88
Chamber Temp – SD, CV (%)	1.21, 12.01%	0.12, 1.19%	0.12, 1.20%	0.06, 0.58%
Chamber RH (%)	41%	53%	81%	92%
Chamber RH - SD, CV (%)	4.94%, 12.08%	3.63%, 6.88%	0.60%, 0.73%	0.57%, 0.62%
Cup RH	2%	34%	58%	75%
Calc. Avg. Specimen RH	21%	43%	69%	84%
Pressure Differential (Pa)	482	228	286	203
5.2.06.1	91.73	75.93	76.51	41.60
5.2.05.1	91.39	81.15	82.91	47.87
5.2.04.1	103.04	80.12	87.19	50.29
5.2 Average	95.38	79.06	82.20	46.59
Standard Deviation	6.63	2.77	5.38	4.48
Coefficient of variation	6.95%	3.50%	6.54%	9.62%

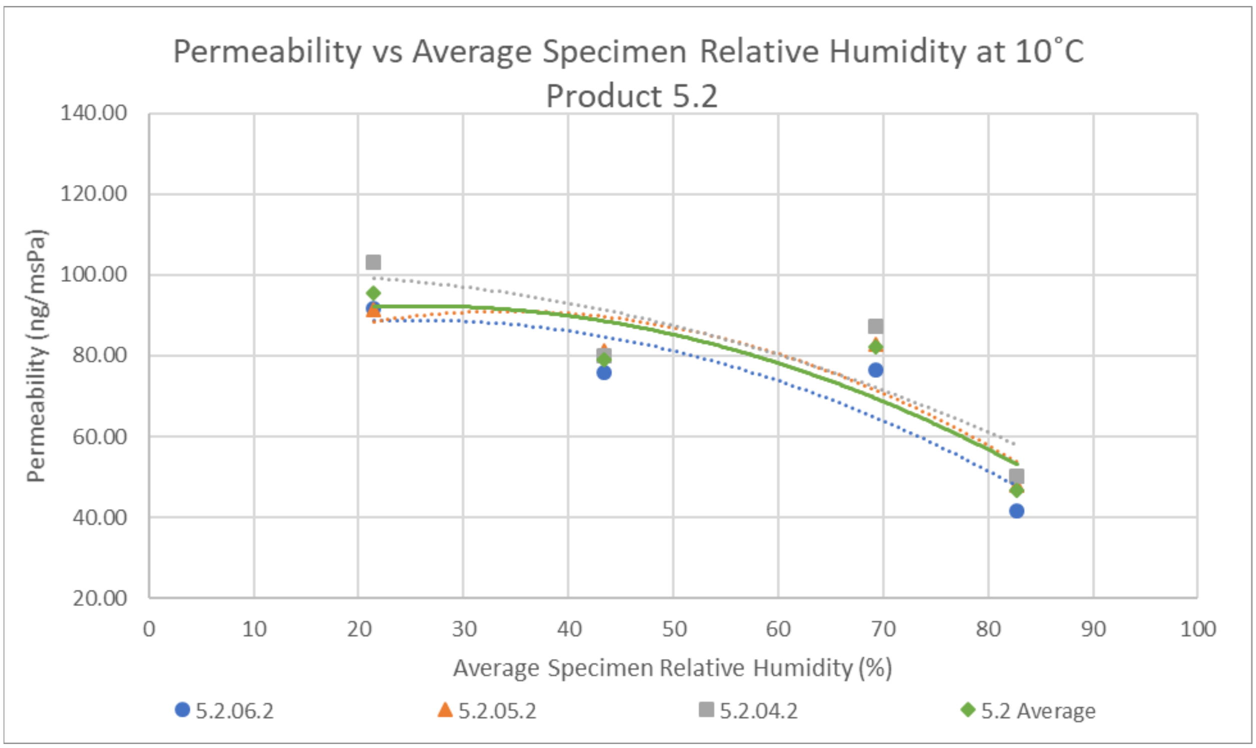


Figure F.13 – Permeabilities of Specimens 5.2.04, 5.2.05, 5.2.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.14 - Permeabilities of Specimens 5.2.04, 5.2.05, 5.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
5.2.06.1	128.02	94.83
5.2.05.1	129.14	97.57
5.2.04.1	126.16	94.83
5.2 Average	127.77	95.74
Standard Deviation	1.51	1.58
Coefficient of variation	1.18%	1.65%

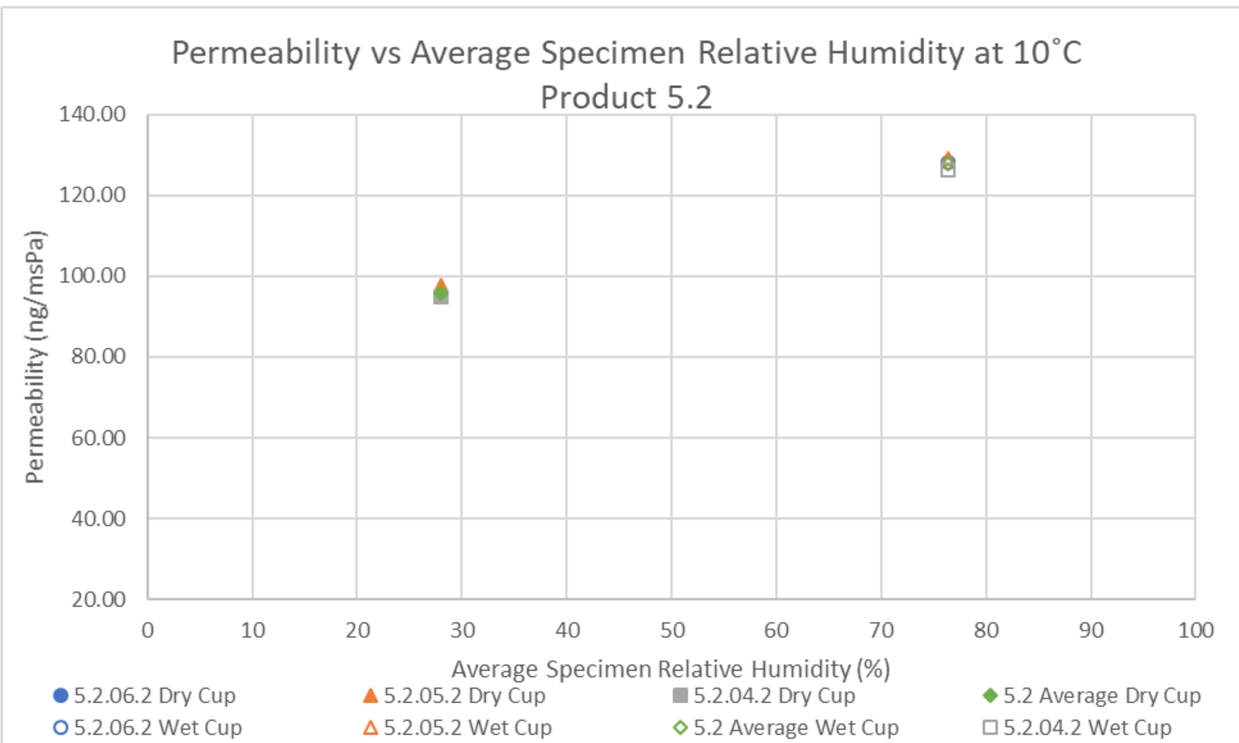


Figure F.14 – Permeabilities of Specimens 5.2.04, 5.2.05, 5.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.15 - Permeabilities of Specimens 5.3.0.4, 5.3.05.1, 5.3.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	*.1*	*.2*	*.3*	*.4*
Chamber Temp (˚C)	10.06	9.83	9.79	9.88
Chamber Temp – SD, CV (%)	1.21, 12.01%	0.12, 1.19%	0.12, 1.20%	0.06, 0.58%
Chamber RH (%)	41%	53%	81%	92%
Chamber RH - SD, CV (%)	4.94%, 12.08%	3.63%, 6.88%	0.60%, 0.73%	0.57%, 0.62%
Cup RH	2%	34%	58%	75%
Calc. Avg. Specimen RH	21%	43%	69%	84%
Pressure Differential (Pa)	482	228	286	203
5.3.06.1	91.26	79.71	-	83.44
5.3.05.1	92.73	88.59	-	103.93
5.3.04.1	93.66	85.01	-	108.10
5.3 Average	92.55	84.43	-	98.49
Standard Deviation	1.21	4.47	-	13.20
Coefficient of variation	1.31%	5.29%	-	13.40%

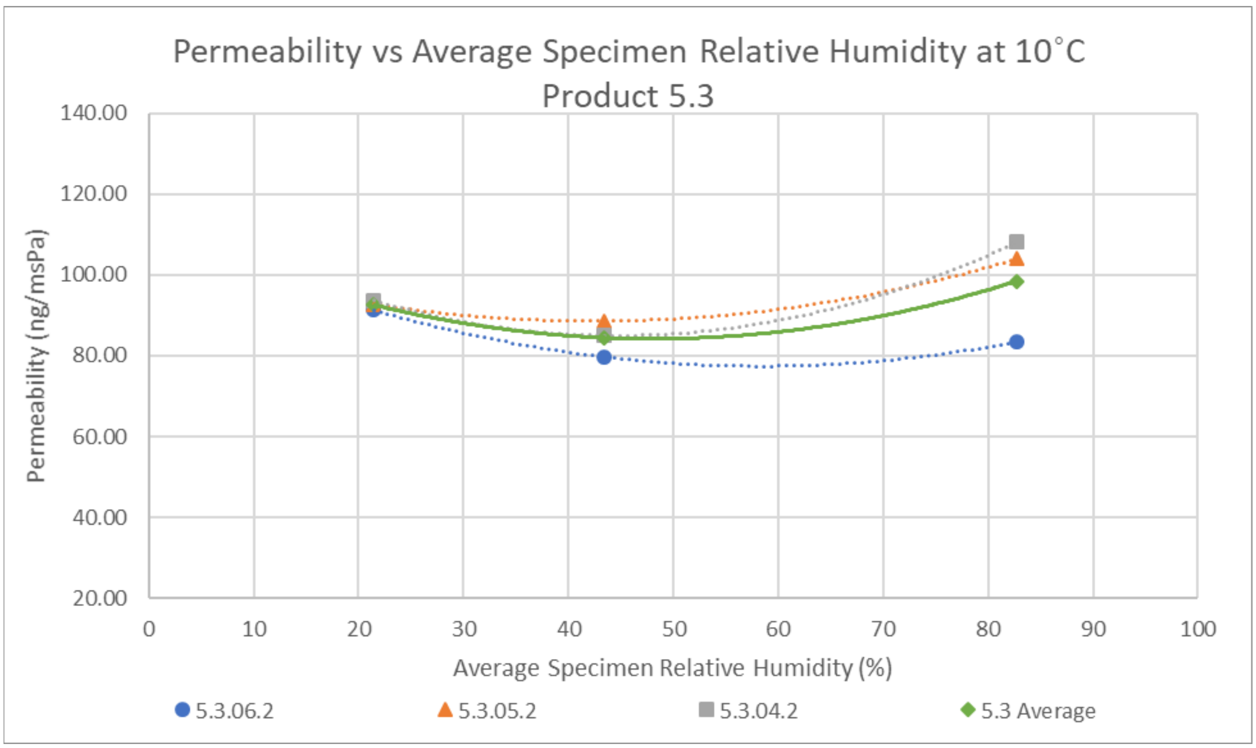


Figure F.15 – Permeabilities of Specimens 5.3.04, 5.3.05, 5.3.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.16 - Permeabilities of Specimens 5.3.04, 5.3.05, 5.3.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
5.3.06.1	109.50	69.50
5.3.05.1	105.27	71.07
5.3.04.1	104.89	71.40
5.3 Average	106.55	70.66
Standard Deviation	2.56	1.02
Coefficient of variation	2.40%	1.44%

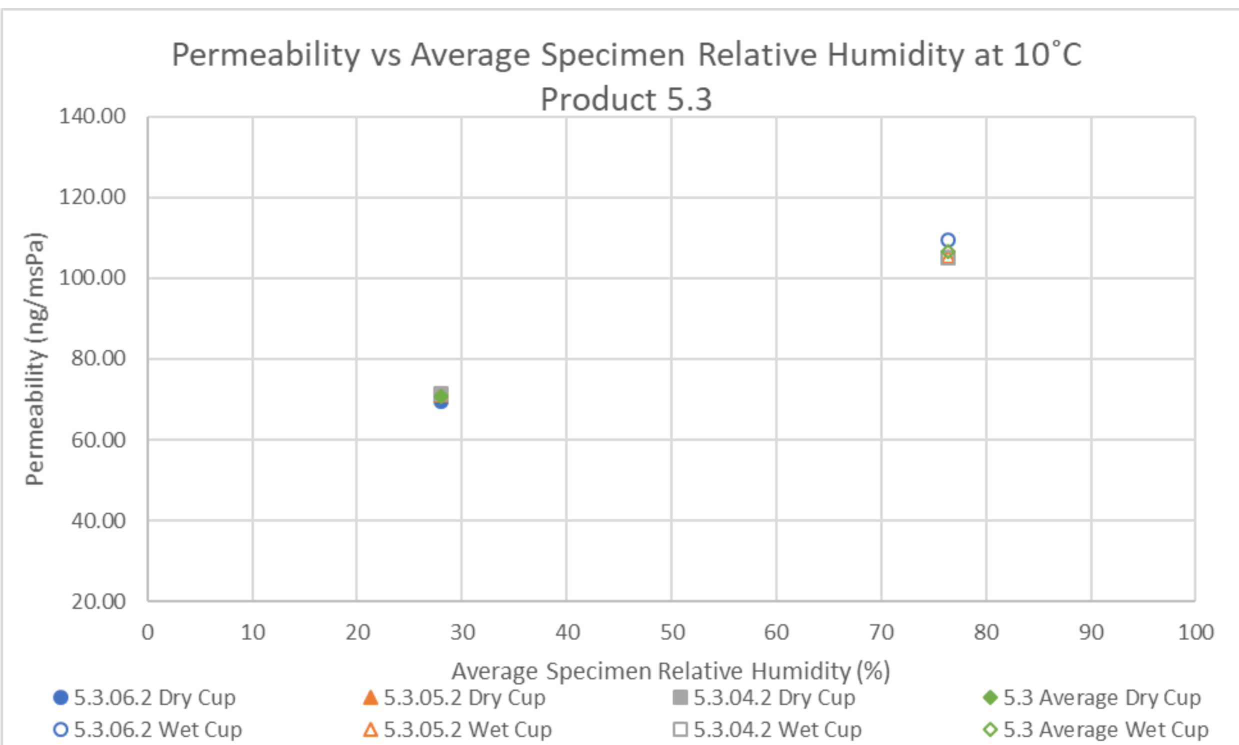


Figure F.16 – Permeabilities of Specimens 5.3.04, 5.3.05, 5.3.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.

Table F.17 - Permeabilities of Specimens 6.2.0.4, 6.2.05.1, 6.2.06.1, and Average for Modified Cup Test Conditions at 10˚C.

Test No.	.1	.2	.3	.4
Chamber Temp (˚C)	10.1	10.02	9.99	10.14
Chamber Temp – SD, CV (%)	0.10, 1.04%	0.11, 1.13%	0.08, 0.85%	0.09, 0.84%
Chamber RH (%)	35%	51%	57%	90%
Chamber RH - SD, CV (%)	1.03%, 2.90%	1.11%, 2.19%	0.89%, 1.11%	1.54%, 1.71%
Cup RH	2%	34%	57%	75%
Calc. Avg. Specimen RH	19%	42%	69%	83%
Pressure Differential (Pa)	413	205	273	186
6.2.06.1	81.65	64.67	65.09	34.83
6.2.05.1	81.21	64.80	68.21	47.49
6.2.04.1	78.72	66.23	73.14	57.44
6.2 Average	80.53	65.23	68.82	46.59
Standard Deviation	1.59	0.87	4.06	11.33
Coefficient of variation	1.97%	1.33%	5.90%	24.32%

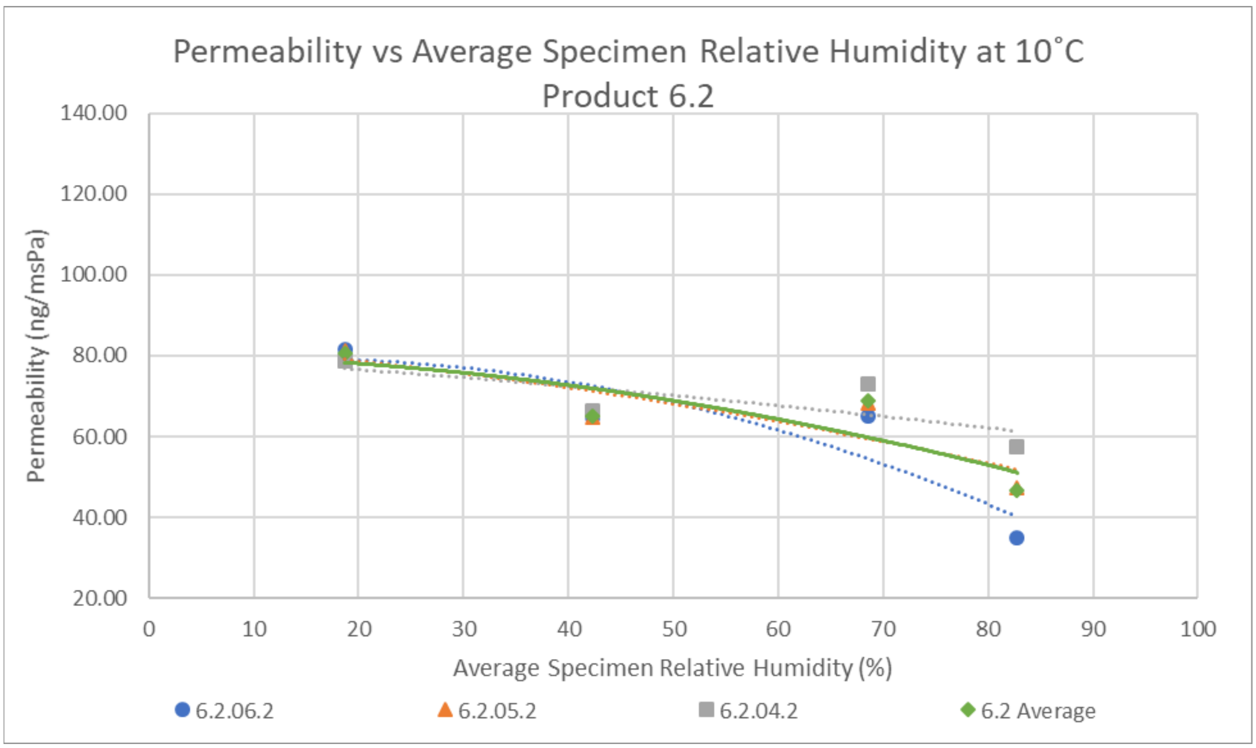


Figure F.17 – Permeabilities of Specimens 6.2.04, 6.2.05, 6.2.06, and Average for Modified Cup Test Conditions at 10˚C.

Table F.18 - Permeabilities of Specimens 6.2.04, 6.2.05, 6.2.06, and Permeability for Wet Cup and Dry Cup Test Conditions at 10˚C.

Test No.	.6	.7
Chamber Temp (˚C)	9.88	9.75
Chamber Temp – SD, CV (%)	0.14, 1.44%	0.17, 1.77%
Chamber RH (%)	53%	54%
Chamber RH - SD, CV (%)	1.98, 3.74%	5.69, 10.53%
Cup RH	100%	2%
Calc. Avg. Specimen RH	76%	28%
Pressure Differential (Pa)	584	645
6.2.06.1	100.56	73.63
6.2.05.1	96.06	76.31
6.2.04.1	90.03	73.71
6.2 Average	95.55	74.55
Standard Deviation	5.29	1.52
Coefficient of variation	5.53%	2.04%

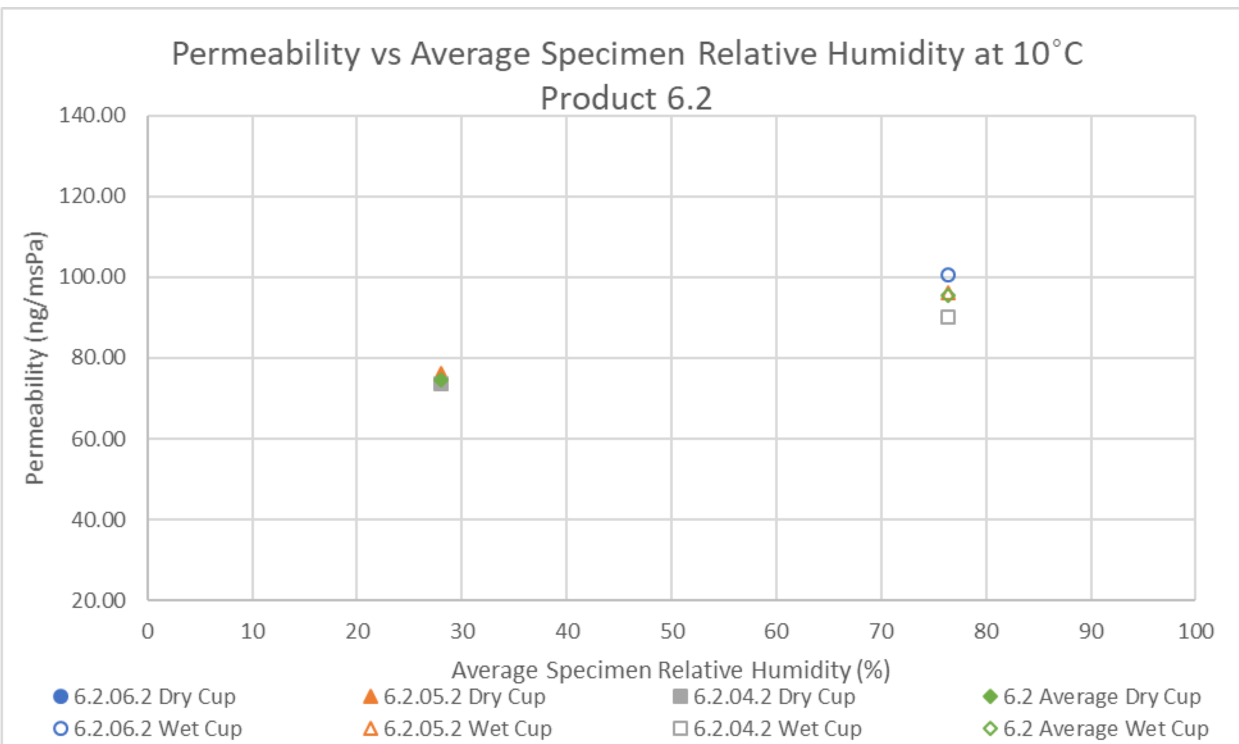
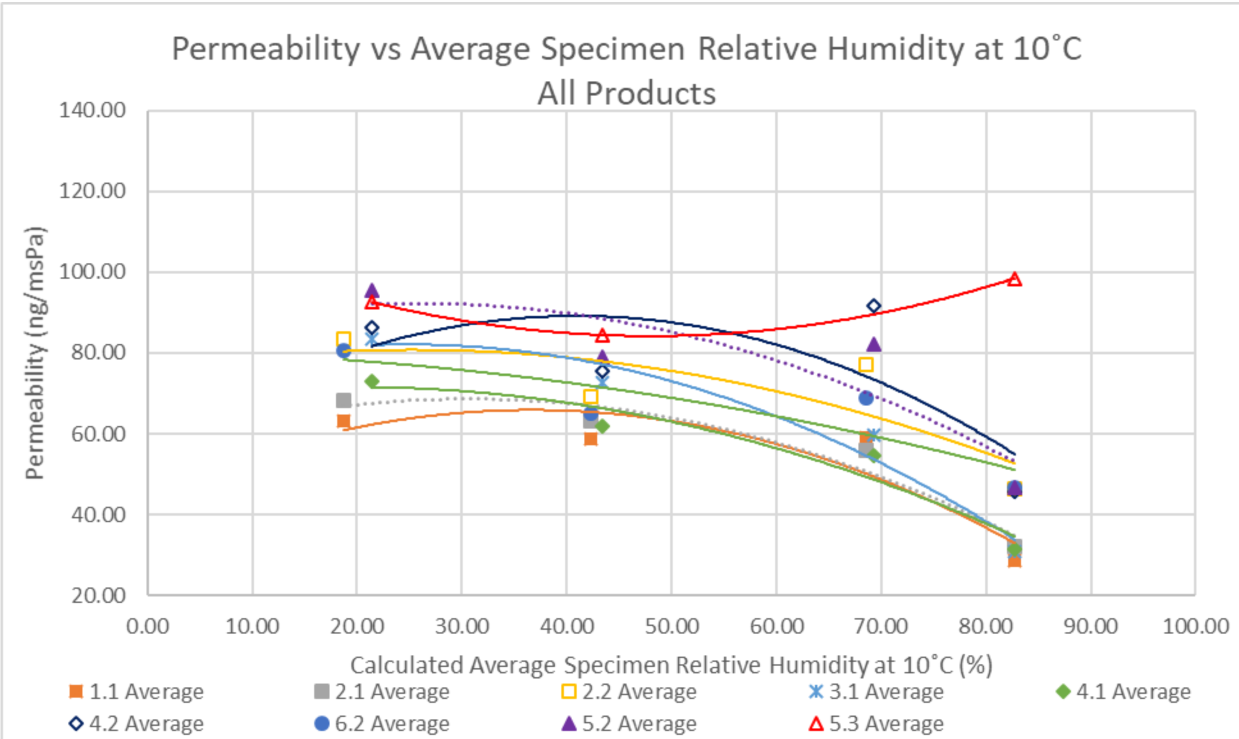
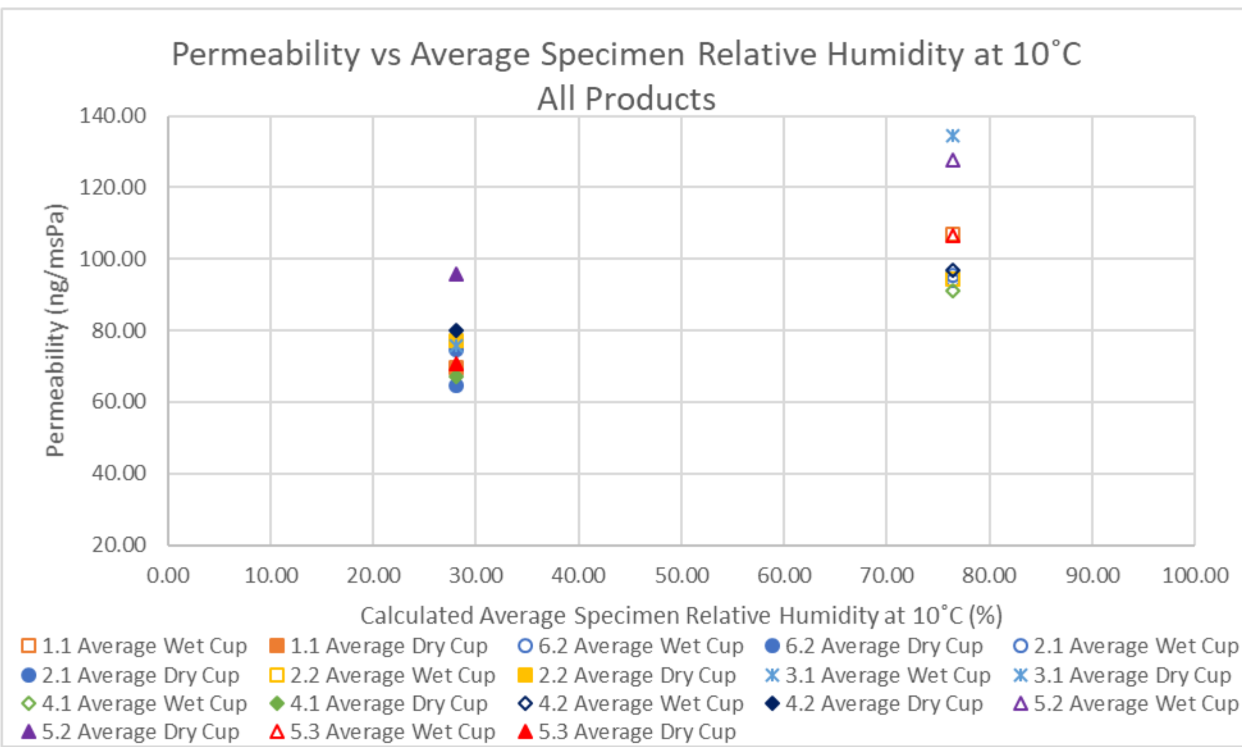


Figure F.18 – Permeabilities of Specimens 6.2.04, 6.2.05, 6.2.06, and Average for Wet Cup and Dry Cup Test Conditions at 10˚C.



. *Figure F.19 – Average Permeabilities for all Products for Modified Cup Test Conditions at 10˚C.*



. *Figure F.20 – Average Permeabilities for all Products for Dry Cup and Wet Cup Test Conditions at 10˚C.*

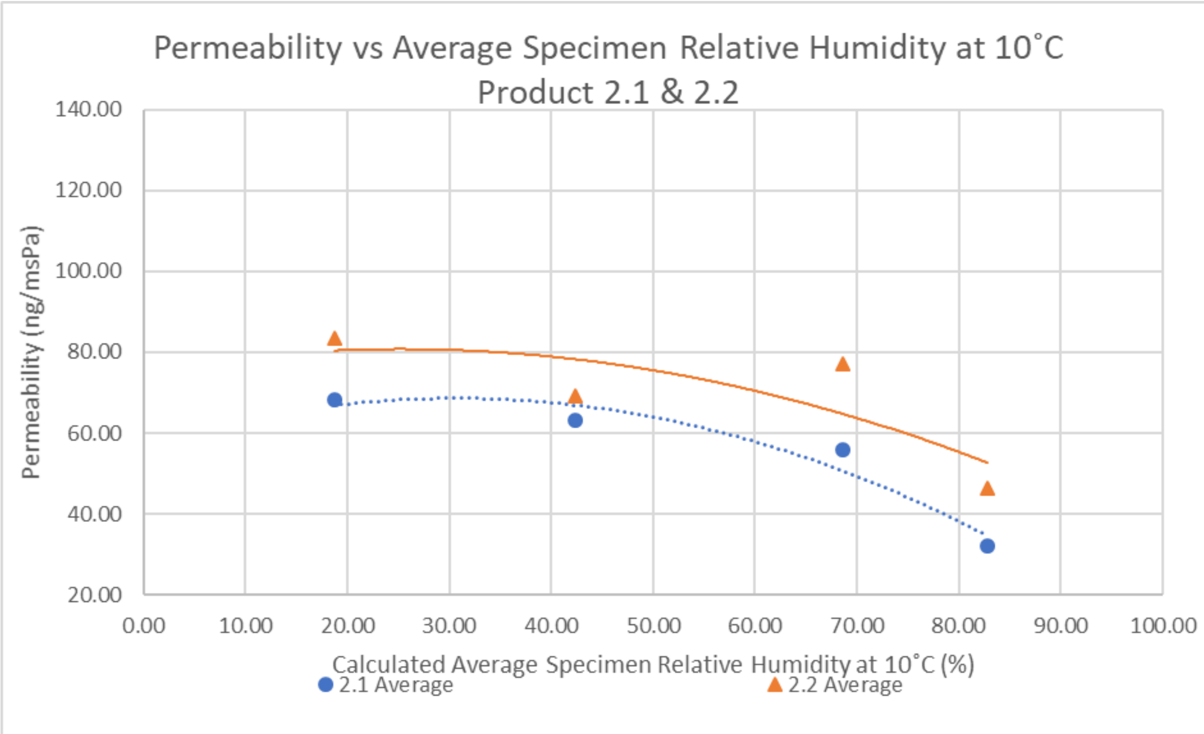


Figure F.21 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) for Modified Cup Test Conditions at 10˚C.

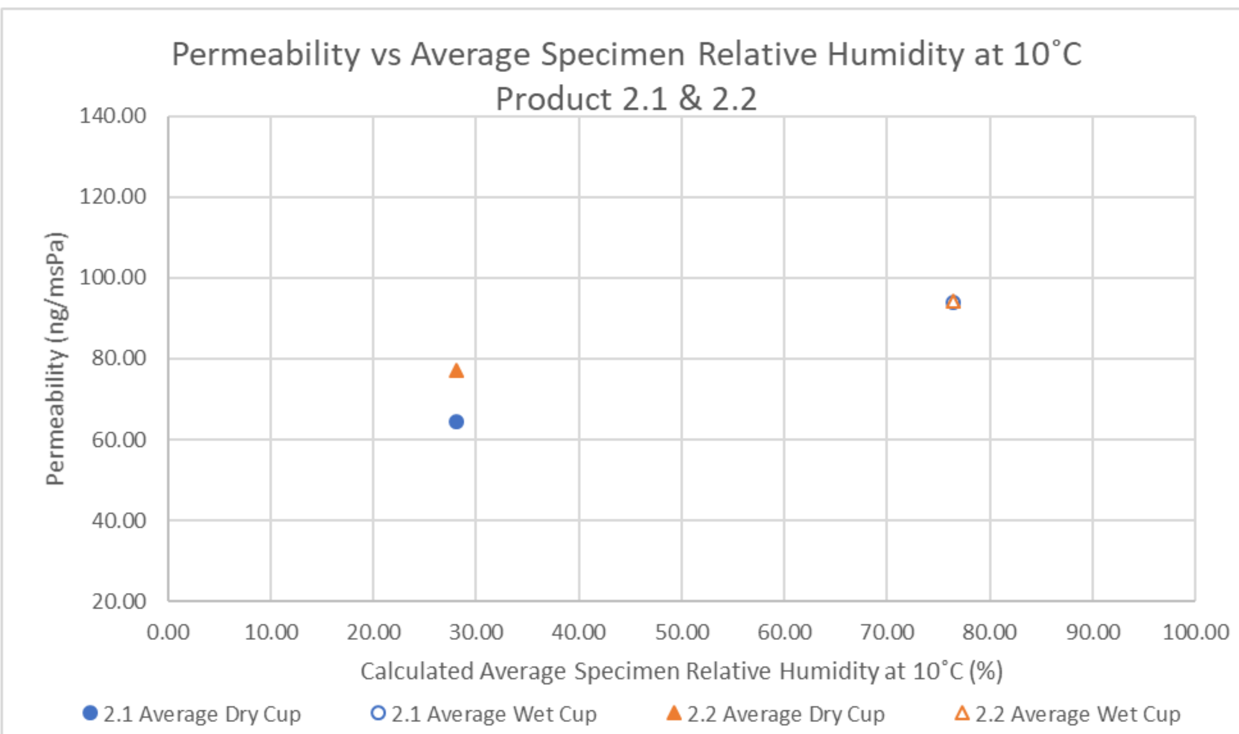


Figure F.22 – Average Permeabilities for Products 2.1 (40mm) and 2.2 (60mm) for Wet Cup and Dry Cup Conditions at 10˚C.

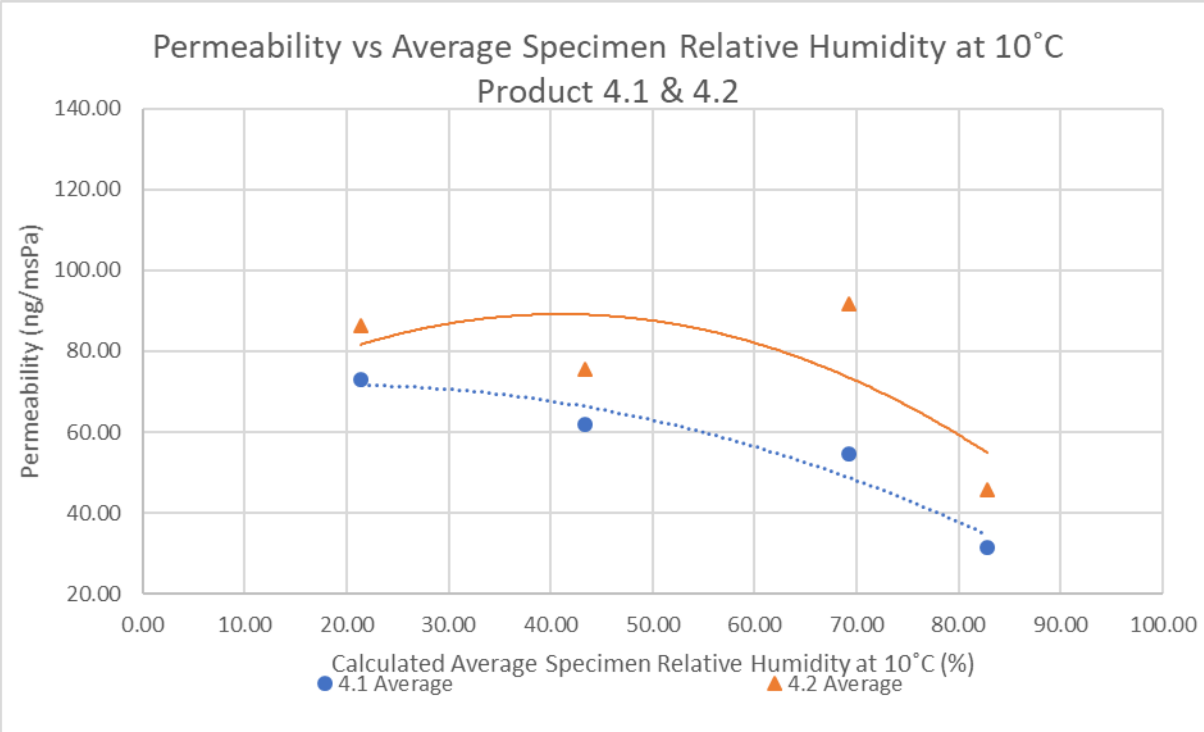


Figure F.23 – Average Permeabilities for Products 4.1 (40mm) and 4.2 (60mm) for Modified Cup Test Conditions at 10˚C.

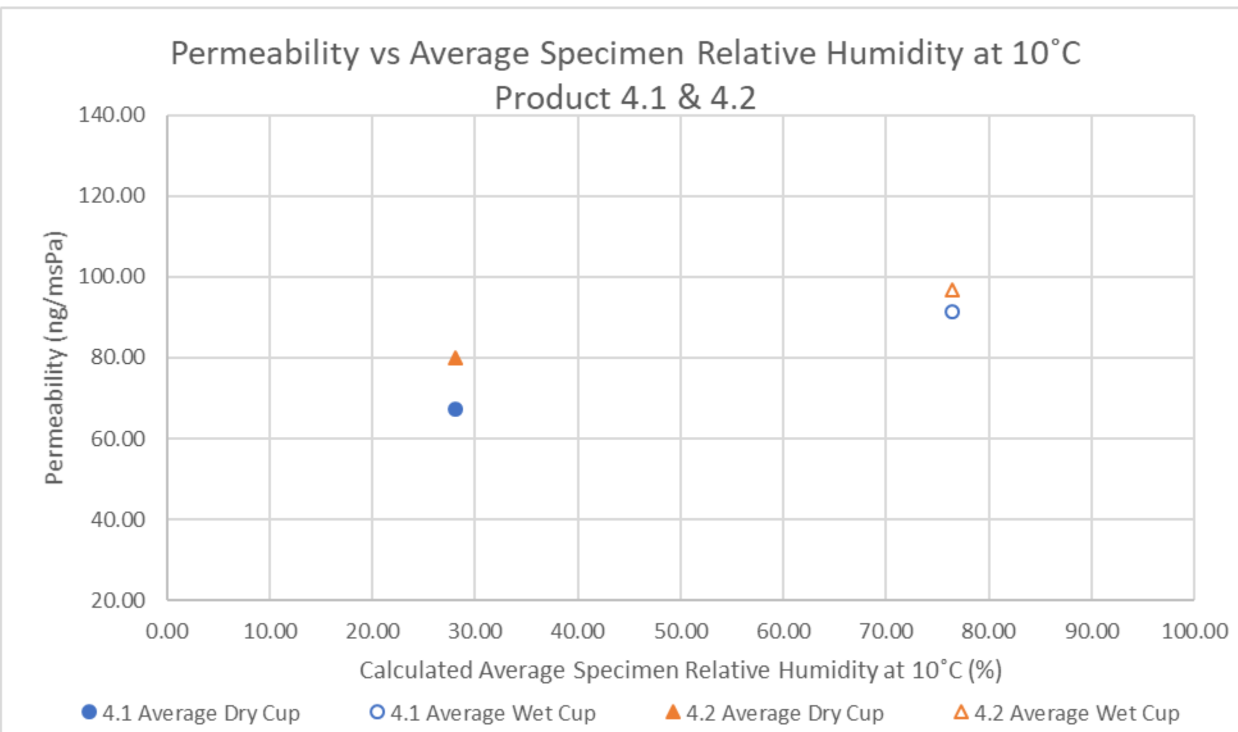


Figure F.24 – Average Permeabilities for Products 4.1 (40mm) and 4.2 (60mm) for Wet Cup and Dry Cup Conditions at 10˚C.

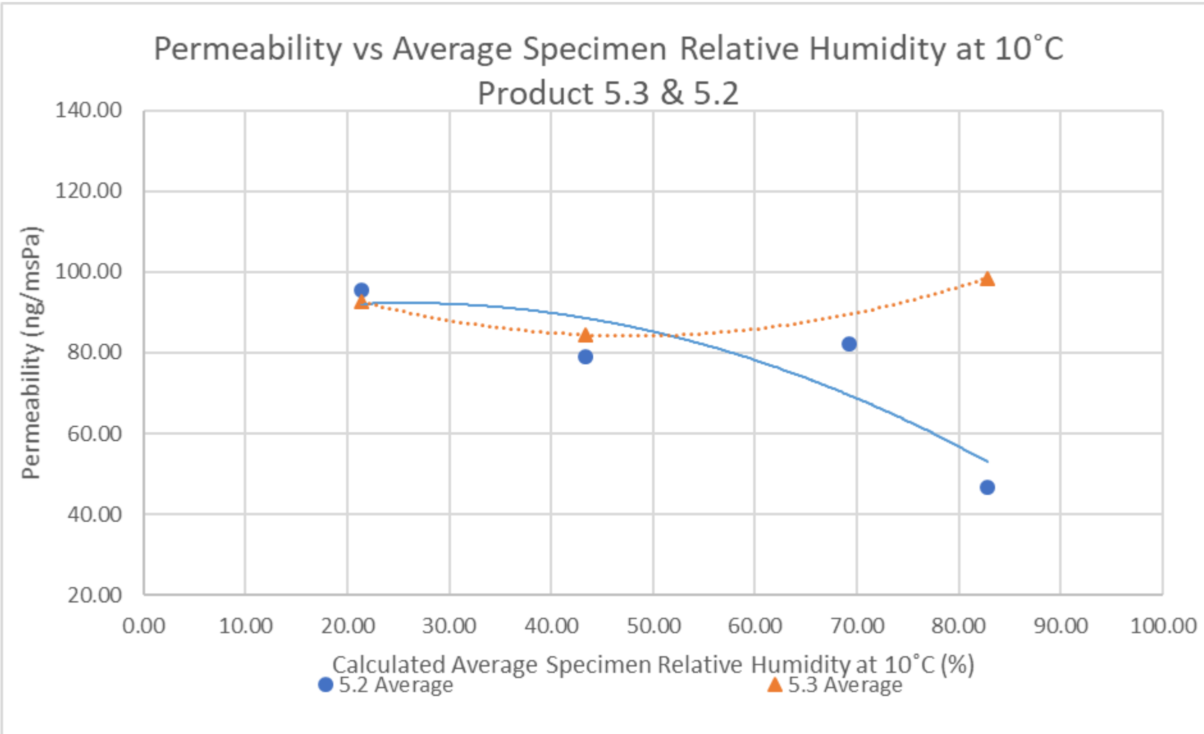


Figure F.25 – Average Permeabilities for Products 5.2 (60mm) and 5.3 (80mm) for Modified Cup Test Conditions at 10˚C.

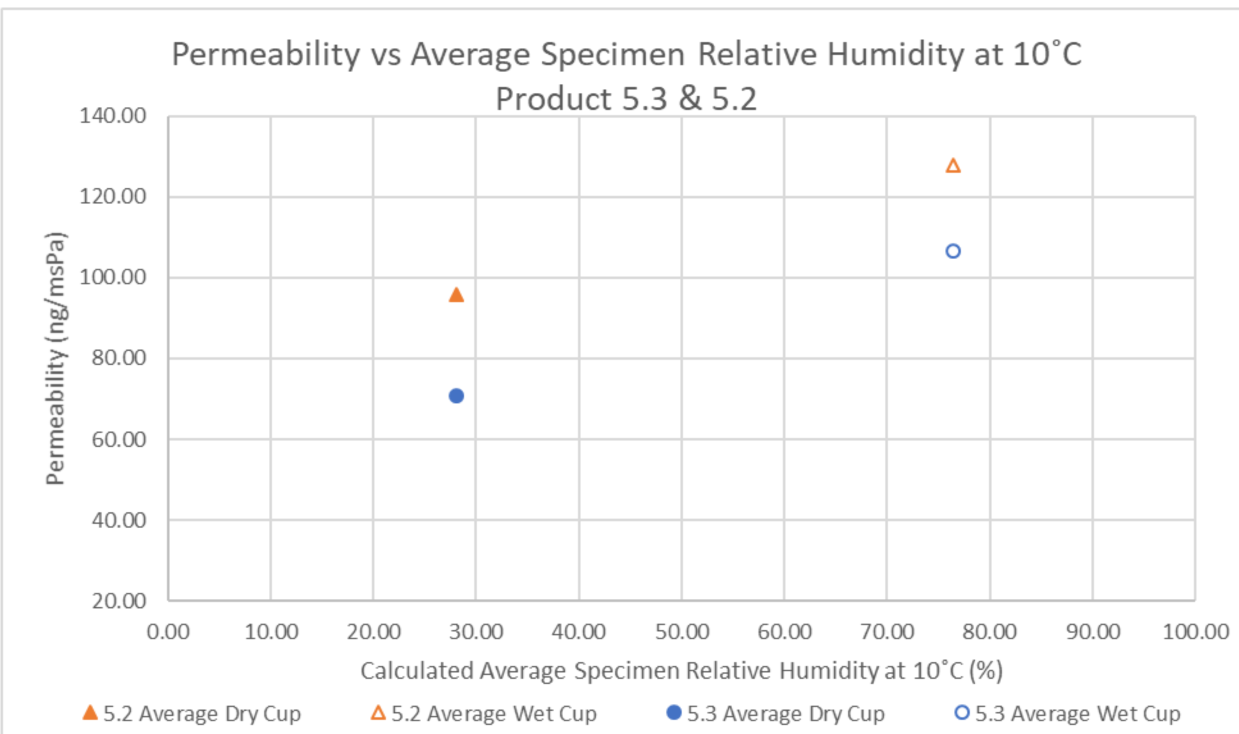


Figure F.26 – Average Permeabilities for Products 5.2 (60mm) and 5.3 (80mm) for Wet Cup and Dry Cup Conditions at 10˚C.

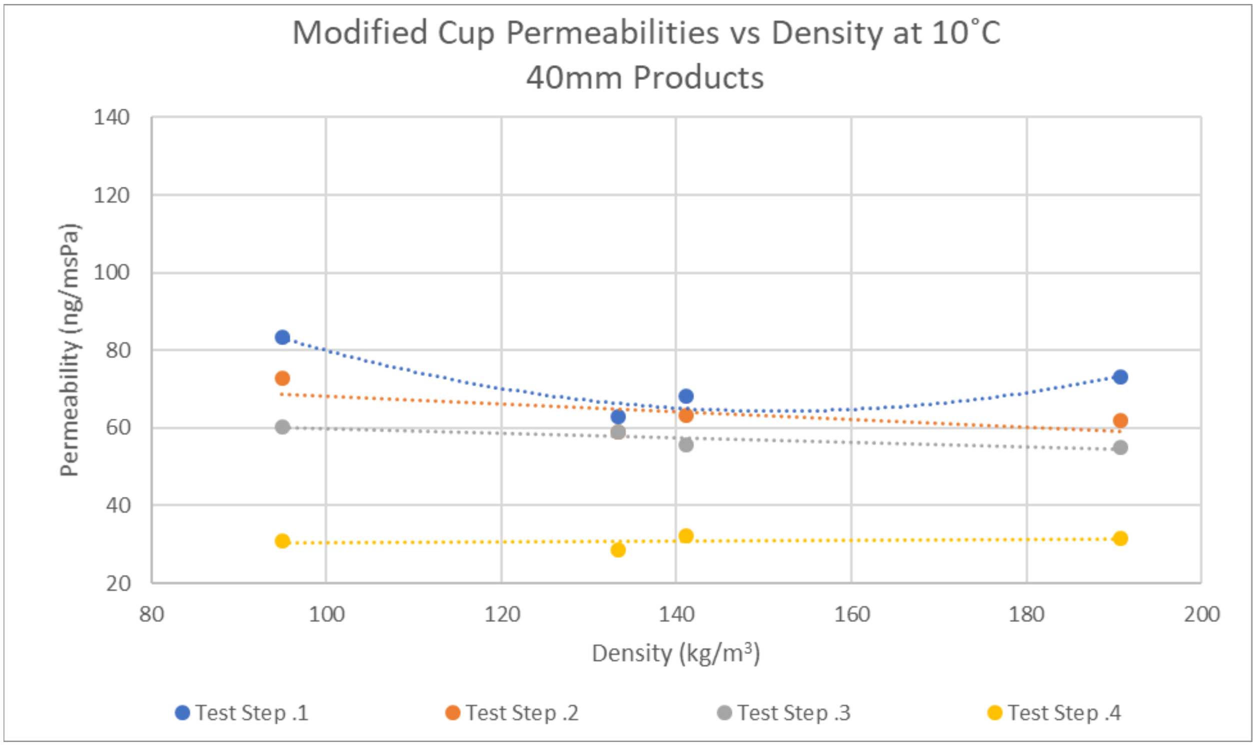


Figure F.27 – Permeability vs Density for 40mm Products for Modified Cup Test Conditions at 10˚C.

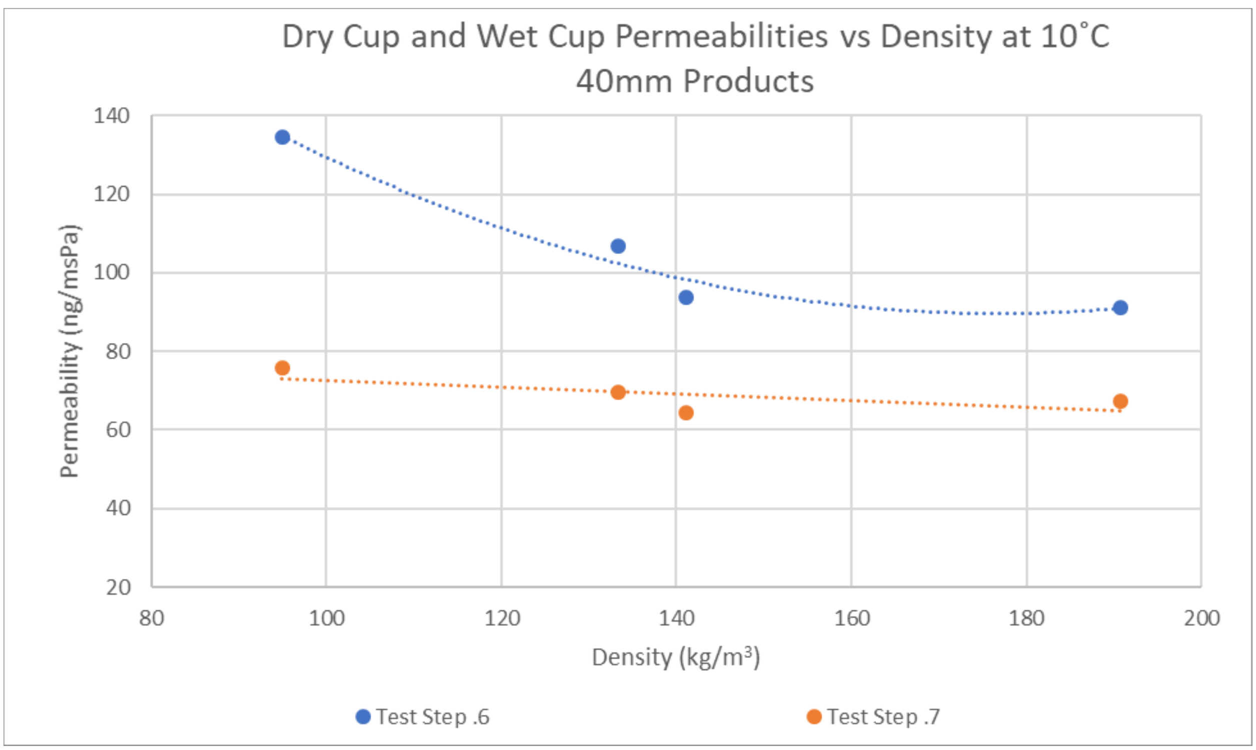


Figure F.28 – Permeability vs Density for 40mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C.

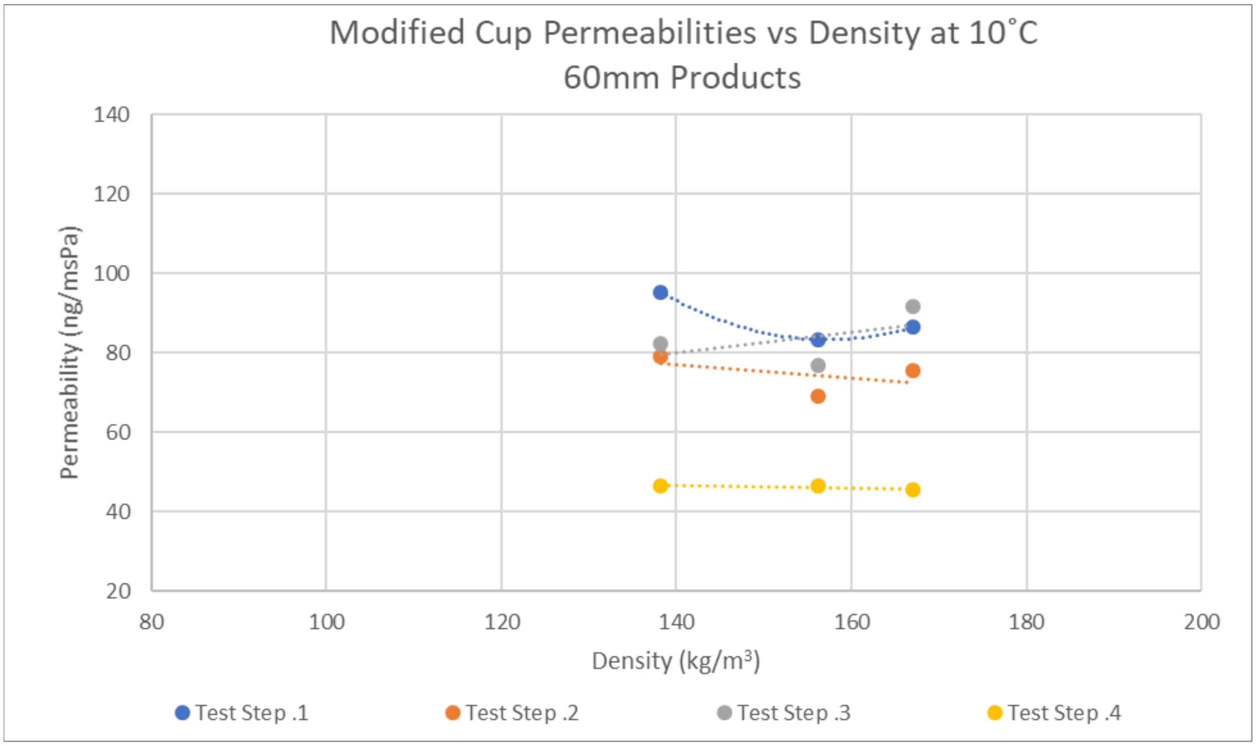


Figure F.29 – Permeability vs Density for 60mm Products for Modified Cup Test Conditions at 10˚C.

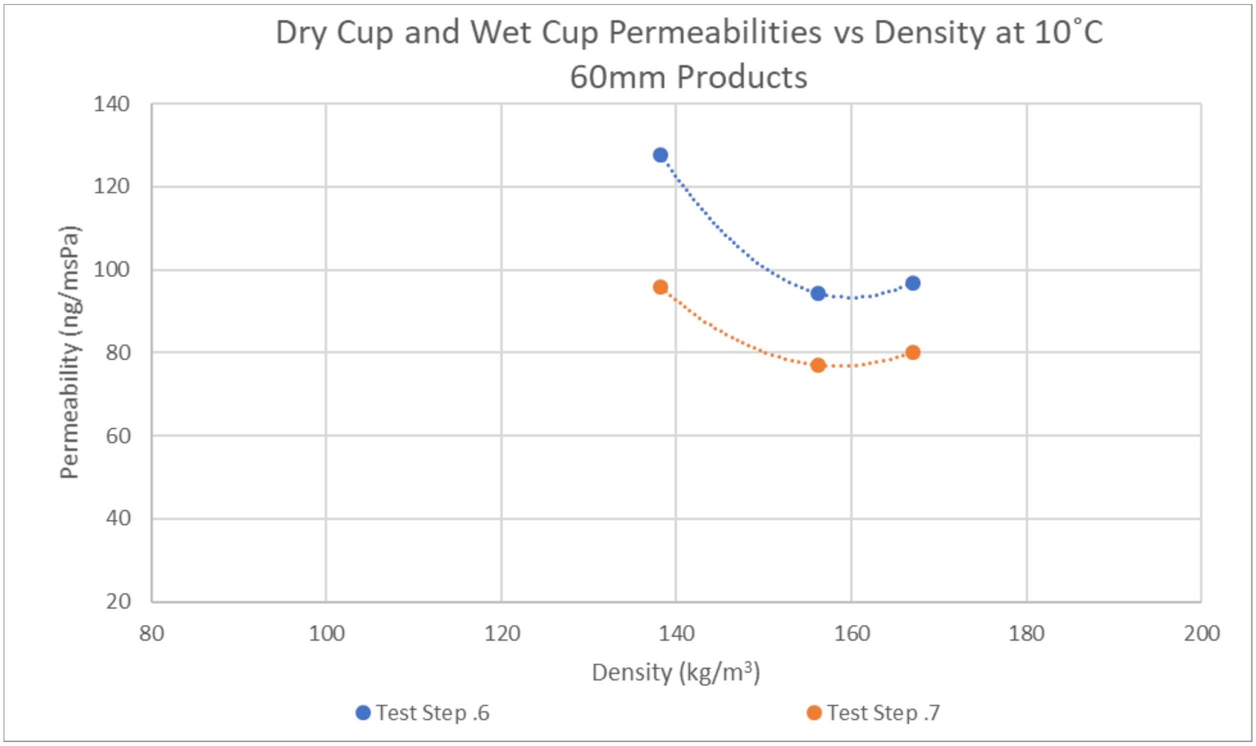


Figure F.30 – Permeability vs Density for 60mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C.

Appendix H - Vapour Permeability Test Results at 10˚C and 25˚C

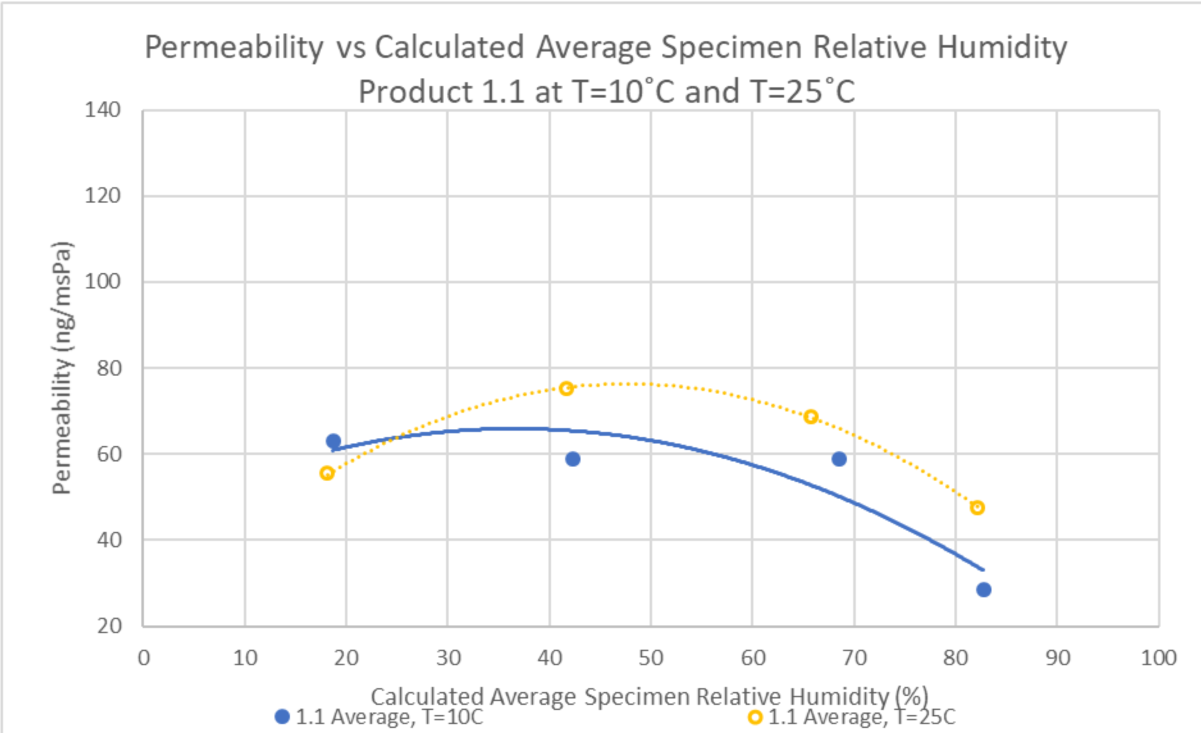


Figure G.1 – Average Permeabilities for Product 1.1 for Modified Cup Test Conditions at 10˚C and 25˚C.

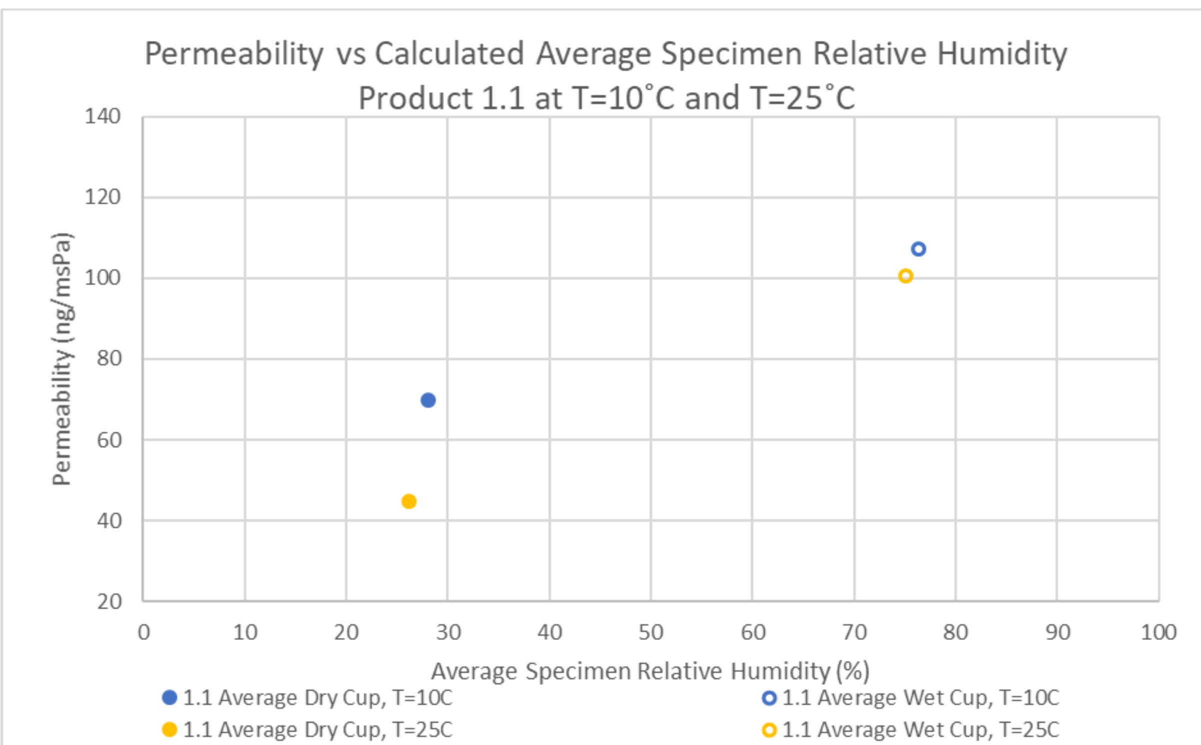


Figure G.2 – Average Permeabilities for Product 1.1 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

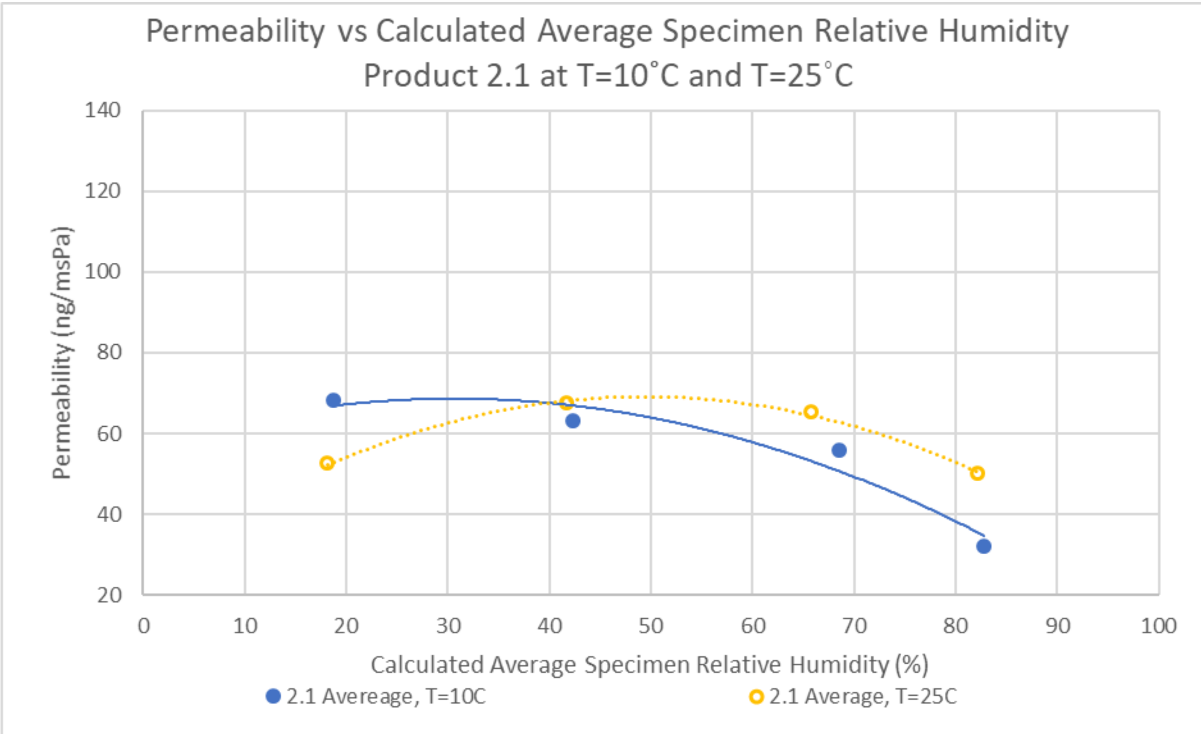


Figure G.3 – Average Permeabilities for Product 2.1 for Modified Cup Test Conditions at 10˚C and 25˚C.

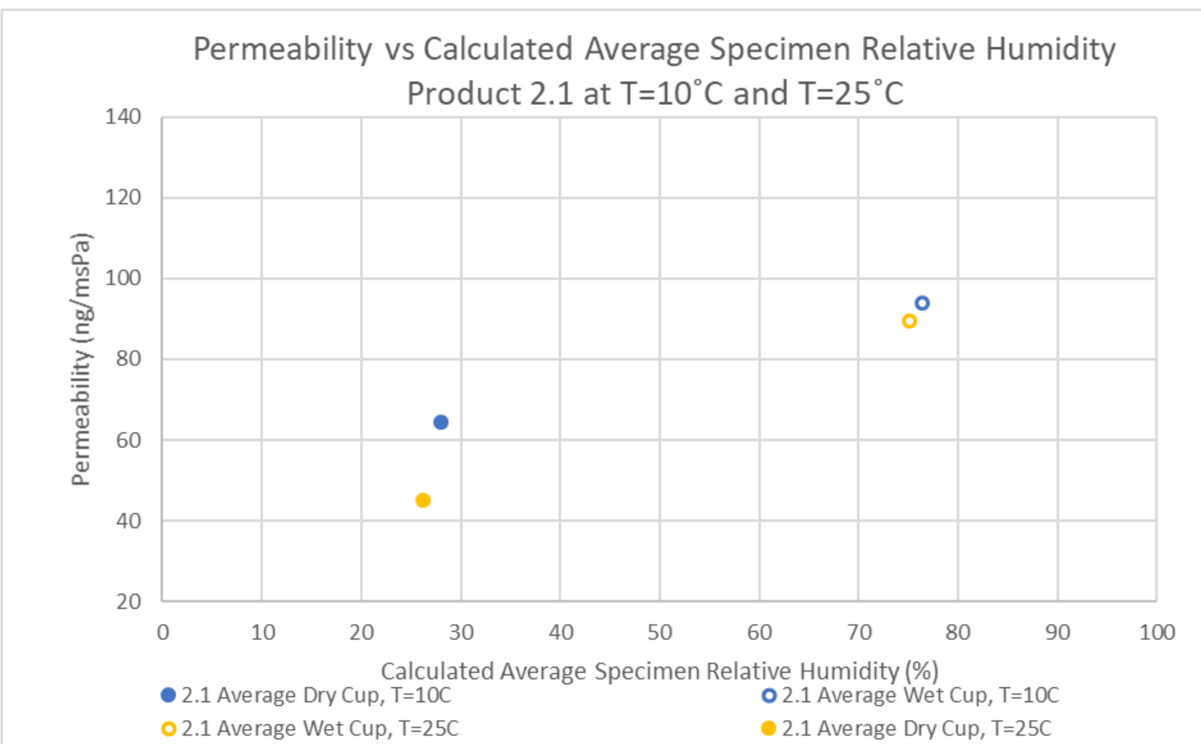


Figure G.4 – Average Permeabilities for Product 2.1 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

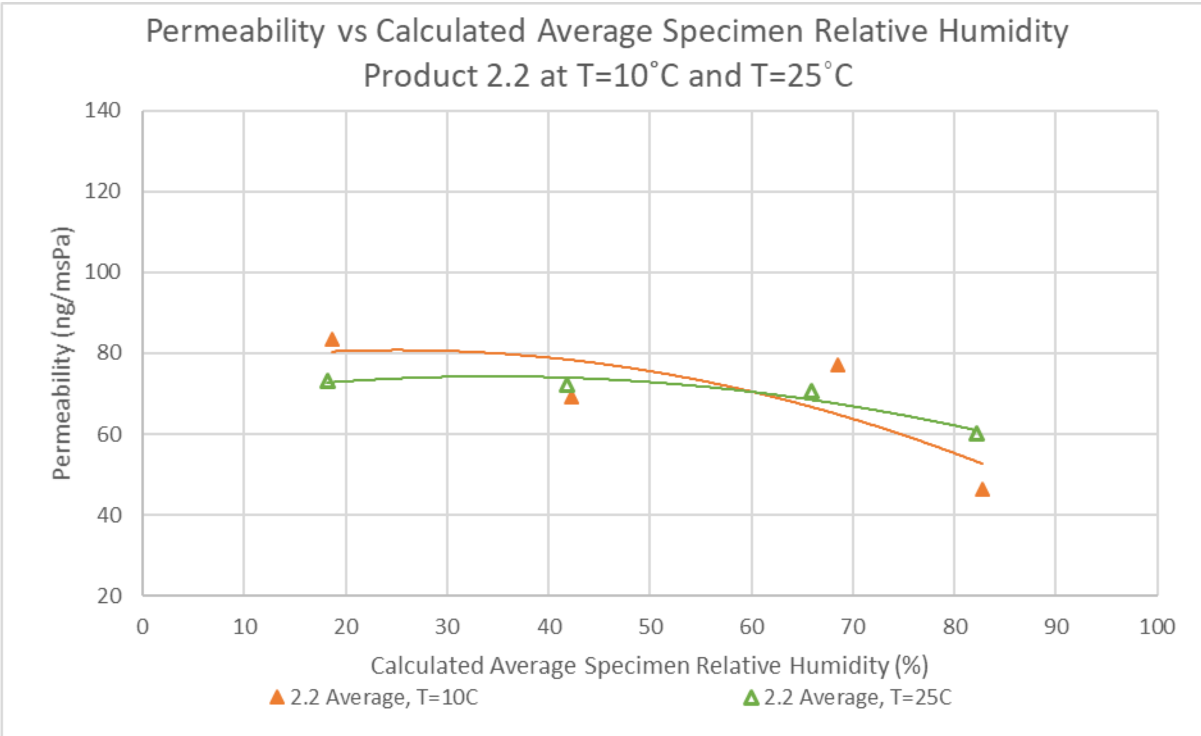


Figure G.5 – Average Permeabilities for Product 2.2 for Modified Cup Test Conditions at 10˚C and 25˚C.

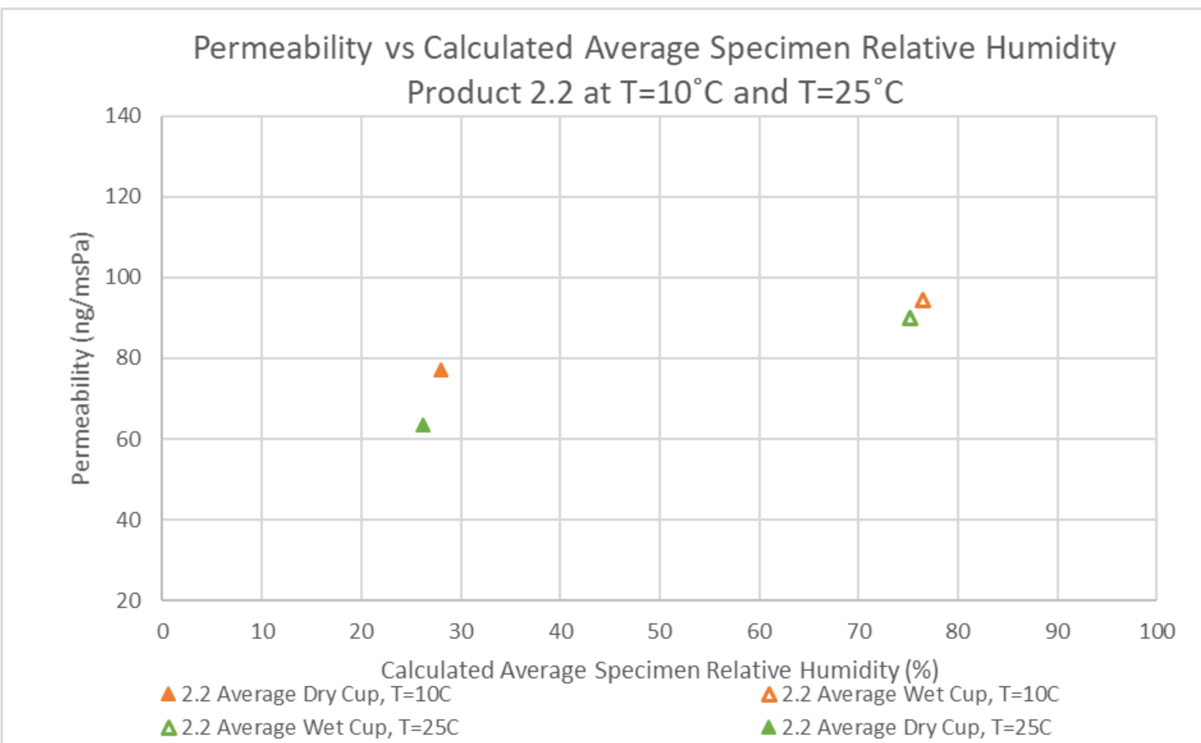


Figure G.6 – Average Permeabilities for Product 2.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

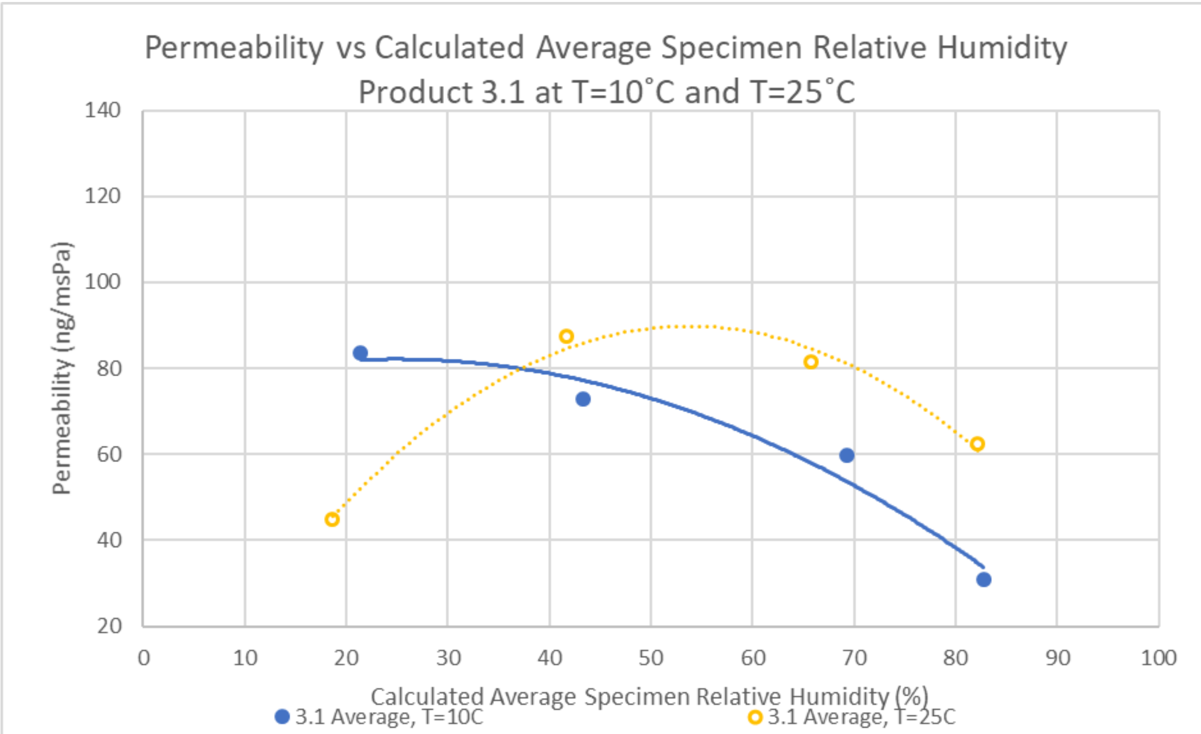


Figure G.7 – Average Permeabilities for Product 3.1 for Modified Cup Test Conditions at 10˚C and 25˚C.

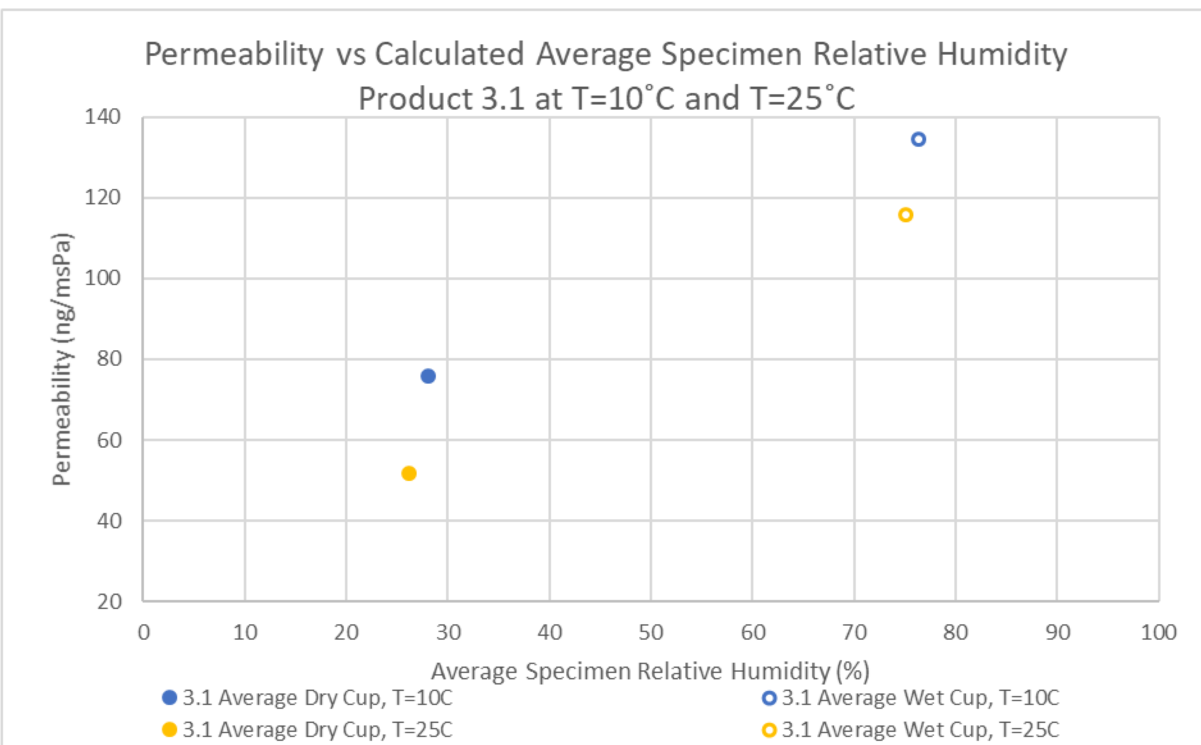


Figure G.8 – Average Permeabilities for Product 3.1 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

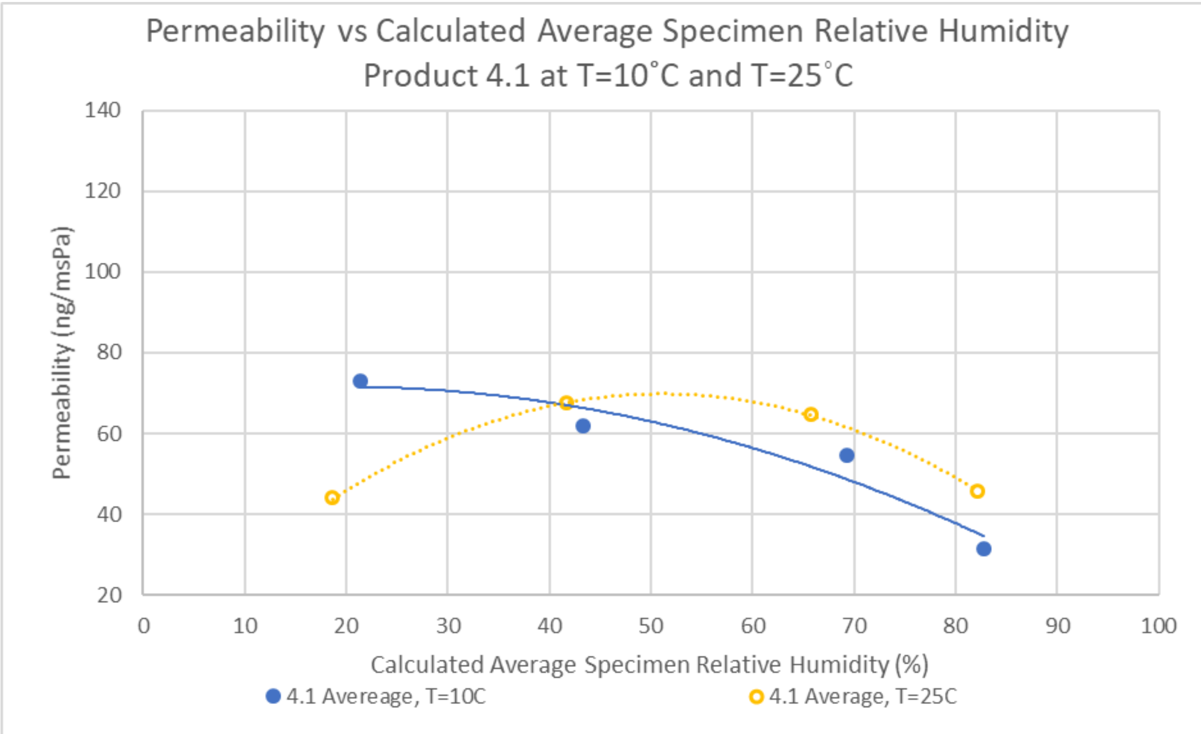


Figure G.9 – Average Permeabilities for Product 4.1 for Modified Cup Test Conditions at 10˚C and 25˚C.

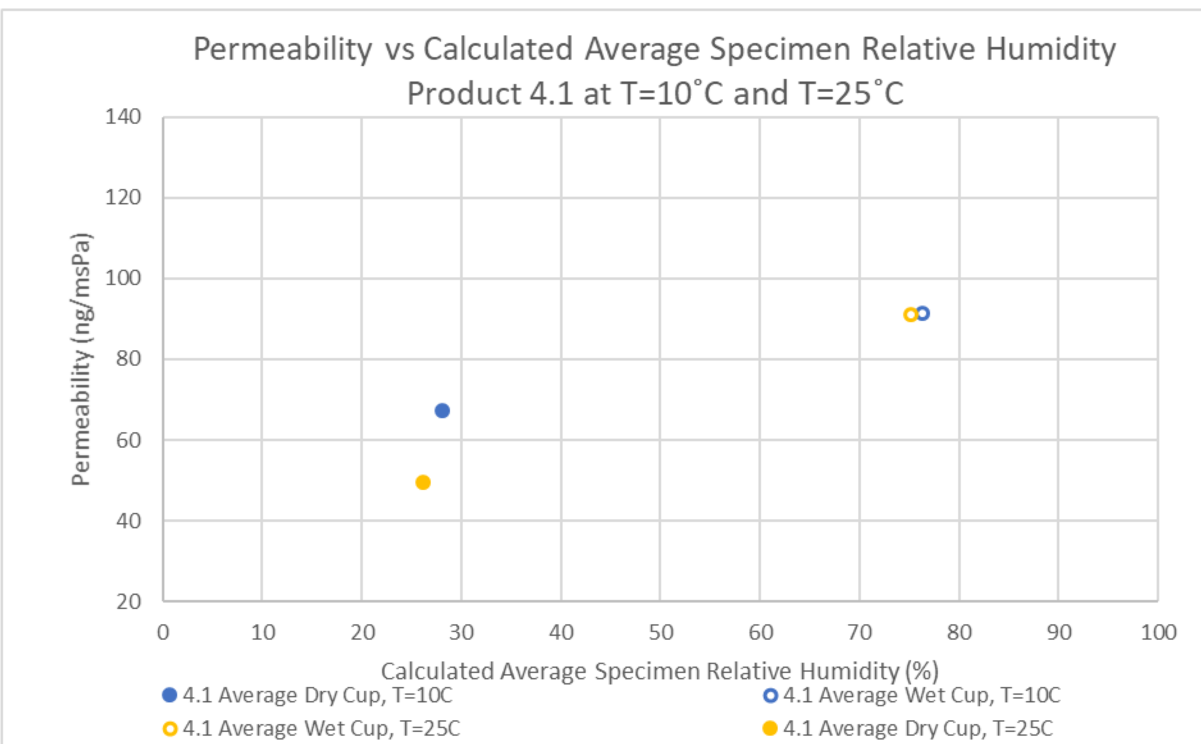


Figure G.10 – Average Permeabilities for Product 4.1 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

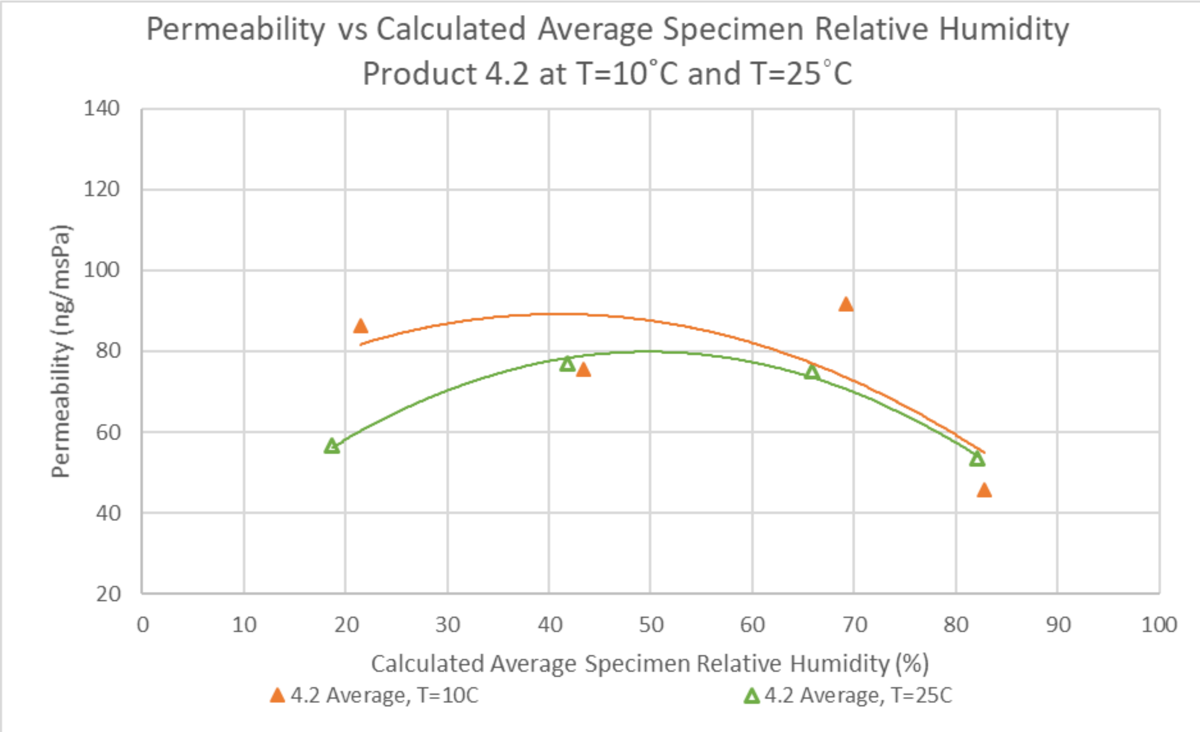


Figure G.11 – Average Permeabilities for Product 4.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

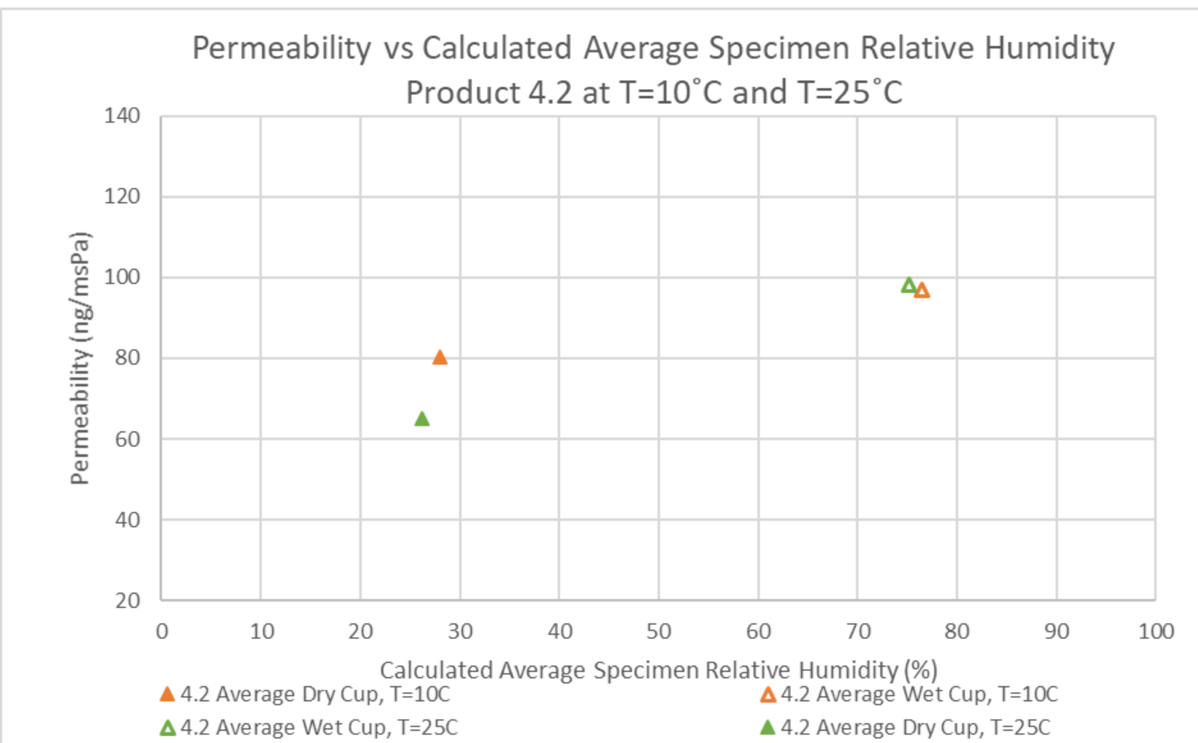


Figure G.12 – Average Permeabilities for Product 4.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

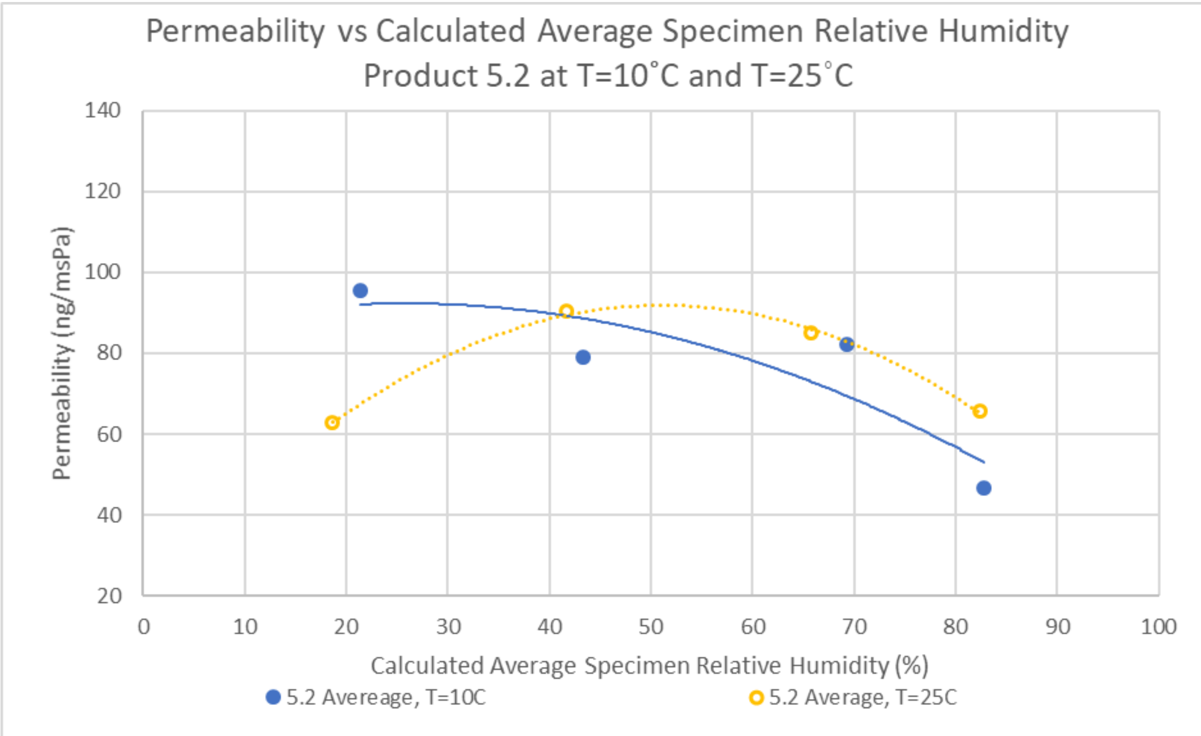


Figure G.13 – Average Permeabilities for Product 5.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

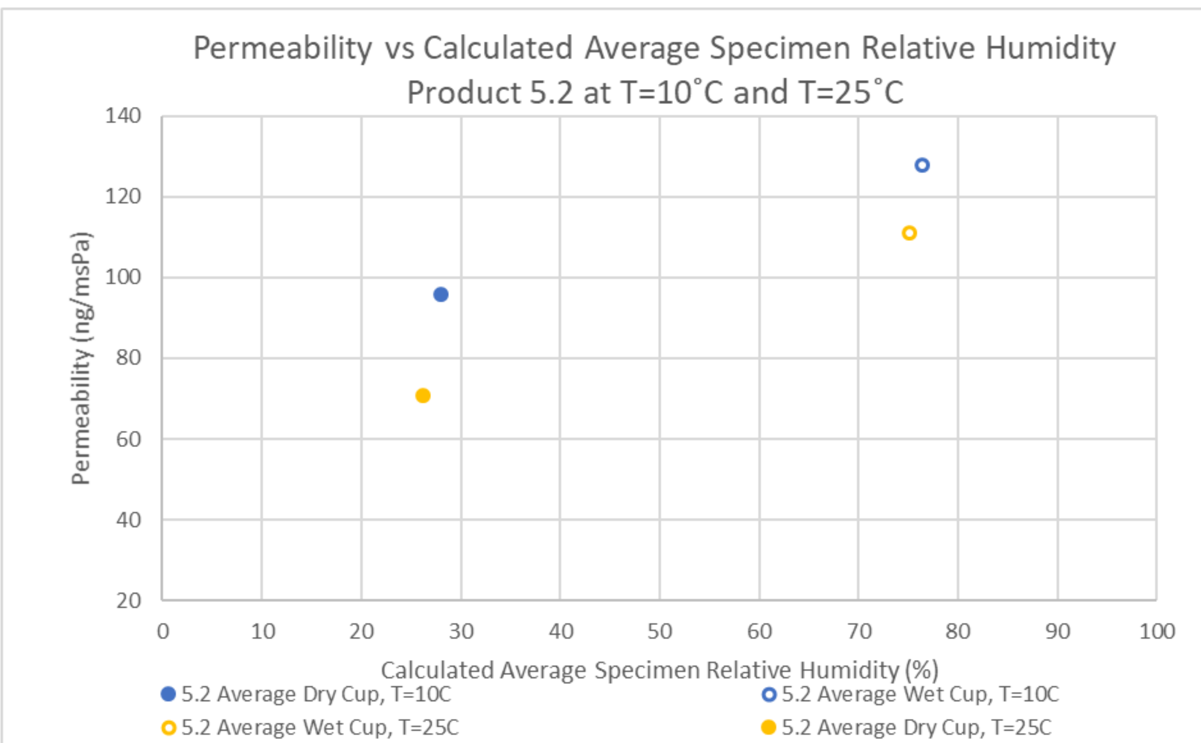


Figure G.14 – Average Permeabilities for Product 5.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

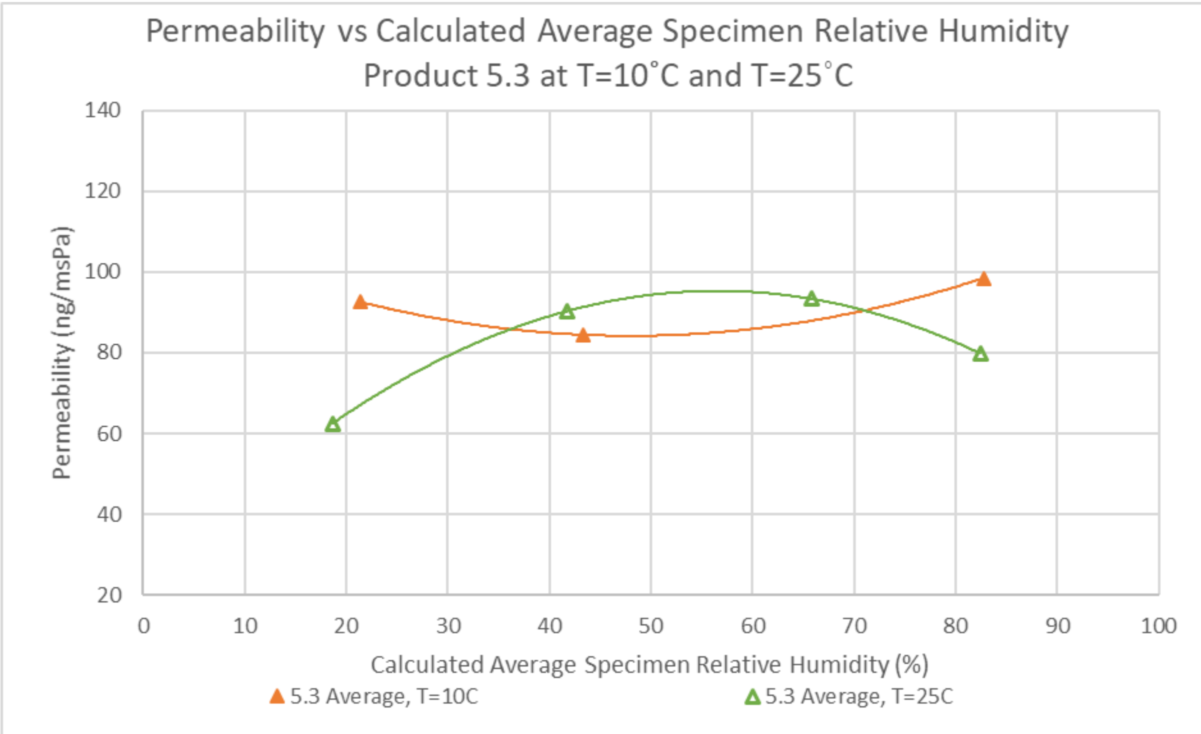


Figure G.15 – Average Permeabilities for Product 5.3 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

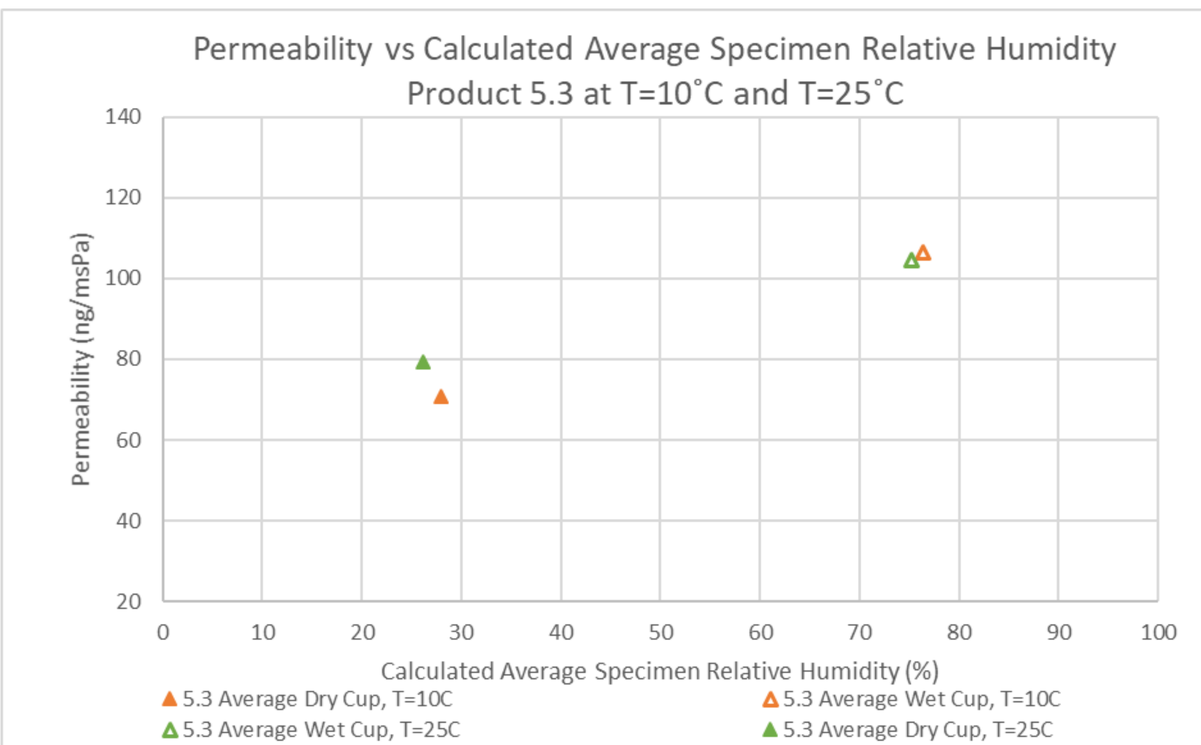


Figure G.16 – Average Permeabilities for Product 5.3 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

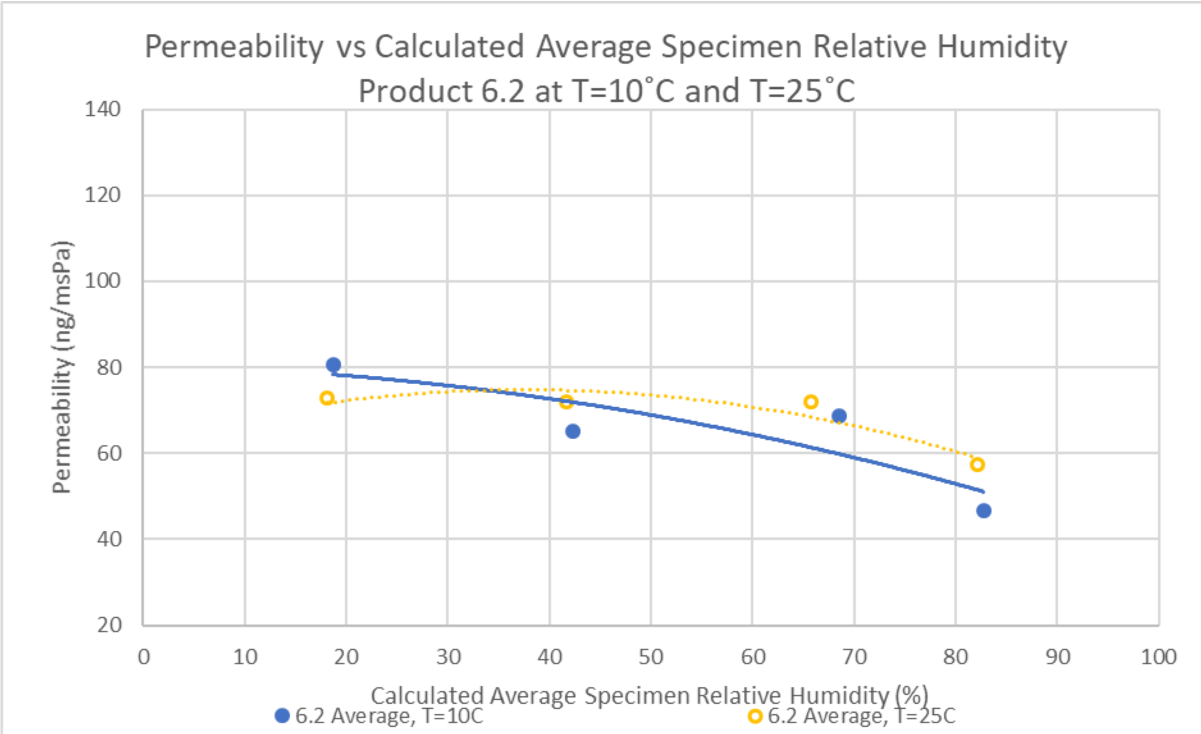


Figure G.17 – Average Permeabilities for Product 6.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

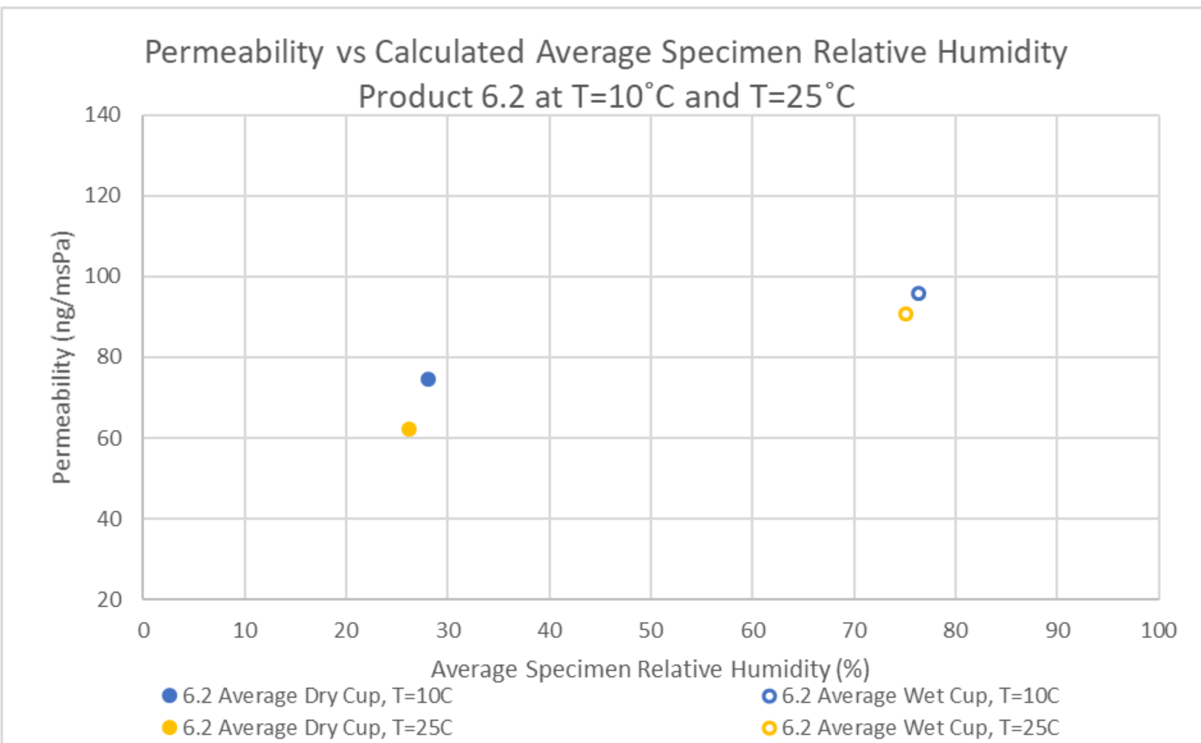


Figure G.18 – Average Permeabilities for Product 6.2 for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

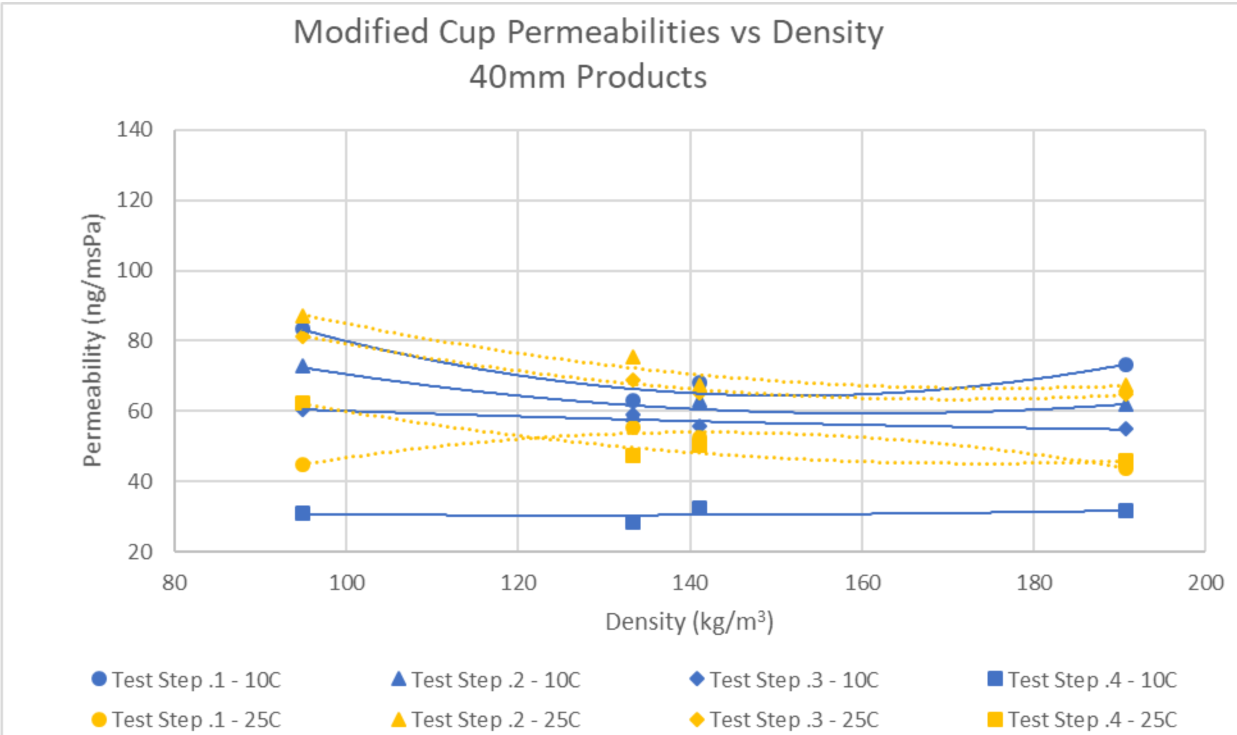


Figure G.19 – Permeability vs Density for 40mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

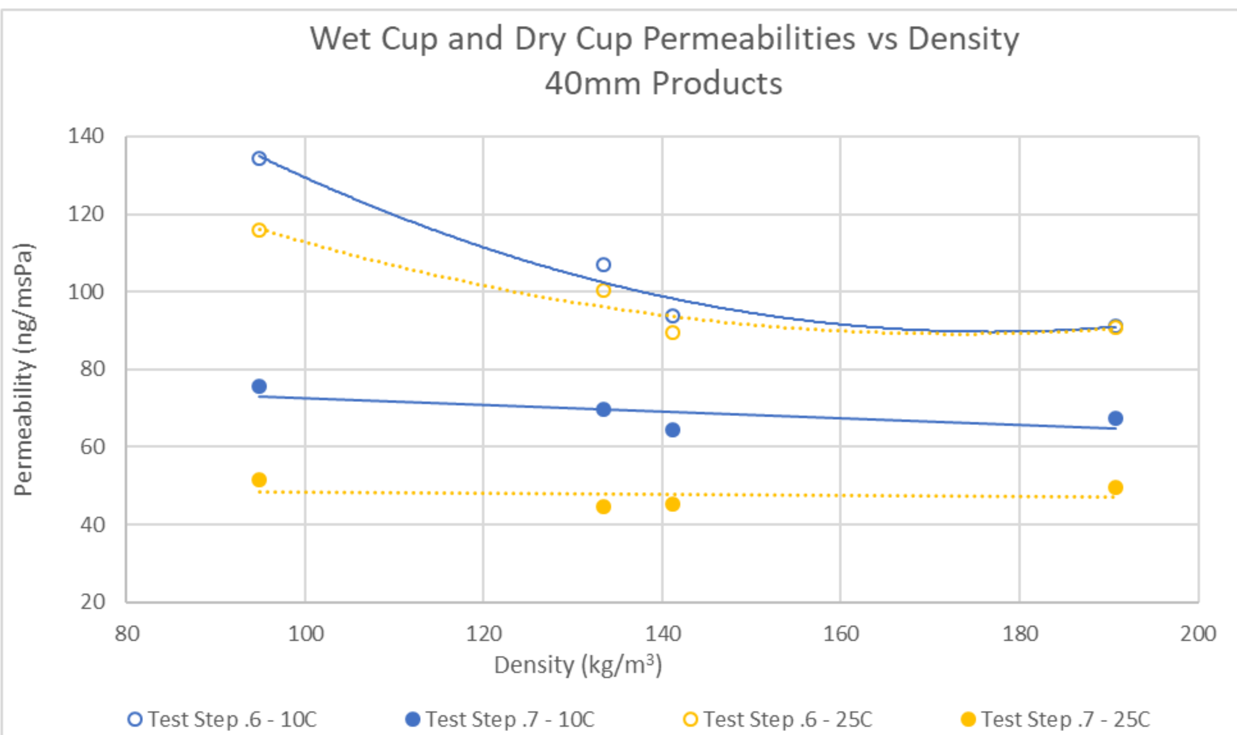


Figure G.20 – Permeability vs Density for 40mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

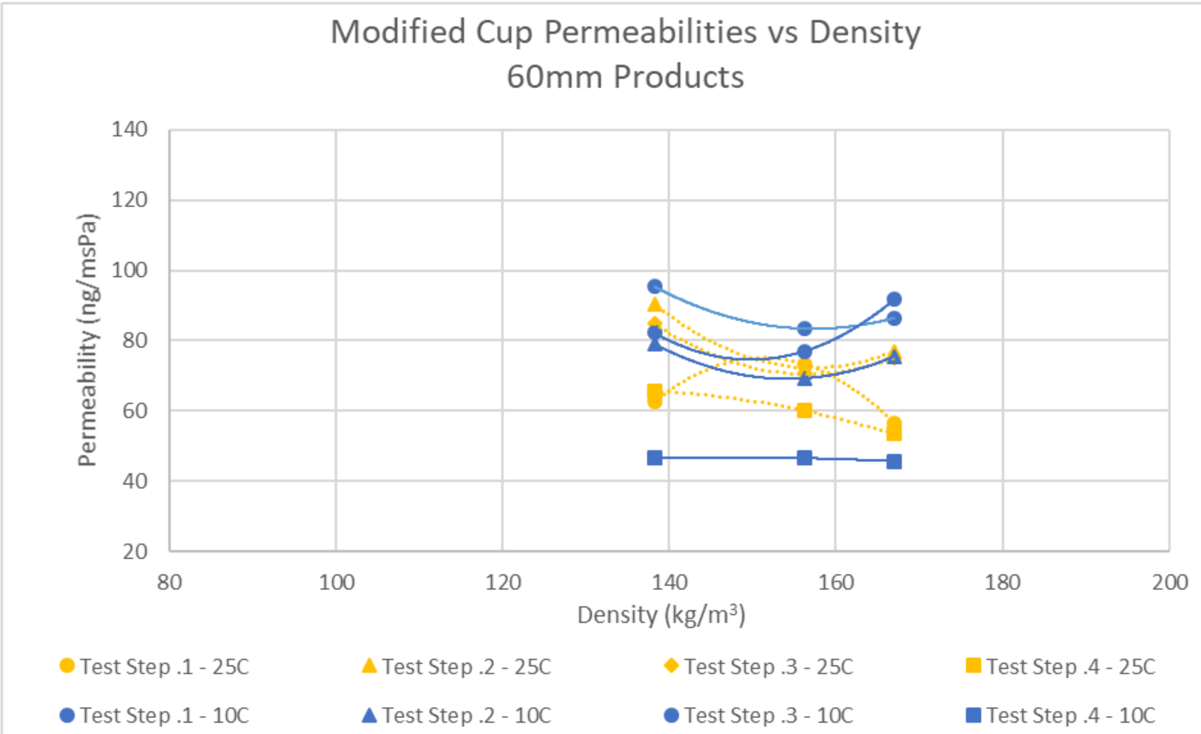


Figure G.21 – Permeability vs Density for 60mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

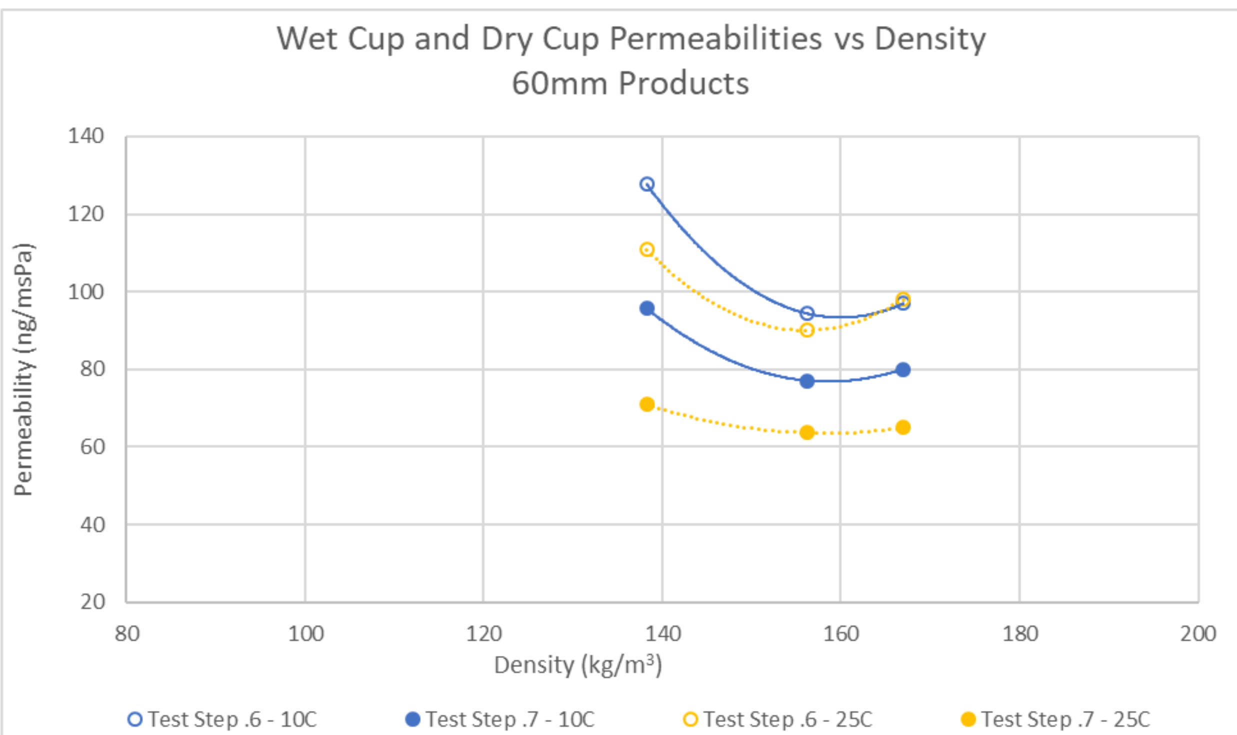


Figure G.22 – Permeability vs Density for 60mm Products for Wet Cup and Dry Cup Test Conditions at 10˚C and 25˚C.

Appendix I - Thermal Conductivity Test Results

Table H.1 - Thermal Conductivities for Specimens 1.1.01, 1.1.02, 1.1.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
1.1.01 - 6% MC		1.1.02 - 6% MC		1.1.03 - 6% MC		1.1 Average – 6%MC		
-9.66	0.037033	-10.31	0.038478	-8.71	0.040142	-9.56	0.038551	0.001556, 4.04%
1.77	0.039121	-1.07	0.038867	1.73	0.039459	0.81	0.039149	0.000297, 0.76%
10.54	0.041857	10.79	0.041353	11.74	0.041817	11.02	0.041676	0.000280, 0.67%
20.47	0.043496	20.51	0.044046	21.31	0.045419	20.76	0.044320	0.000990, 2.23%
31.86	0.043005	31.79	0.045233	28.61	0.044487	30.75	0.044242	0.001134, 2.56%
1.1.01 - 10% MC		1.1.02 - 9% MC		1.1.03 - 9% MC		1.1 Average – 9%MC		
-10.44	0.037208	-9.41	0.039365	-9.54	0.039329	-9.80	0.038634	0.001235, 3.2%
0.53	0.035312	1.38	0.042705	1.46	0.042897	1.42	0.042801	0.000136, 0.32%
10.53	0.044231	9.92	0.045126	10.23	0.045285	10.23	0.044881	0.000568, 1.27%
20.49	0.045835	20.97	0.046314	21.06	0.047247	20.84	0.046465	0.000718, 1.55%
30.45	0.047781	31.26	0.047102	30.67	0.049928	30.79	0.048270	0.001475, 3.06%
1.1.01 - 14% MC		1.1.02 - 14% MC		1.1.03 - 14% MC		1.1 Average – 14%MC		
-10.2	0.038575	-9.5	0.040941	-9.24	0.040869	-9.65	0.040128	0.001346, 3.35%
1.71	0.042802	2.07	0.04434	1.34	0.044015	1.71	0.043719	0.000811, 1.85%
10.53	0.046988	10.25	0.047768	11.7	0.048482	10.83	0.047746	0.000747, 1.57%
20.63	0.049407	19.85	0.052705	20.63	0.053637	20.37	0.051916	0.002223, 4.28%
30.53	0.053972	30.34	0.060757	30.53	0.060361	30.47	0.058363	0.003808, 6.52%
1.1.01 - 19% MC		1.1.02 - 18% MC		1.1.03 - 18% MC		1.1 Average – 18%MC		
-8.68	0.041078	-11.11	0.042516	-10.94	0.04227	-10.24	0.041955	0.000769, 1.83%
0.53	0.045013	-0.59	0.046269	1.1	0.046811	0.35	0.046031	0.000922, 2%
9.27	0.04745	9.32	0.049644	10.06	0.049915	9.55	0.049003	0.001352, 2.76%
21.75	0.05539	21.14	0.059109	21.51	0.057139	21.47	0.057213	0.001861, 3.25%
31.21	0.063426	30.81	0.071036	30.9	0.069327	30.97	0.067930	0.003993, 5.88%

Table H.2 - Chamber Temperature and Relative Humidity Data for Specimens 1.1.01, 1.1.02, 1.1.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
1.1.01	23.98	0.75, 3.13%	30.69%	0.63%, 2.06%
1.1.02	23.98	0.74, 3.11%	30.71%	0.68%, 2.2%
1.1.03	23.94	0.79, 3.32%	29.84%	1.45%, 4.94%
1.1.01	26.52	0.47, 1.75%	71.41%	6.10%, 8.62%
1.1.02	26.08	0.12, 0.46%	62.90%	3.22%, 5.26%
1.1.03	26.22	0.17, 0.65%	61.41%	2.89%, 4.78%
1.1.01	24.42	1.19, 4.91%	80.21%	3.73%, 4.63%
1.1.02	24.40	1.19, 4.97%	81.08%	3.78%, 4.61%
1.1.03	24.76	1.07, 4.36%	79.85%	4.25%, 5.28%
1.1.01	24.24	0.85, 3.54%	93.99%	2.77%, 2.95%
1.1.02	24.25	0.85, 3.51%	93.74%	2.75%, 2.93%
1.1.03	24.32	0.88, 3.64%	93.80%	2.60%, 2.76%

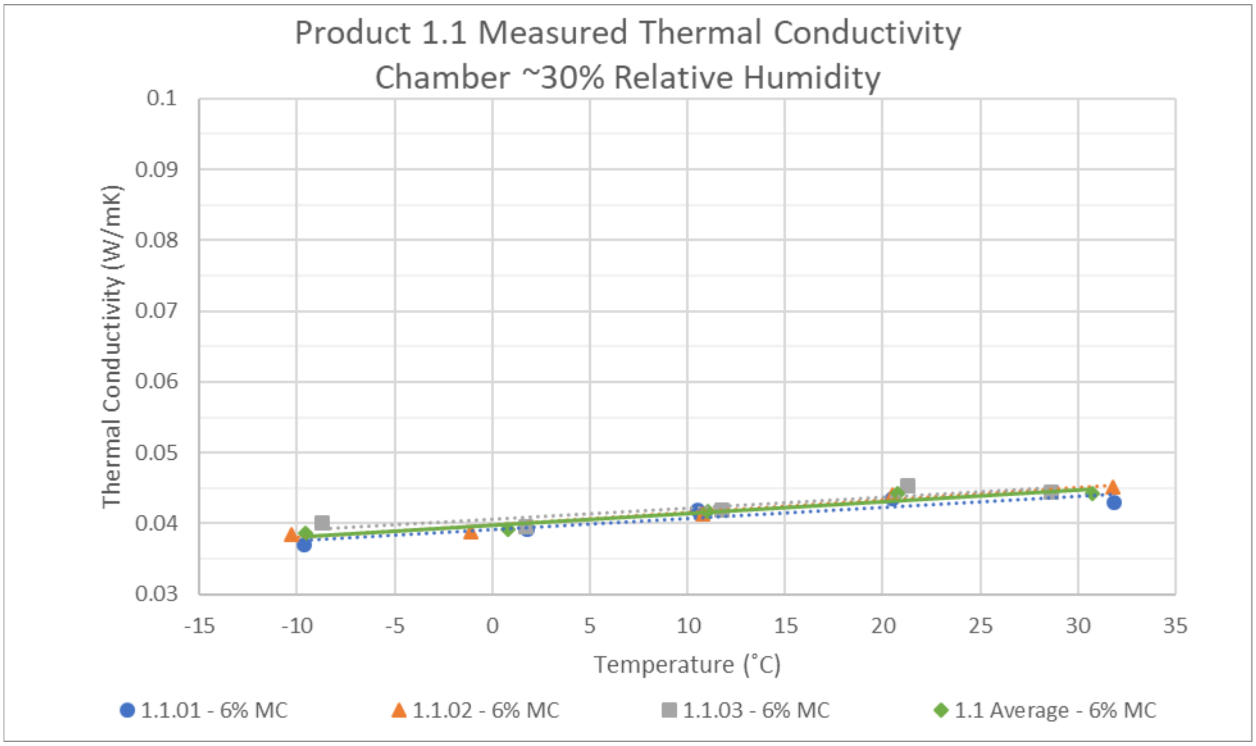


Figure H.1 – Thermal Conductivities for Product 1.1 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

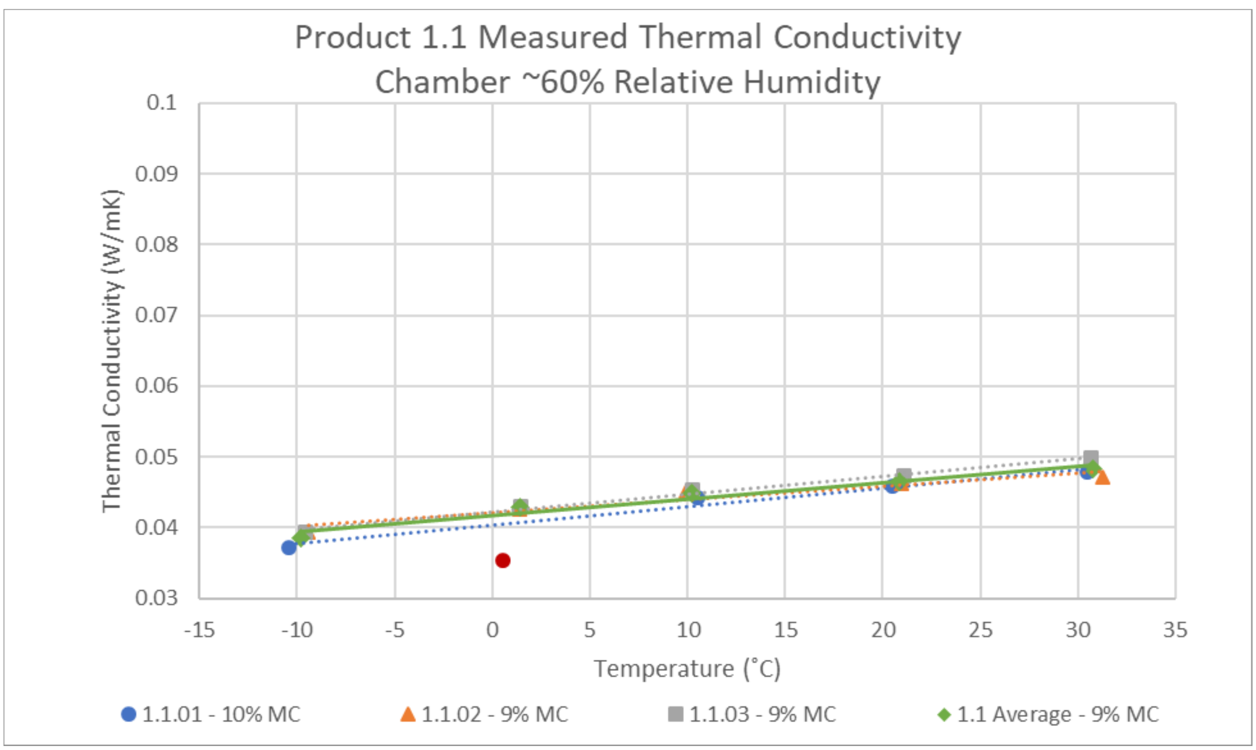


Figure H.2 – Thermal Conductivities for Product 1.1 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

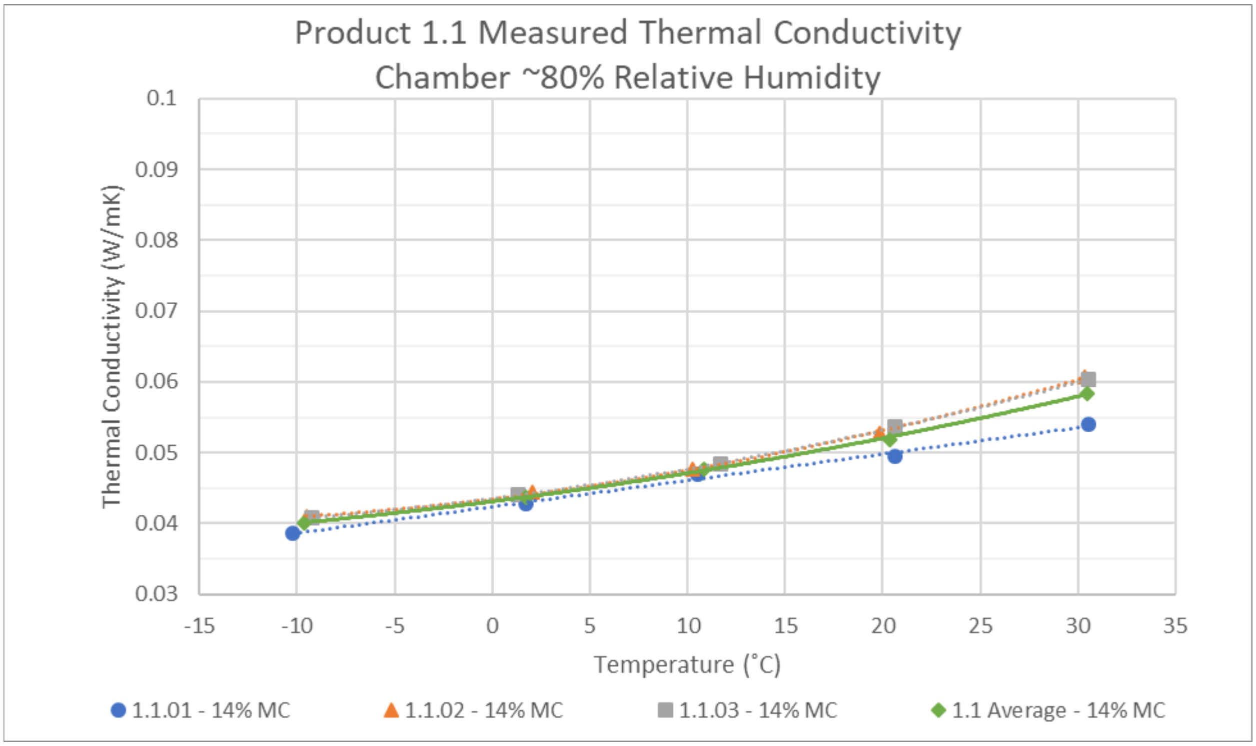


Figure H.3 – Thermal Conductivities for Product 1.1 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

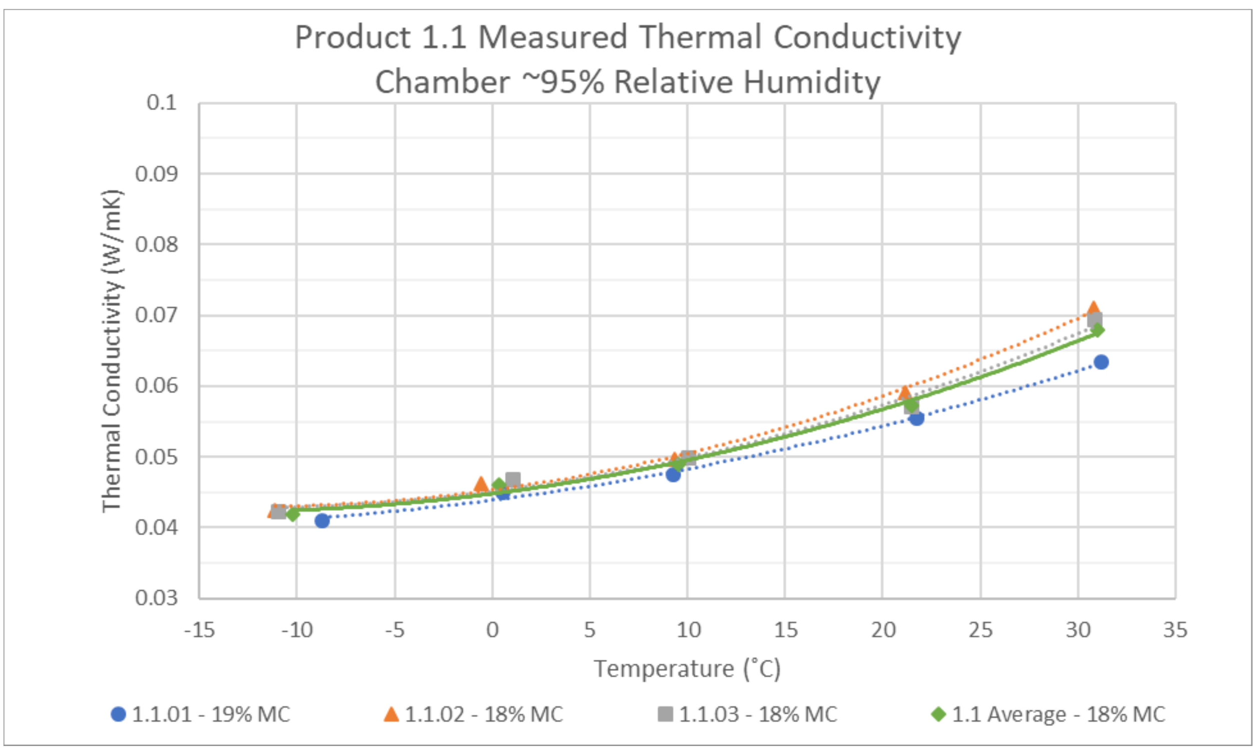


Figure H.4 – Thermal Conductivities for Product 1.1 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

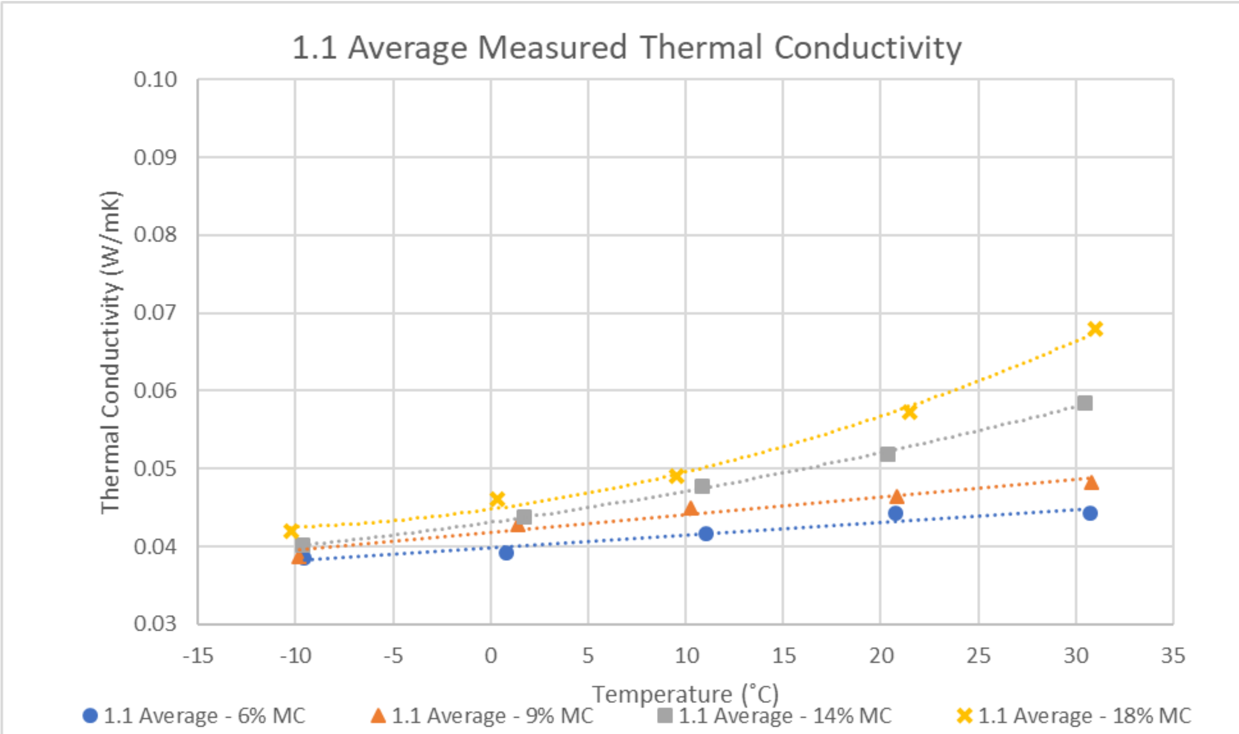


Figure H.5 – Thermal Conductivities for Product 1.1 over Full Temperature Range and Relative Humidity Range.

Table H.3 - Thermal Conductivities for Specimens 2.1.01, 2.1.02, 2.1.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
2.1.01 - 6% MC		2.1.02 - 6% MC		2.1.03 - 6% MC		2.1 Average – 6%MC		
-10.36	0.037174	-11.16	0.039353	-9.89	0.039274	-10.47	0.038600	0.001236, 3.2%
0.81	0.036576	-0.91	0.041334	1.6	0.041598	0.35	0.041466	0.000187, 0.45%
10.44	0.043431	11.39	0.04503	10.39	0.04378	10.74	0.044080	0.000841, 1.91%
20.65	0.046516	20.53	0.047454	18.85	0.045416	20.01	0.046462	0.00102, 2.2%
30.41	0.047335	28.75	0.047851	30.94	0.047699	30.03	0.047628	0.000265, 0.56%
2.1.01 - 9% MC		2.1.02 - 9% MC		2.1.03 - 9% MC		2.1 Average – 9%MC		
-8.68	0.039002	-7.99	0.037913	-8.3	0.039627	-8.32	0.038847	0.000867, 2.23%
0.61	0.041007	1.79	0.042494	1.21	0.042277	1.20	0.041926	0.000803, 1.92%
10.35	0.045427	10.49	0.045818	11.19	0.046885	10.68	0.046043	0.000755, 1.64%
20.53	0.047306	20.55	0.048184	20.66	0.048039	20.58	0.047843	0.000471, 0.98%
30.34	0.049088	30.47	0.049	30.57	0.050471	30.46	0.049520	0.000825, 1.67%
2.1.01 - 14% MC		2.1.02 - 14% MC		2.1.03 - 13% MC		2.1 Average – 13%MC		
-9.81	0.044275	-8.36	0.040975	-8.03	0.040049	-8.73	0.041766	0.002221, 5.32%
0.01	0.046625	1.1	0.044931	1.58	0.045073	0.90	0.045543	0.00094, 2.06%
11.75	0.048825	9.98	0.049348	10.34	0.048386	10.69	0.048853	0.000482, 0.99%
20.66	0.053504	20.66	0.052736	20.67	0.052082	20.66	0.052774	0.000712, 1.35%
30.55	0.058211	30.65	0.058156	30.7	0.056259	30.63	0.057542	0.001111, 1.93%
2.1.01 - 18% MC		2.1.02 - 17% MC		2.1.03 - 17% MC		2.1 Average – 17%MC		
-8.4	0.043087	-9.24	0.044315	-8.04	0.043763	-8.56	0.043722	0.000615, 1.41%
1.57	0.046227	1.88	0.046279	0.99	0.046138	1.48	0.046215	0.000071, 0.15%
10.19	0.04975	11.22	0.050588	11.57	0.049559	10.99	0.049966	0.000547, 1.1%
20.57	0.056615	20.59	0.056959	20.44	0.056686	20.53	0.056753	0.000182, 0.32%
30.45	0.064704	30.39	0.064988	30.51	0.06519	30.45	0.064961	0.000244, 0.38%

Table H.4 - Chamber Temperature and Relative Humidity Data for Specimens 2.1.01, 2.1.02, 2.1.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
2.1.01	24.01	0.73, 3.06%	30.90%	0.73%, 2.38%
2.1.02	24.05	0.77, 3.24%	31.01%	0.69%, 2.23%
2.1.03	24.05	0.75, 3.19%	31.01%	1.06%, 3.54%
2.1.01	29.18	2.26, 7.74%	58.40%	3.99%, 6.88%
2.1.02	28.66	2.31, 8.29%	59.12%	4.47%, 7.57%
2.1.03	28.82	2.73, 9.79%	58.70%	5.37%, 9.16%
2.1.01	24.44	1.16, 4.85%	81.16%	3.85, 4.69%
2.1.02	24.21	0.69, 2.9%	81.14%	3.28, 3.97%
2.1.03	24.19	0.59, 2.44%	80.14%	3.28, 4.05%
2.1.01	24.84	1.14, 4.67%	92.16	4.51, 4.85%
2.1.02	24.79	1.17, 4.81%	92.77	4.38, 4.66%
2.1.03	24.82	1.17, 4.79%	92.13	4.52, 4.86%

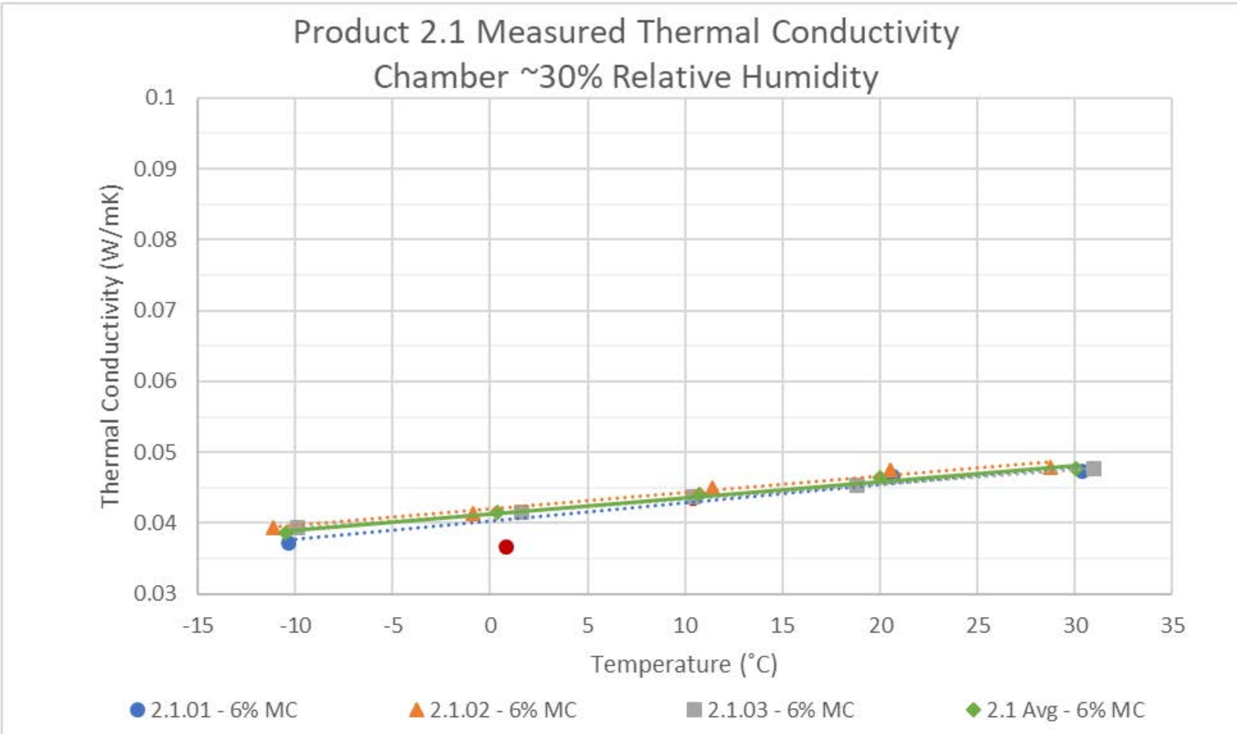


Figure H.6 – Thermal Conductivities for Product 2.1 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

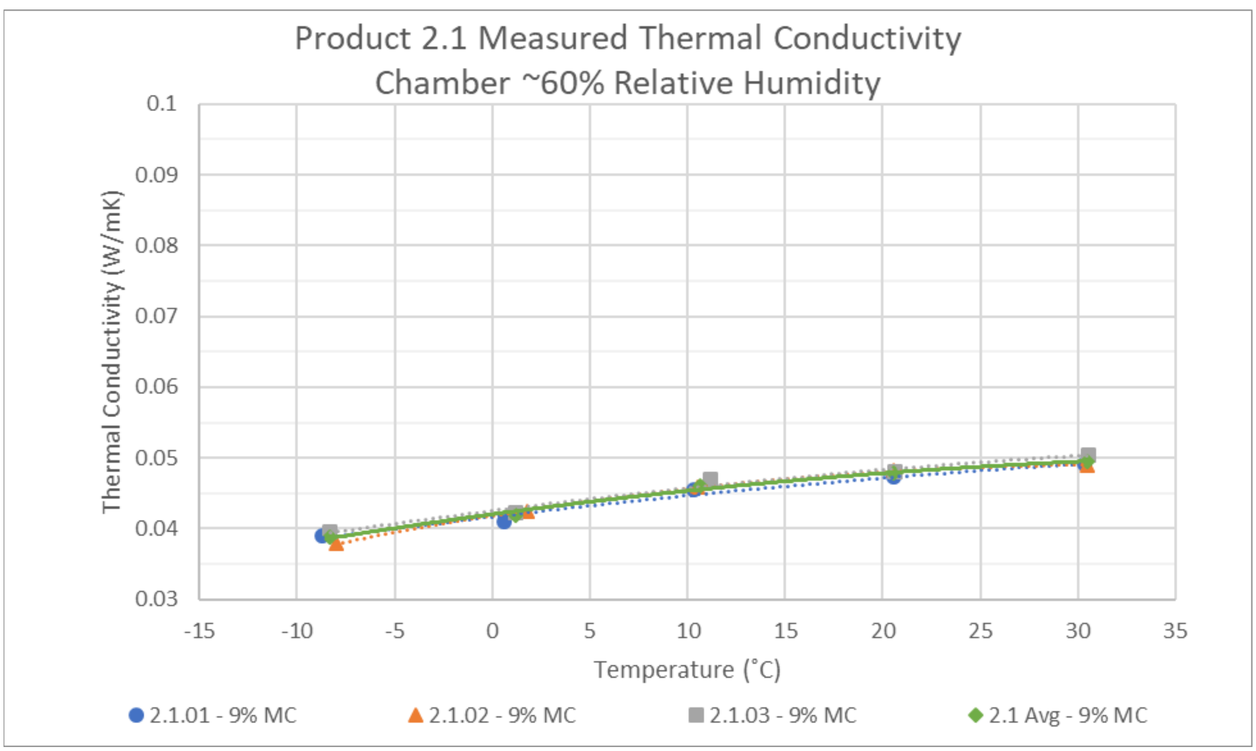


Figure H.7 – Thermal Conductivities for Product 2.1 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

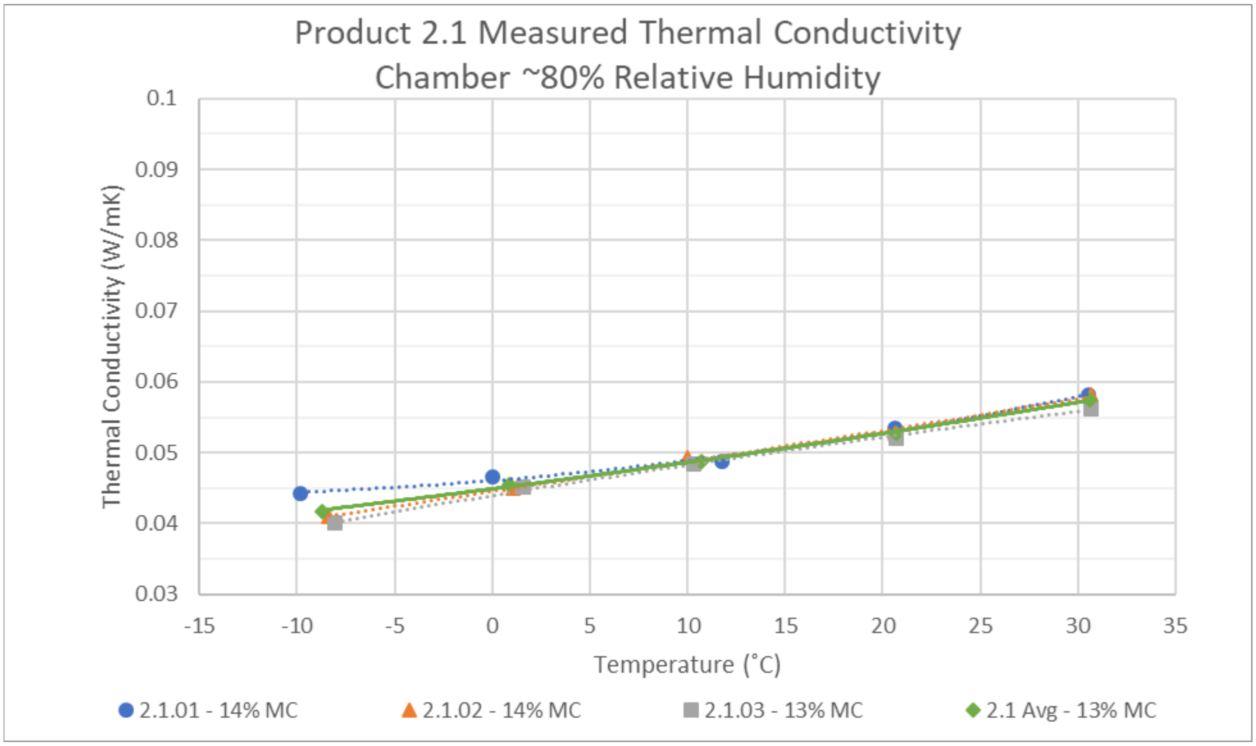


Figure H.8 – Thermal Conductivities for Product 2.1 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

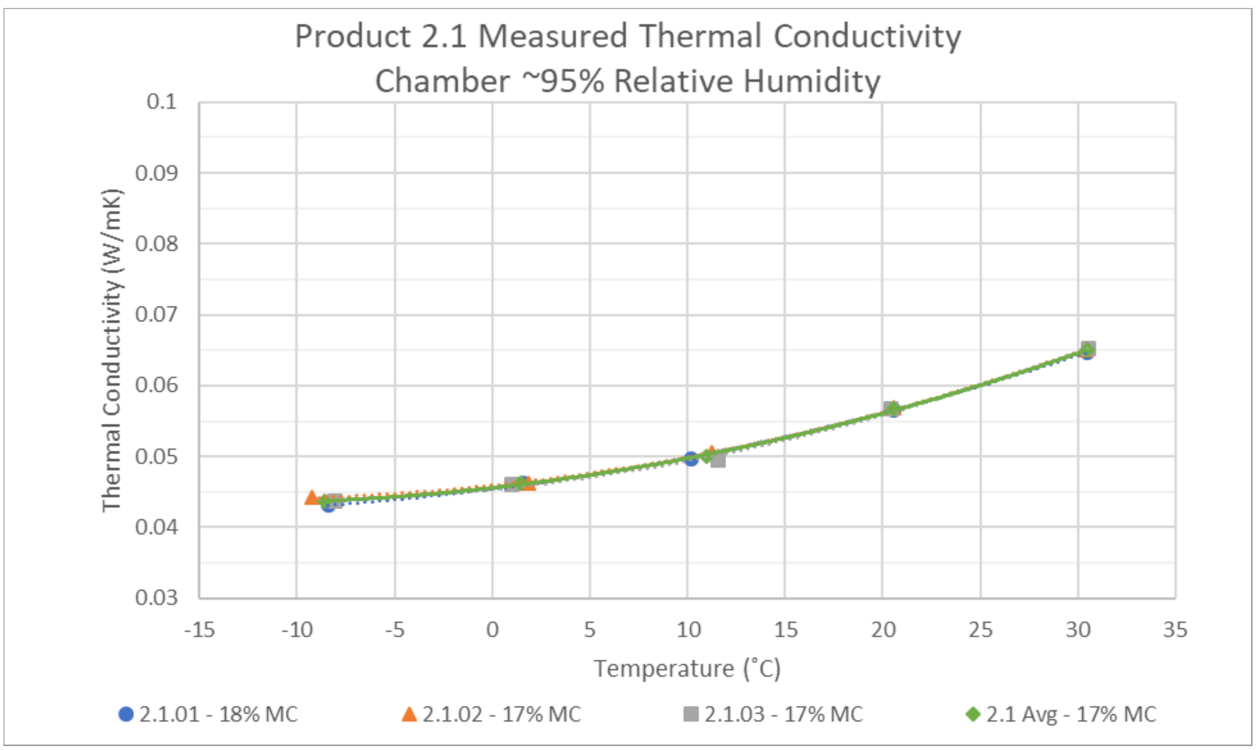


Figure H.9 – Thermal Conductivities for Product 2.1 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

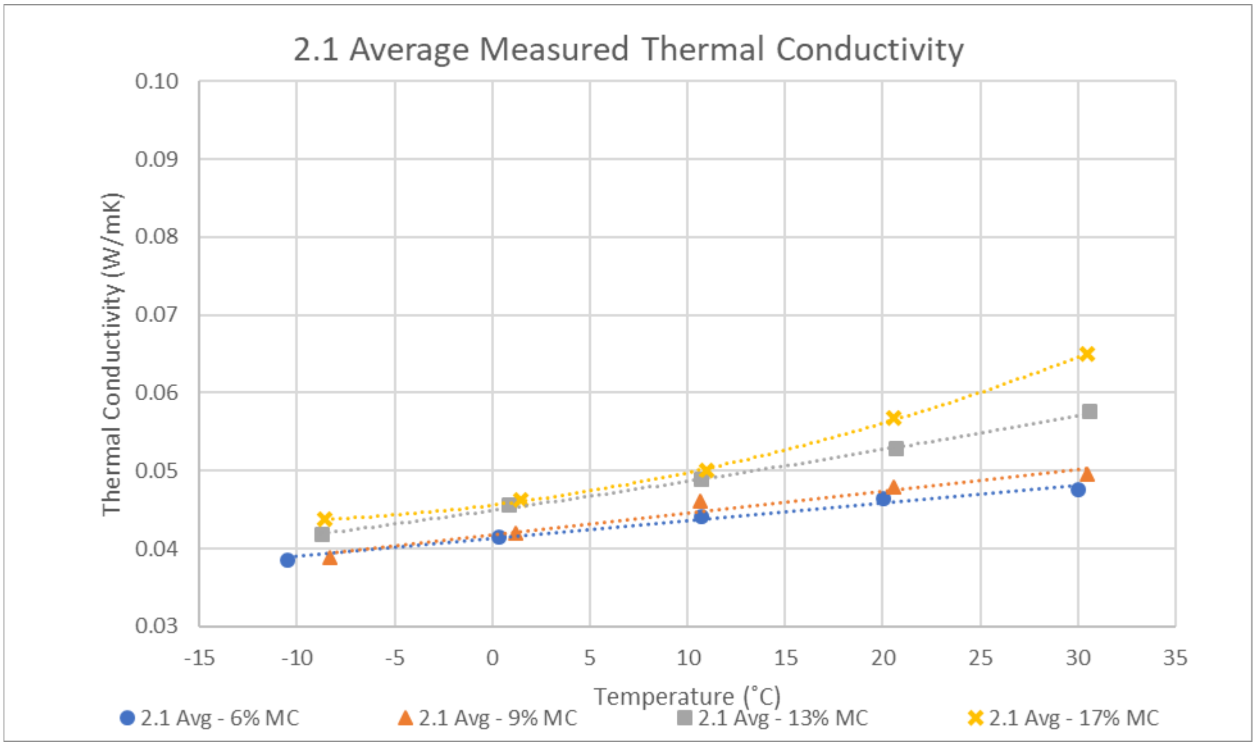


Figure H.10 – Thermal Conductivities for Product 2.1 over Full Temperature Range and Relative Humidity Range.

Table H.5 - Thermal Conductivities for Specimens 2.2.01, 2.2.02, 2.2.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
2.2.01 - 6% MC		2.2.02 - 6% MC		2.2.03 - 6% MC		2.2 Average – 6%MC		
-10.69	0.04302	-10.81	0.044741	-11.1	0.040327	-10.87	0.042696	0.002225, 5.21%
1.78	0.042218	1.28	0.042877	0.85	0.042914	1.30	0.042670	0.000392, 0.92%
10.52	0.044147	10.01	0.04439	11.07	0.045841	10.53	0.044793	0.000916, 2.04%
21.69	0.046856	21.18	0.048523	21.17	0.04844	21.35	0.047940	0.000939, 1.96%
30.43	0.051448	30.5	0.049497	31.02	0.052027	30.65	0.050991	0.001326, 2.6%
2.2.01 - 9% MC		2.2.02 - 9% MC		2.2.03 - 9% MC		2.2 Average – 9%MC		
-11.15	0.041536	-10.7	0.048484	-10	0.042433	-10.62	0.044151	0.003779, 8.56%
1.33	0.047547	0.94	0.042681	1.57	0.043077	1.28	0.044435	0.002702, 6.08%
11.45	0.049296	9.92	0.047931	10.27	0.045219	10.55	0.047482	0.002075, 4.37%
22.05	0.056015	21.28	0.049213	20.54	0.049541	21.29	0.051590	0.003836, 7.44%
31.03	0.061417	30.83	0.052747	30.53	0.054252	30.80	0.056139	0.004633, 8.25%
2.2.01 - 14% MC		2.2.02 - 14% MC		2.2.03 - 13% MC		2.2 Average – 13%MC		
-10.9	0.043967	-9.23	0.049794	-8.53	0.046532	-9.55	0.046764	0.00292, 6.25%
1.87	0.049992	1.36	0.046845	0.29	0.044918	1.17	0.047252	0.002561, 5.42%
9.56	0.054445	10.45	0.051468	11.43	0.049325	10.48	0.051746	0.002571, 4.97%
22.03	0.062442	21.77	0.055005	21.82	0.053676	21.87	0.057041	0.004724, 8.28%
31.61	0.07092	30.56	0.06085	30.42	0.060416	30.86	0.064062	0.005943, 9.28%
2.2.01 - 18% MC		2.2.02 - 17% MC		2.2.03 - 17% MC		2.2 Average – 17%MC		
-11.21	0.046311	-8.95	0.048398	-11.5	0.04765	-10.55	0.047453	0.001057, 2.23%
1.79	0.048778	1.66	0.04933	0.41	0.047059	1.29	0.048389	0.001184, 2.45%
10.37	0.055108	10.27	0.053372	9.1	0.045837	10.32	0.054240	0.001228, 2.26%
21.53	0.063975	19.18	0.066702	20.68	0.056722	20.46	0.062466	0.005158, 8.26%
30.55	0.075286	31.61	0.068819	29.9	0.062643	30.69	0.068916	0.006322, 9.17%

Table H.6 - Chamber Temperature and Relative Humidity Data for Specimens 2.2.01, 2.2.02, 2.2.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
2.2.01	24.08	0.34, 1.47%	30.77%	1.14%, 3.84%
2.2.02	24.08	0.31, 1.31%	30.80%	1.03%, 3.48
2.2.03	23.97	0.42, 1.77%	30.43%	1.19%, 3.93%
2.2.01	27.13	3.42, 13.47%	59.42%	3.76%, 6.47%
2.2.02	26.41	0.44, 1.67%	69.66%	5.47%, 7.88%
2.2.03	29.08	2.39, 8.16%	59.18%	5.01%, 8.57%
2.2.01	23.72	0.66, 2.8%	83.21%	1.18%, 1.41%
2.2.02	23.75	0.62, 2.65%	82.68%	2.21%, 2.65%
2.2.03	23.87	0.69, 2.89%	81.80%	2.96%, 3.55%
2.2.01	24.71	1.15, 4.73%	92.21	4.71%, 5.11%
2.2.02	24.73	1.1, 4.49%	92.69	3.26%, 3.54%
2.2.03	24.07	0.63, 2.64%	93.84	2.92%, 3.11%

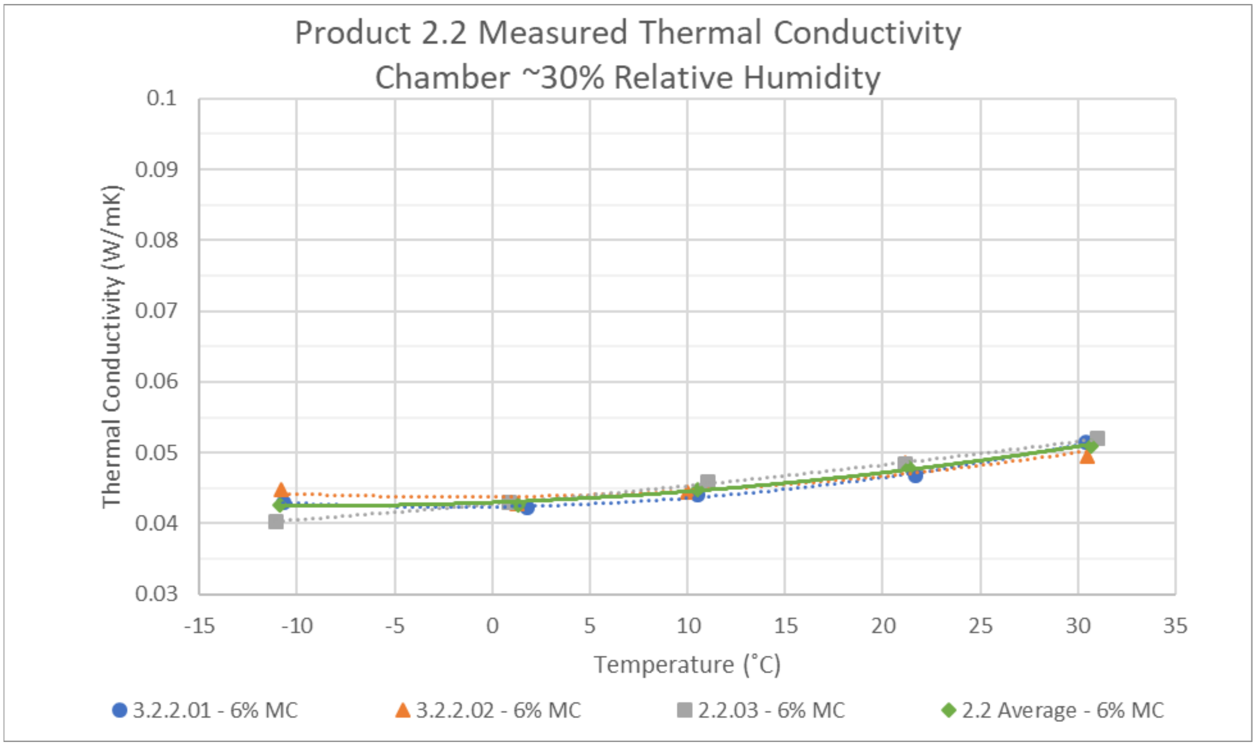


Figure H.11 – Thermal Conductivities for Product 2.2 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

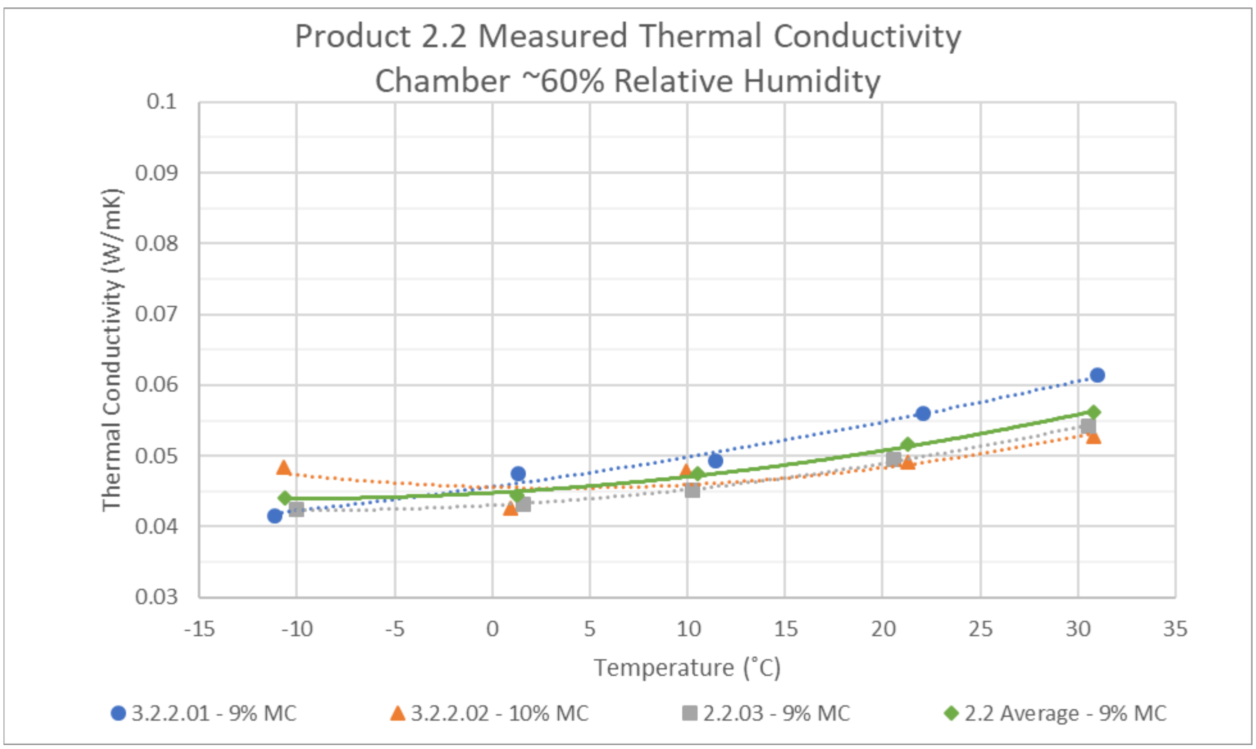


Figure H.12 – Thermal Conductivities for Product 2.2 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

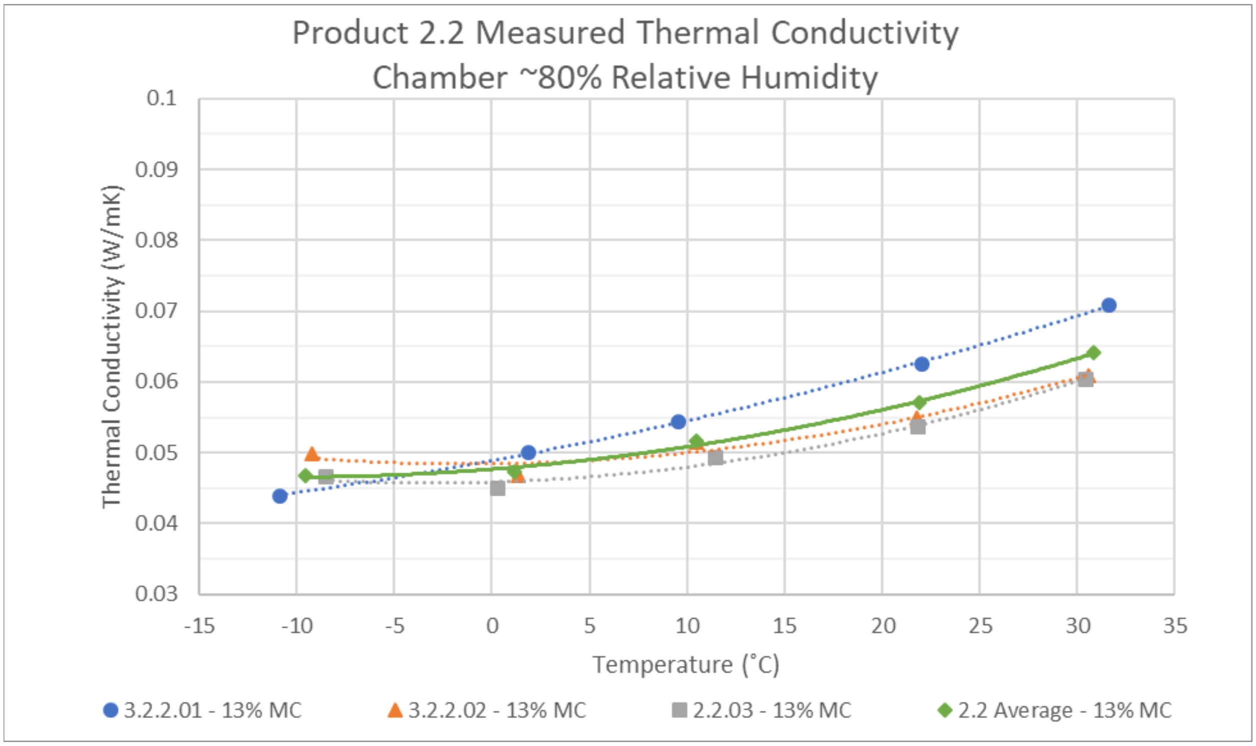


Figure H.13 – Thermal Conductivities for Product 2.2 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

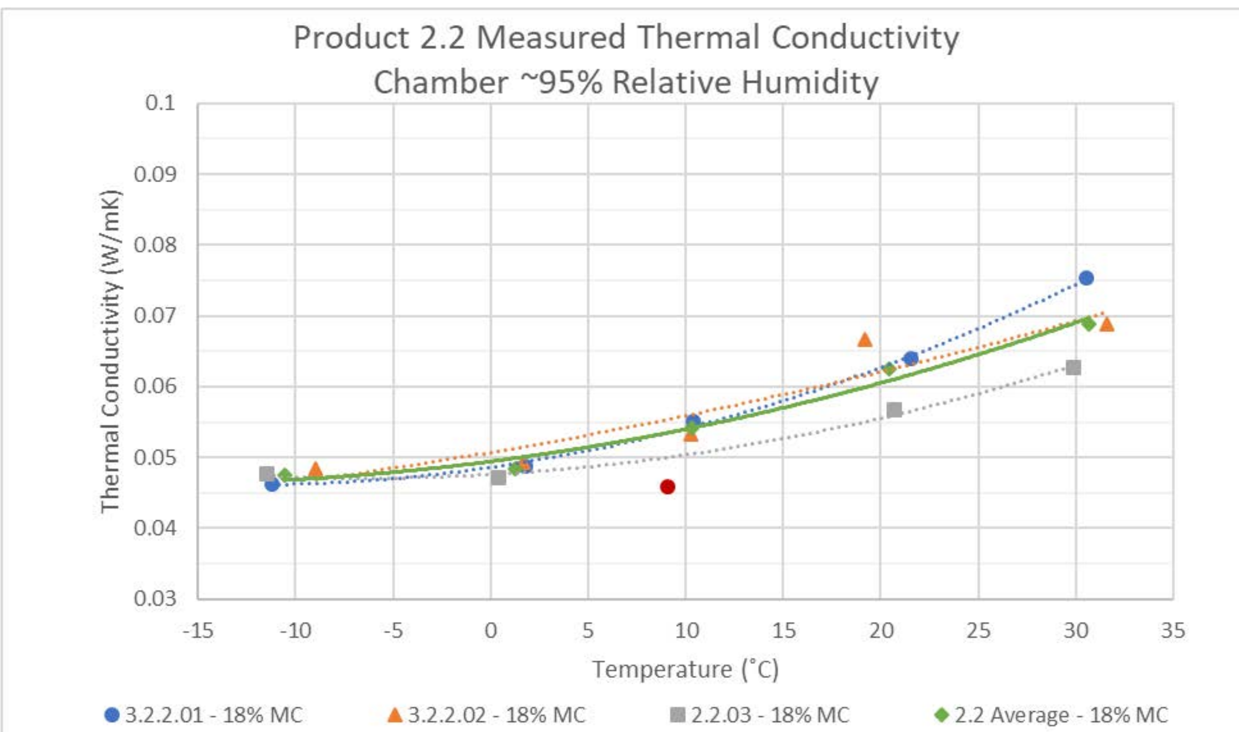


Figure H.14 – Thermal Conductivities for Product 2.2 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

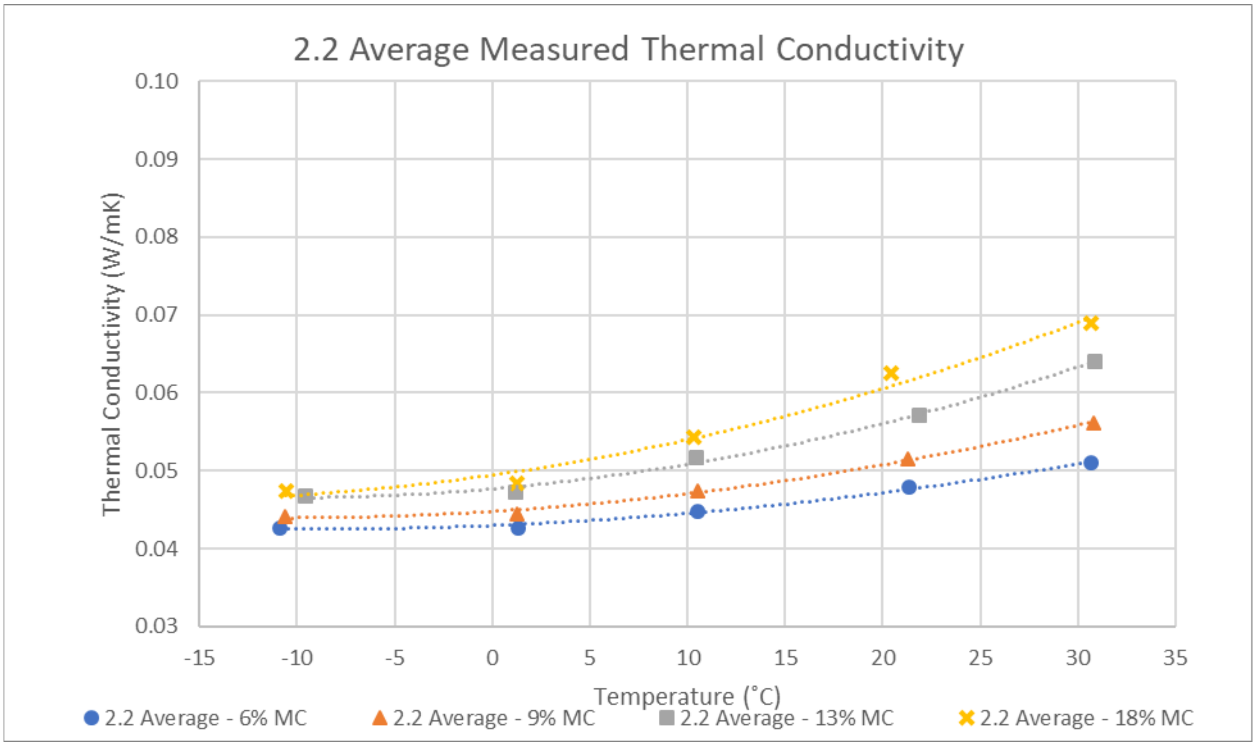


Figure H.15 – Thermal Conductivities for Product 2.2 over Full Temperature Range and Relative Humidity Range.

Table H.7 - Thermal Conductivities for Specimens 3.1.01, 3.1.02, 3.1.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
3.1.01 - 5% MC		3.1.02 - 5% MC		3.1.03 - 5% MC		3.1 Average – 5%MC		
-10.28	0.035183	-10.22	0.034755	-10.22	0.035139	-10.24	0.035026	0.000235, 0.67%
1.18	0.037077	0.68	0.037647	1.56	0.037427	1.14	0.037384	0.000287, 0.77%
9.97	0.038181	11	0.03851	10.15	0.038711	10.37	0.038467	0.000268, 0.7%
21.01	0.040615	21.25	0.039988	21.01	0.040689	21.09	0.040431	0.000385, 0.95%
31.32	0.041772	30.11	0.040389	31.38	0.041901	30.94	0.041354	0.000838, 2.03%
3.1.01 - 10% MC		3.1.02 - 10% MC		3.1.03 - 9% MC		3.1 Average – 10%MC		
-11.61	0.039293	-9.9	0.036124	-8.98	0.037677	-10.16	0.037698	0.001585, 4.2%
1.9	0.039258	1.63	0.038249	0.89	0.03943	1.47	0.038979	0.000638, 1.64%
11.78	0.040737	11.35	0.04078	10.88	0.040119	11.34	0.040545	0.00037, 0.91%
21.55	0.04284	20.75	0.043639	20.47	0.042346	20.92	0.042942	0.000652, 1.52%
30.18	0.044505	30.65	0.04525	30.54	0.044164	30.46	0.044640	0.000555, 1.24%
3.1.01 - 12% MC		3.1.02 - 12% MC		3.1.03 - 12% MC		3.1 Average – 13%MC		
-8.87	0.03667	-10.09	0.036199	-8.71	0.038275	-9.22	0.037048	0.001088, 2.94%
1.94	0.03882	-0.69	0.041893	1.87	0.039882	1.04	0.040198	0.001561, 3.88%
10.77	0.043478	11.25	0.042393	11.95	0.040141	11.01	0.042936	0.001702, 3.96%
21.26	0.046656	20.48	0.044797	19.02	0.046664	20.25	0.046039	0.001076, 2.34%
30.55	0.053269	30.47	0.050933	30.56	0.051797	30.53	0.052000	0.001181, 2.27%
3.1.01 - 17% MC		3.1.02 - 17% MC		3.1.03 - 18% MC		3.1 Average – 17%MC		
-9.16	0.040523	-10.73	0.03998	-10.78	0.04105	-10.22	0.040518	0.000535, 1.32%
1.32	0.044177	0.67	0.04074	0.08	0.043383	0.69	0.042767	0.001799, 4.21%
9.75	0.04589	10.34	0.047941	9.57	0.050803	9.89	0.048211	0.002468, 5.12%
20.68	0.056167	21.06	0.057993	20.54	0.058889	20.76	0.057683	0.001387, 2.4%
30.65	0.06647	30.36	0.066042	31.83	0.065969	30.95	0.066160	0.000271, 0.41%

Table H.8 - Chamber Temperature and Relative Humidity Data for Specimens 3.1.01, 3.1.02, 3.1.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
3.1.01	23.34	0.45, 1.97%	25.42%	1.15%, 4.54%
3.1.02	23.37	0.43, 1.87%	25.77%	1.22%, 4.76%
3.1.03	23.34	0.41, 1.76%	26.15%	1.18%, 4.52%
3.1.01	26.72	0.57, 2.15%	68.46%	3.14%, 4.57%
3.1.02	26.96	0.54, 1.99%	67.84%	3.73%, 5.46%
3.1.03	27.32	0.44, 1.62%	63.86%	5.68%, 8.57%
3.1.01	24.30	0.7, 2.9%	80.66%	2.69%, 3.33%
3.1.02	24.75	1.16, 4.77%	80.03%	3.41%, 4.25%
3.1.03	25.26	1.44, 5.7%	80.11%	3.46%, 4.25%
3.1.01	24.14	0.85, 3.54%	94.39%	2.82%, 2.97%
3.1.02	24.16	0.85, 3.52%	95.07%	2.92%, 3.04%
3.1.03	23.85	0.56, 2.34%	96.15%	1.98%, 2.06%

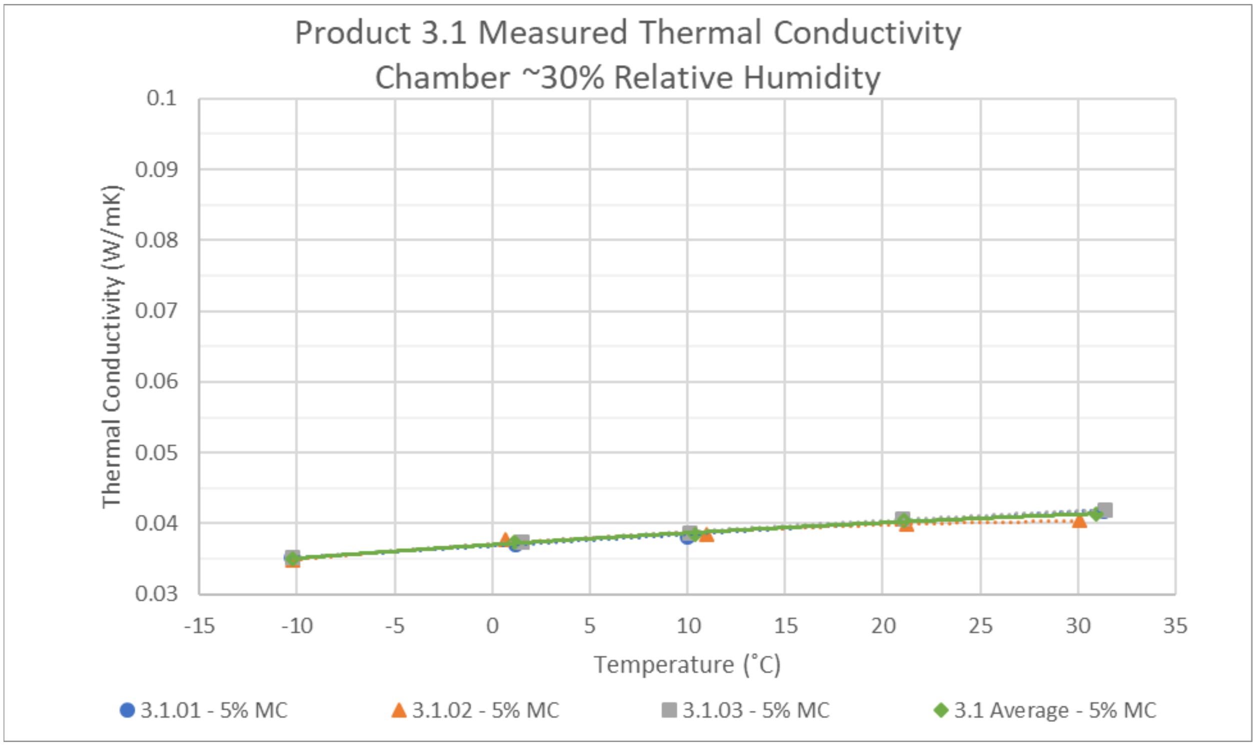


Figure H.16 – Thermal Conductivities for Product 3.1 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

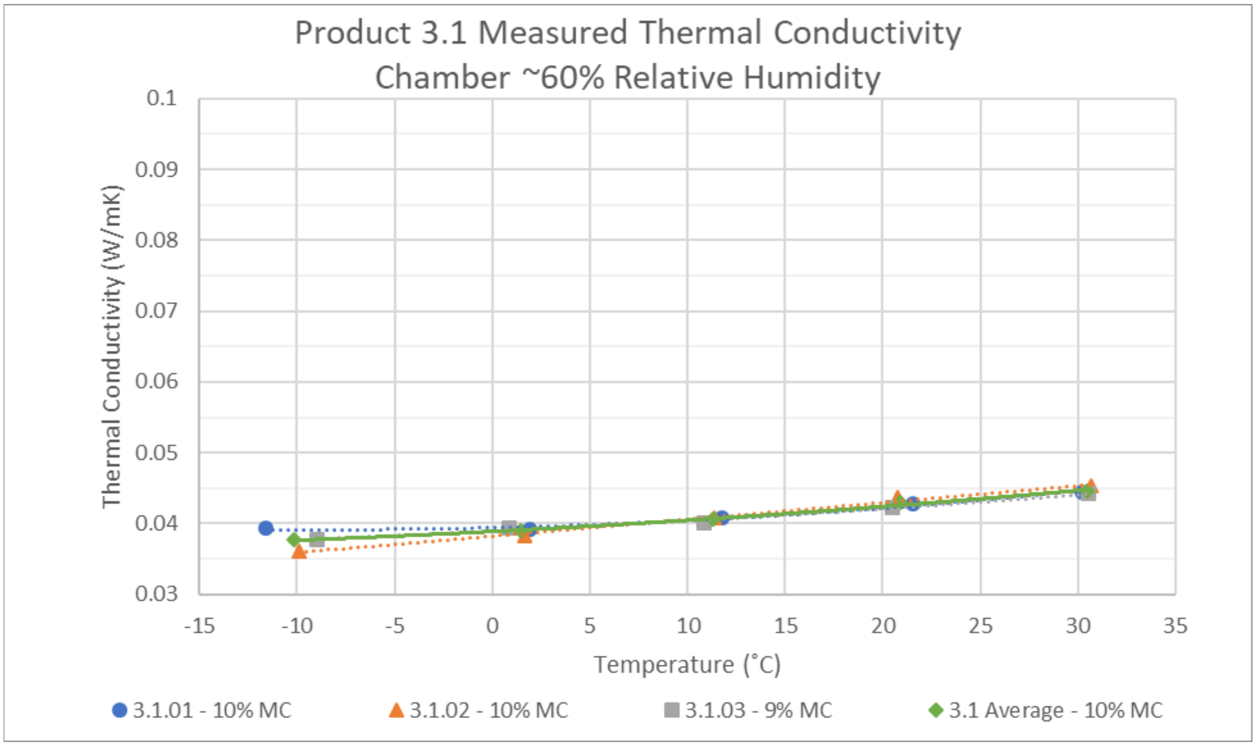


Figure H.17 – Thermal Conductivities for Product 3.1 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

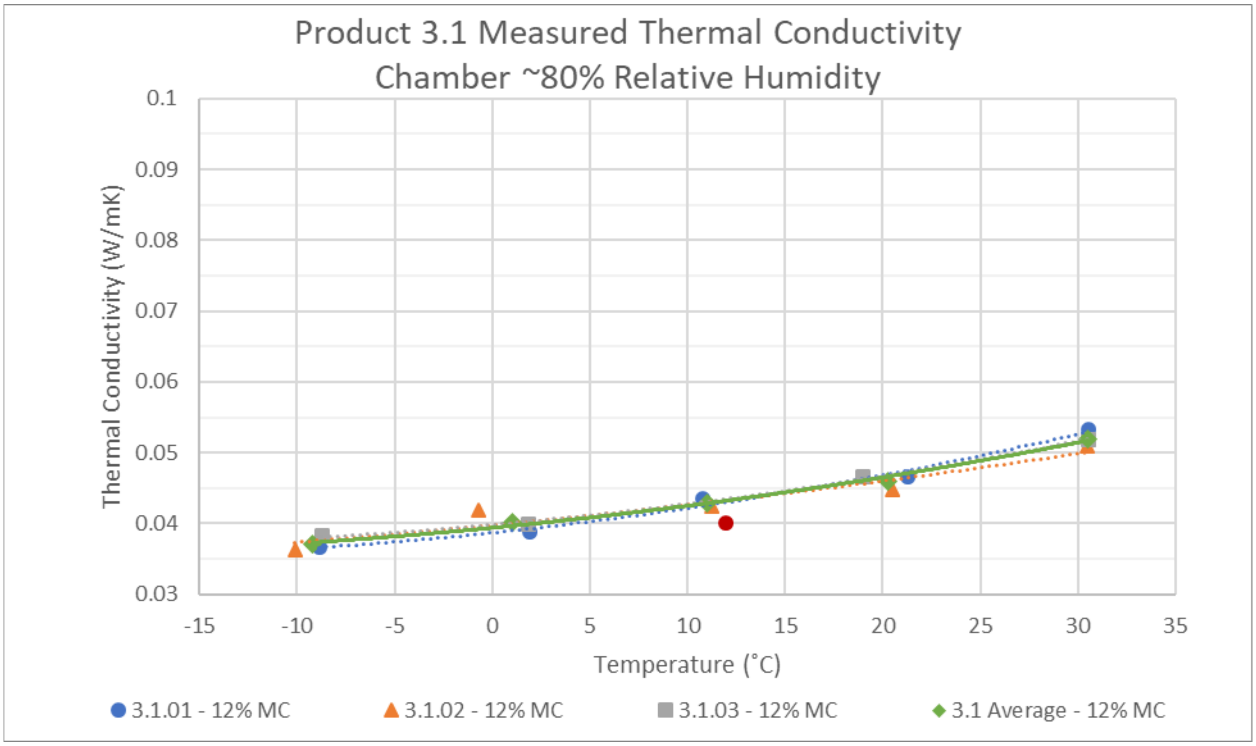


Figure H.18 – Thermal Conductivities for Product 3.1 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

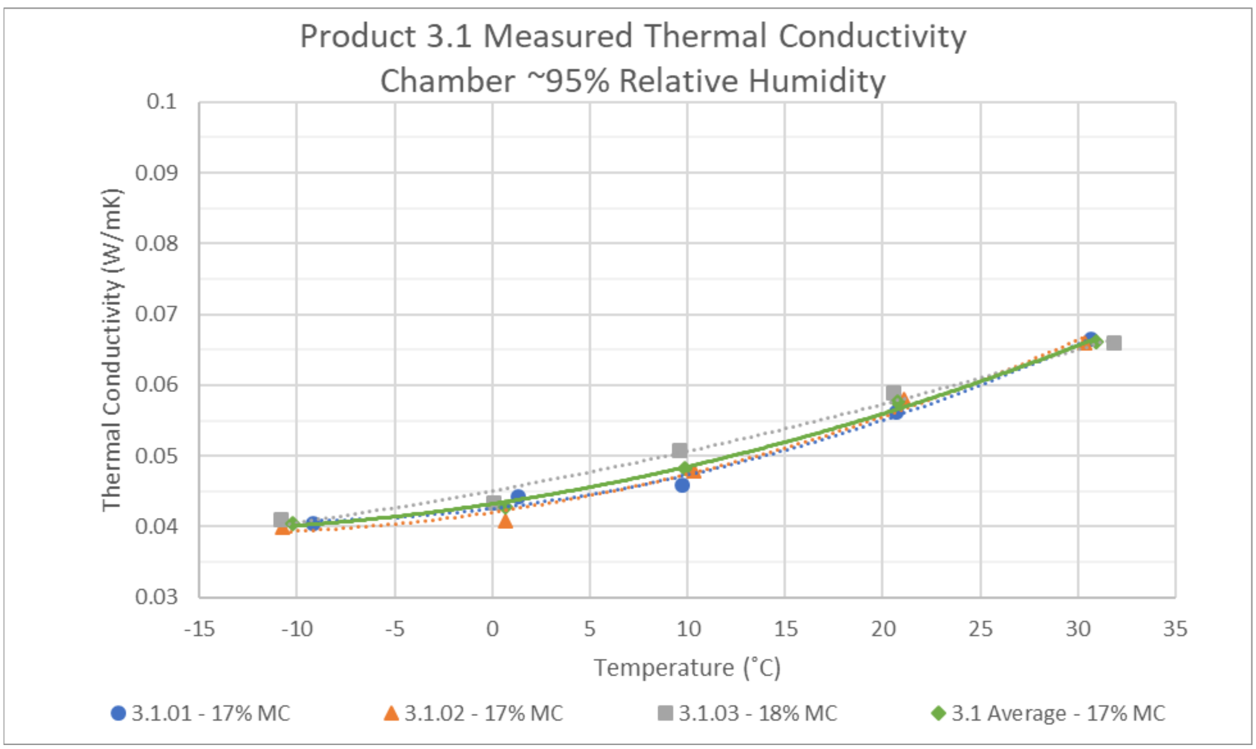


Figure H.19 – Thermal Conductivities for Product 3.1 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

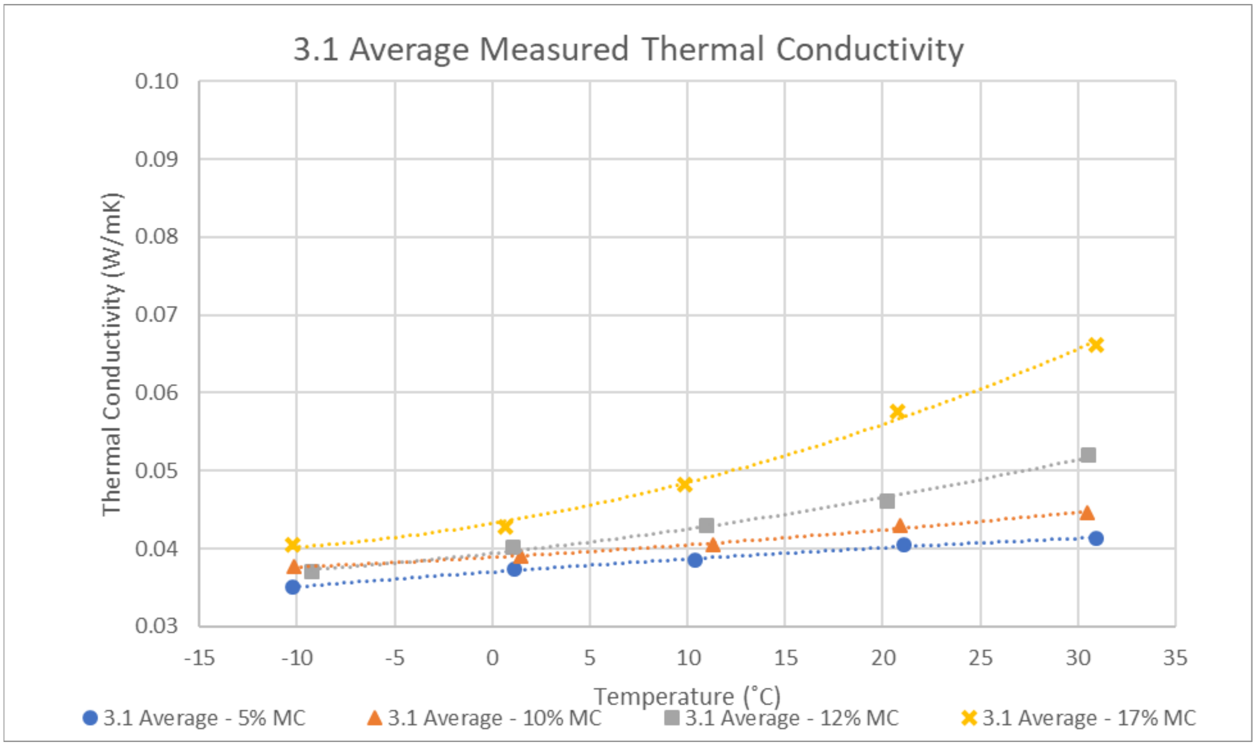


Figure H.20 – Thermal Conductivities for Product 3.1 over Full Temperature Range and Relative Humidity Range.

Table H.9 - Thermal Conductivities for Specimens 4.1.01, 4.1.02, 4.1.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
4.1.01 - 6% MC		4.1.02 - 6% MC		4.1.03 - 6% MC		4.1 Average – 6%MC		
-10.79	0.041898	-9.28	0.040521	-10.76	0.042049	-10.28	0.041489	0.000842, 2.03%
1.37	0.040066	1.48	0.04474	0.77	0.045469	1.21	0.043425	0.002932, 6.75%
10.95	0.047924	11.1	0.047319	11.42	0.044829	11.16	0.046691	0.00164, 3.51%
21.95	0.049854	20.53	0.049355	20.35	0.046439	20.94	0.048549	0.001845, 3.8%
30.47	0.052273	30.52	0.050975	30.98	0.052267	30.66	0.051838	0.000748, 1.44%
4.1.01 - 9% MC		4.1.02 - 9% MC		4.1.03 - 9% MC		4.1 Average – 9%MC		
-8.15	0.04267	-10.45	0.044359	-8.2	0.043292	-8.93	0.043440	0.000854, 1.97%
0.97	0.047926	0.87	0.045866	0.92	0.04817	0.92	0.047321	0.001266, 2.67%
11.65	0.051103	9.93	0.051361	11.8	0.048301	11.13	0.050255	0.001697, 3.38%
20.44	0.053632	20.05	0.055181	20.52	0.051388	20.34	0.053400	0.001907, 3.57%
30.65	0.057498	30.38	0.058039	31.04	0.057268	30.69	0.057602	0.000396, 0.69%
4.1.01 - 12% MC		4.1.02 - 13% MC		4.1.03 - 13% MC		4.1 Average – 13%MC		
-9.66	0.044085	-8.25	0.045299	-10.52	0.045502	-9.48	0.044962	0.000766, 1.7%
1.61	0.049668	0.75	0.049609	-0.31	0.049932	0.68	0.049736	0.000172, 0.35%
10.52	0.054021	11.62	0.049284	9.81	0.053643	10.17	0.053832	0.000267, 0.5%
20.76	0.058345	20.34	0.05122	20.28	0.057498	20.52	0.057922	0.000599, 1.03%
30.85	0.063428	29.87	0.063548	29.83	0.064926	30.18	0.063967	0.000832, 1.3%
4.1.01 - 17% MC		4.1.02 - 17% MC		4.1.03 - 17% MC		4.1 Average – 17%MC		
-10.73	0.047269	-11.03	0.04718	-10.71	0.04719	-10.82	0.047213	0.000049, 0.1%
0.4	0.051997	-0.22	0.048114	0.32	0.051944	0.17	0.050685	0.002227, 4.39%
10.56	0.054828	11.07	0.057294	10.46	0.055463	10.70	0.055862	0.00128, 2.29%
21.79	0.06279	21.12	0.064001	21.43	0.062962	21.45	0.063251	0.000655, 1.04%
31.49	0.072441	31.78	0.07485	31.54	0.074042	31.60	0.073778	0.001226, 1.66%

Table H.10 - Chamber Temperature and Relative Humidity Data for Specimens 4.1.01, 4.1.02, 4.1.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
4.1.01	23.03	0.3, 1.32%	27.38%	1.02%, 3.75%
4.1.02	23.04	0.32, 1.39%	28.40%	0.99%, 3.51%
4.1.03	23.09	0.34, 1.5%	29.51%	1.76%, 6.04%
4.1.01	26.82	0.14, 0.53%	58.39%	0.41%, 0.7%
4.1.02	27.12	0.48, 1.8%	66.30%	4.74%, 6.97%
4.1.03	26.81	0.26, 0.98%	58.46%	5%, 8.52%
4.1.01	27.98	0.79, 2.85%	81.64%	2.48%, 3.02%
4.1.02	28.10	0.82, 2.96%	82.21%	2.88%, 3.51%
4.1.03	28.10	0.84, 3.04%	83.52%	3.5%, 4.14%
4.1.01	23.85	0.52, 2.19%	95.84	1.81%, 1.89%
4.1.02	23.87	0.51, 2.13%	95.20	1.96%, 2.06%
4.1.03	23.97	0.61, 2.55%	95.43	2.31%, 2.41%

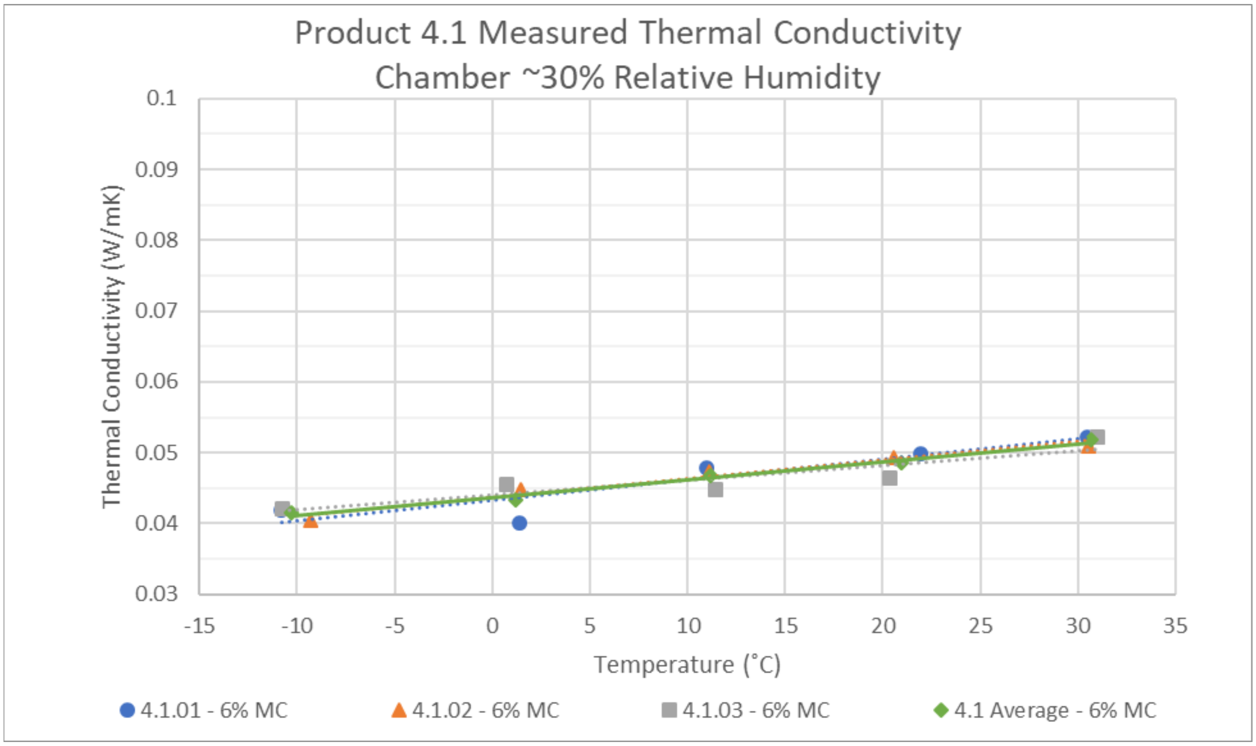


Figure H.21 – Thermal Conductivities for Product 4.1 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

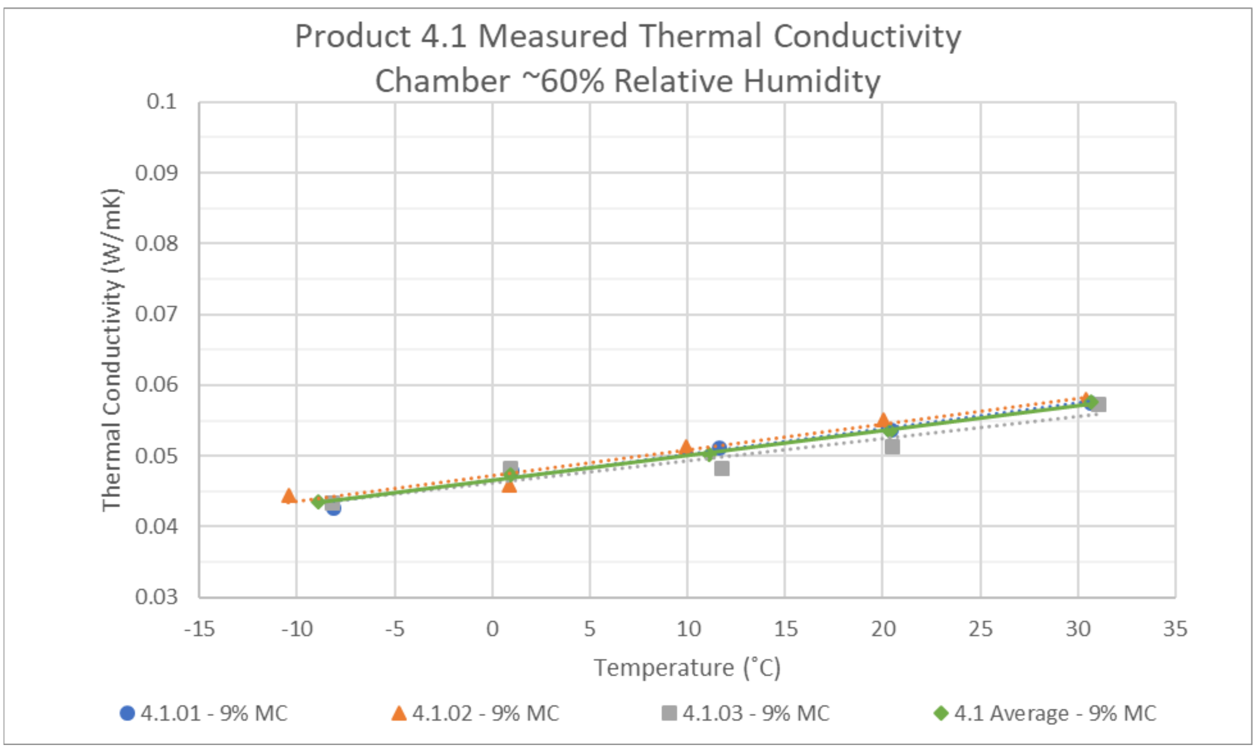


Figure H.22 – Thermal Conductivities for Product 4.1 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

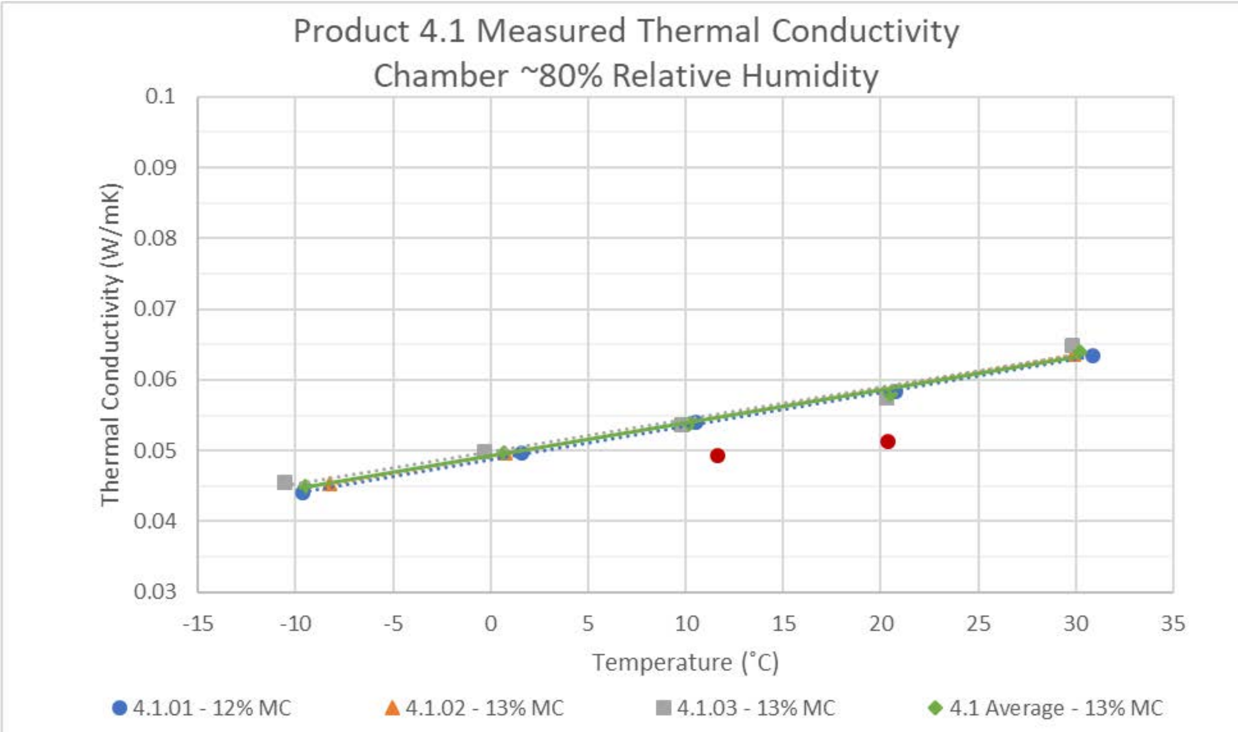


Figure H.23 – Thermal Conductivities for Product 4.1 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

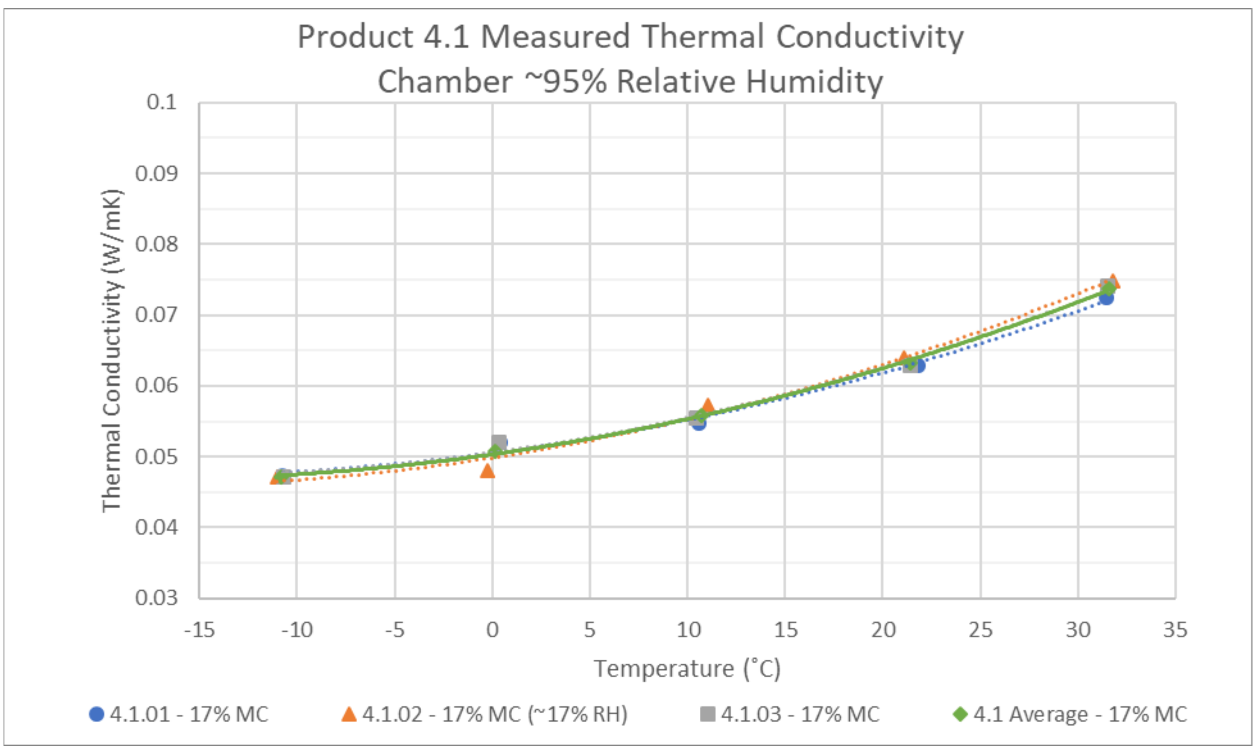


Figure H.24 – Thermal Conductivities for Product 4.1 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

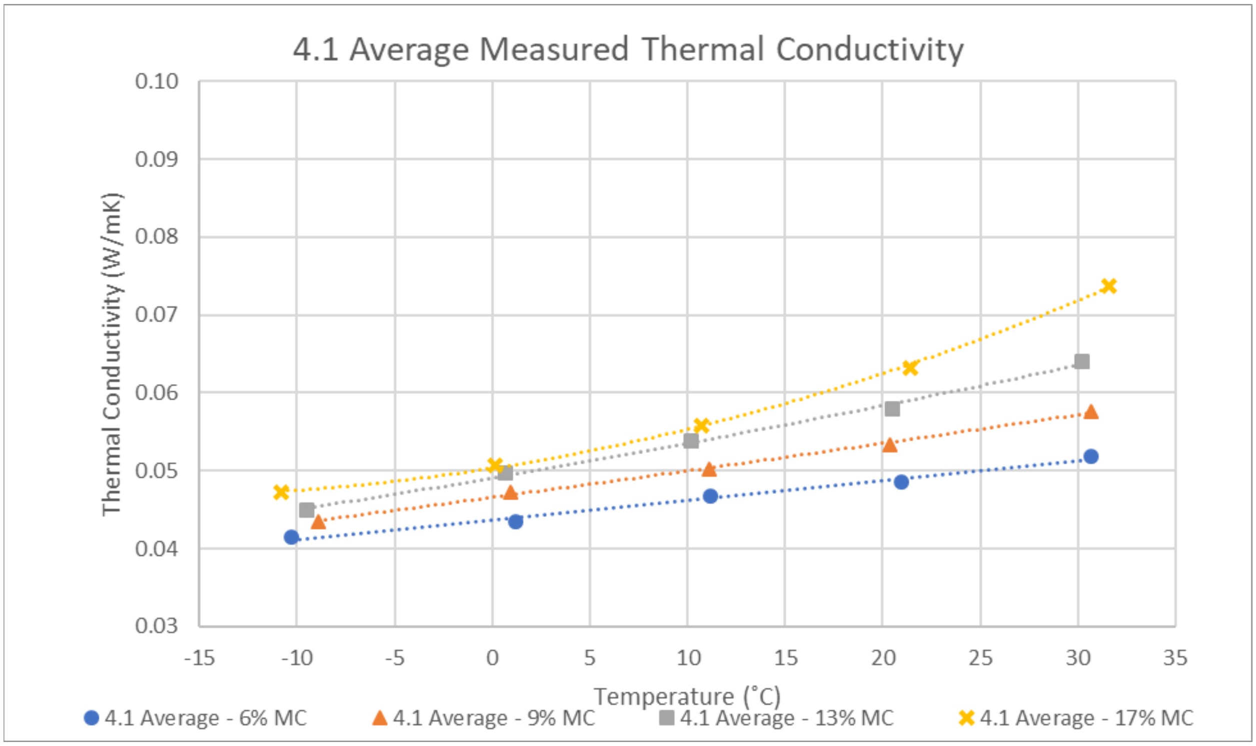


Figure H.25 – Thermal Conductivities for Product 4.1 over Full Temperature Range and Relative Humidity Range.

Table H.11 - Thermal Conductivities for Specimens 4.2.01, 4.2.02, 4.2.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
4.2.01 - 6% MC		4.2.02 - 6% MC		4.2.03 - 6% MC		4.2 Average – 6%MC		
-10.33	0.042621	-10.97	0.041731	-11.65	0.04831	-10.98	0.044221	0.003569, 8.07%
1.82	0.042624	1.63	0.043595	-0.82	0.043257	0.88	0.043159	0.000493, 1.14%
10.41	0.044984	9.39	0.045185	10.86	0.044351	10.22	0.044840	0.000435, 0.97%
19.75	0.045989	21.8	0.049746	19.87	0.04503	20.47	0.046922	0.002493, 5.31%
31.92	0.049828	30.95	0.053143	31.32	0.053019	31.40	0.051997	0.001879, 3.61%
4.2.01 - 9% MC		4.2.02 - 9% MC		4.2.03 - 9% MC		4.2 Average – 9%MC		
-10.62	0.045405	-11.24	0.043327	-11.51	0.052942	-10.93	0.044366	0.001469, 3.31%
1.73	0.043691	1.71	0.042651	0.78	0.045634	1.41	0.043992	0.001514, 3.44%
10.61	0.04849	11.69	0.046065	11.5	0.046201	11.27	0.046919	0.001363, 2.9%
20.59	0.051459	21.89	0.054051	20.74	0.055109	21.07	0.053540	0.001878, 3.51%
30.62	0.054958	30.47	0.058486	31.19	0.057534	30.76	0.056993	0.001825, 3.2%
4.2.01 - 12% MC		4.2.02 - 13% MC		4.2.03 - 13% MC		4.2 Average – 13%MC		
-8.97	0.049258	-11	0.045222	-11.14	0.047741	-10.37	0.047407	0.002039, 4.3%
-0.38	0.046434	1.4	0.048291	1.27	0.0489	0.76	0.047875	0.001285, 2.68%
11.39	0.050197	11.2	0.052439	11.9	0.049928	11.65	0.050063	0.001379, 2.75%
20.54	0.056923	20.44	0.056798	20.42	0.051251	20.48	0.054087	0.003239, 5.99%
30.53	0.063849	31.55	0.070308	31.69	0.064542	31.26	0.066233	0.003546, 5.35%
4.2.01 - 17% MC		4.2.02 - 17% MC		4.2.03 - 17% MC		4.2 Average – 17%MC		
-11.29	0.04779	-11.59	0.047327	-11.44	0.049593	-11.44	0.048237	0.001197, 2.48%
0.42	0.049436	-0.07	0.047808	0.09	0.048287	0.15	0.048510	0.000837, 1.72%
8.98	0.050675	10.23	0.053789	10.59	0.054656	9.93	0.053040	0.002094, 3.95%
20.66	0.053791	21.66	0.061795	20.68	0.066873	21.00	0.060820	0.006595, 10.84%
30.2	0.06836	31.26	0.072274	31.09	0.076522	30.85	0.072385	0.004082, 5.64%

Table H.12 - Chamber Temperature and Relative Humidity Data for Specimens 4.2.01, 4.2.02, 4.2.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
4.2.01	23.03	0.3, 1.33%	27.65%	0.98%, 3.55%
4.2.02	23.06	0.31, 1.37%	28.65%	1%, 3.51%
4.2.03	23.11	0.33, 1.42%	30.12%	1.96%, 6.64%
4.2.01	26.82	0.25, 0.95%	57.91%	4.77%, 8.15%
4.2.02	26.76	0.3, 1.11%	59.36%	5.7%, 9.66%
4.2.03	26.67	0.32, 1.2%	60.46%	6.22%, 10.3%
4.2.01	25.94	1.27, 4.73%	79.79%	3.29%, 4.06%
4.2.02	26.97	0.78, 2.9%	79.95%	3.08%, 3.81%
4.2.03	27.81	0.3, 1.08%	81.30%	1.47%, 1.8%
4.2.01	24.33	0.61, 2.54%	95.25%	2.28%, 2.4%
4.2.02	24.22	0.55, 2.29%	95.04%	1.92%, 2.02%
4.2.03	24.12	0.51, 2.14%	95.02%	1.9%, 2%

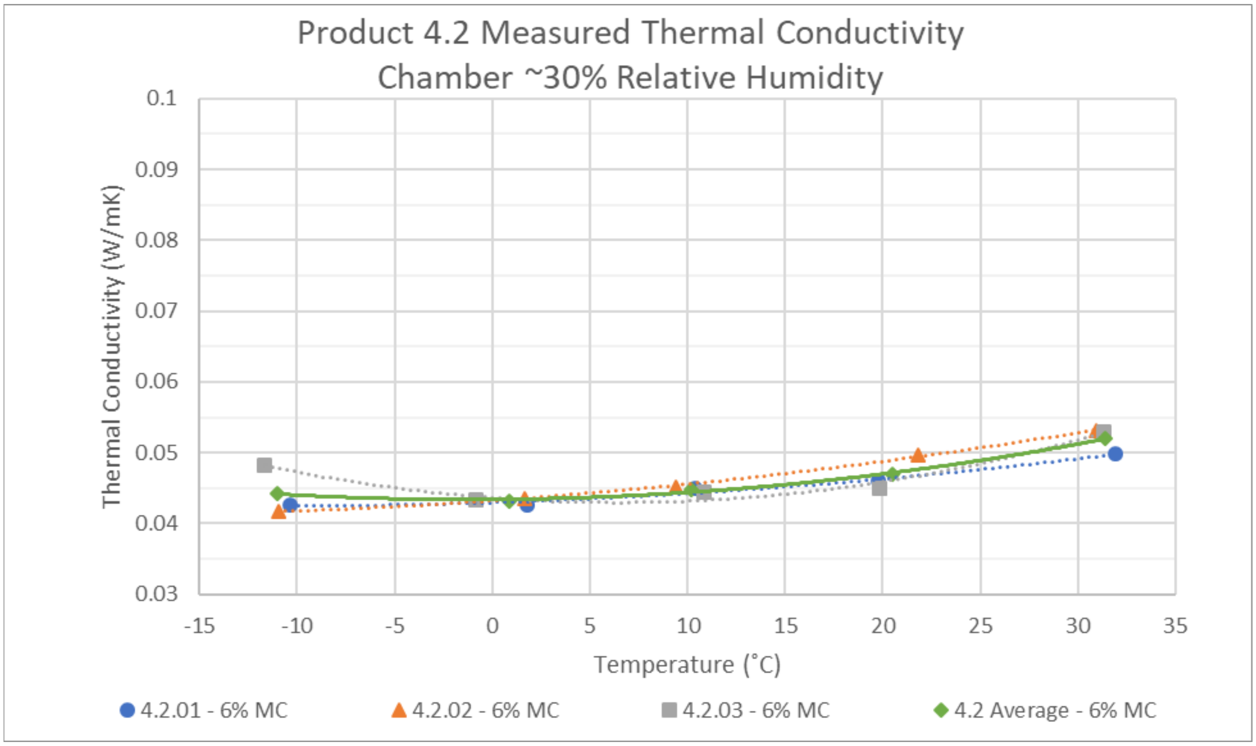


Figure H.26 – Thermal Conductivities for Product 4.2 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

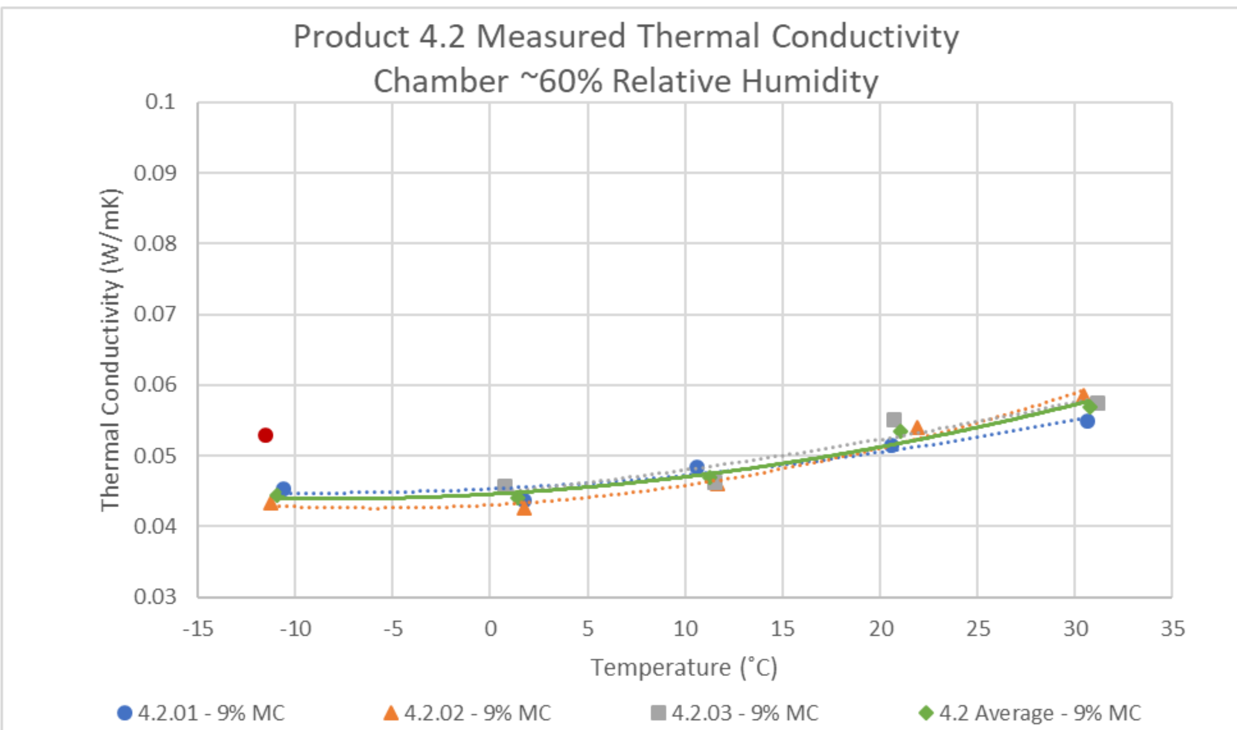


Figure H.27 – Thermal Conductivities for Product 4.2 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

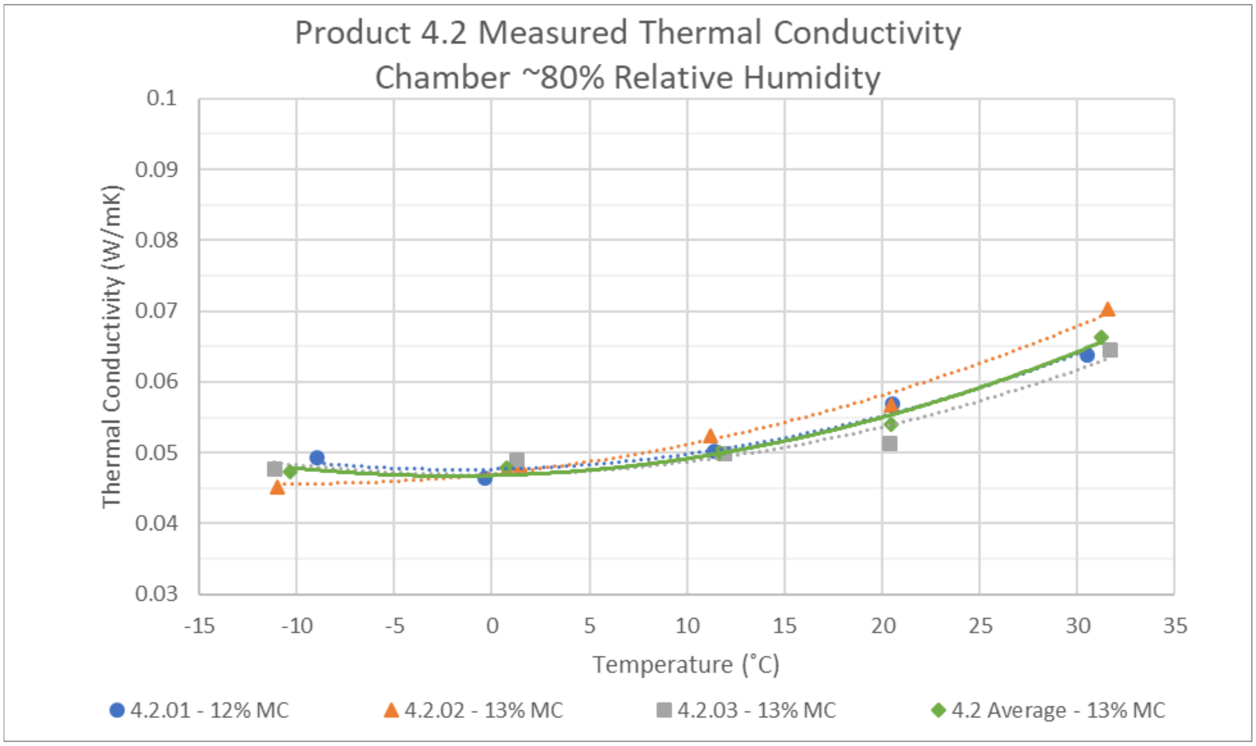


Figure H.28 – Thermal Conductivities for Product 4.2 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

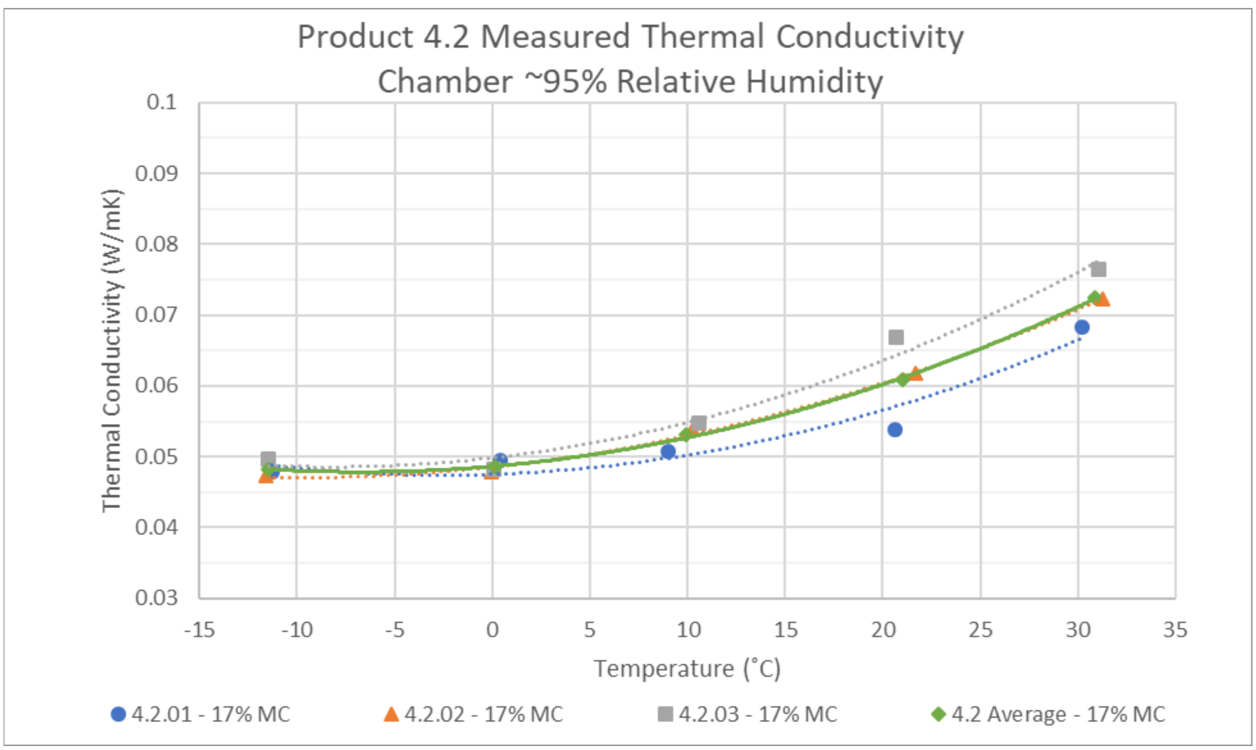


Figure H.29 – Thermal Conductivities for Product 4.2 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

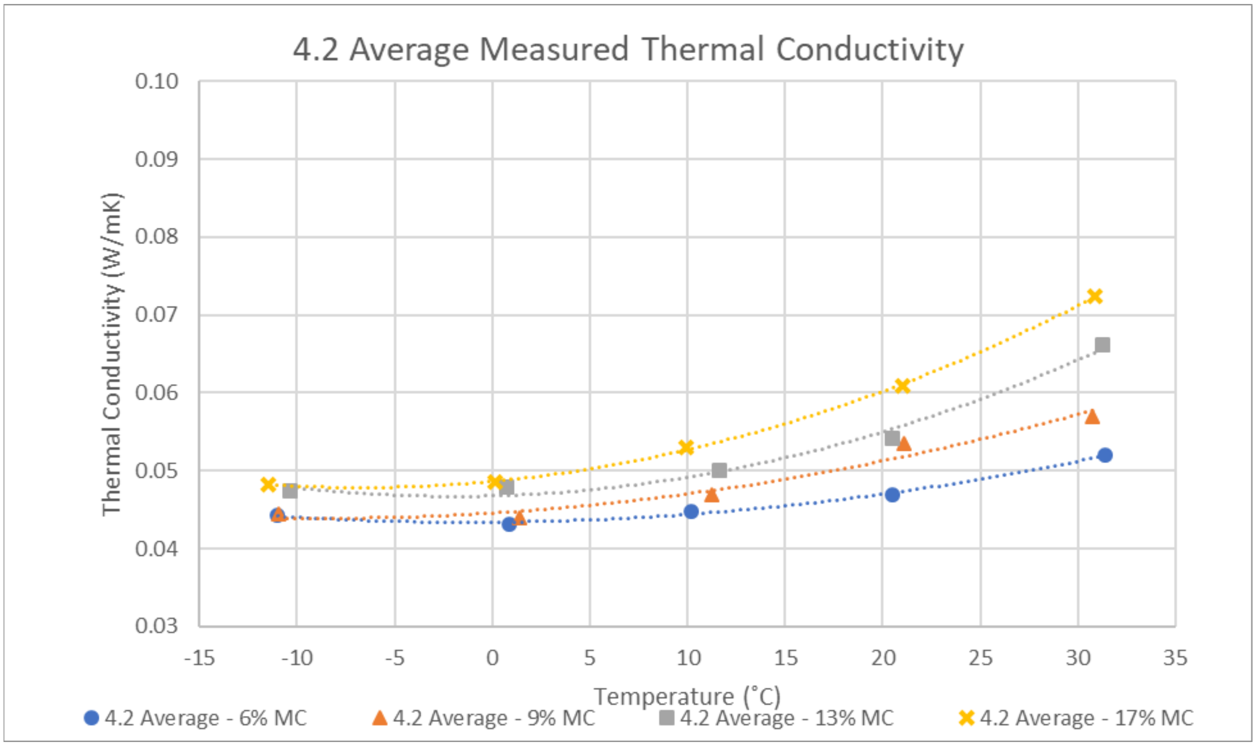


Figure H.30 – Thermal Conductivities for Product 4.1 over Full Temperature Range and Relative Humidity Range.

Table H.13 - Thermal Conductivities for Specimens 5.2.01, 5.2.02, 5.2.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
5.2.01 - 6% MC		5.2.02 - 6% MC		5.2.03 - 6% MC		5.2 Average – 6%MC		
-10.76	0.041081	-10.52	0.039659	-11.1	0.041976	-10.79	0.040905	0.001168, 2.86%
0.89	0.043054	1.04	0.041448	0.72	0.042115	0.88	0.042206	0.000807, 1.91%
9.59	0.045107	9.69	0.043719	9.38	0.042916	9.55	0.043914	0.001108, 2.52%
20.81	0.048573	21.62	0.047448	21.43	0.046192	21.29	0.047404	0.001191, 2.51%
30.15	0.051615	31.98	0.05054	30.98	0.047475	31.04	0.049877	0.002148, 4.31%
5.2.01 - 8% MC		5.2.02 - 8% MC		5.2.03 - 9% MC		5.2 Average – 8%MC		
-8.88	0.042375	-10.08	0.041653	-10.17	0.041592	-9.71	0.041873	0.000436, 1.04%
-0.02	0.043225	0.75	0.038499	1.37	0.044025	0.70	0.041916	0.002986, 7.12%
11.38	0.047798	10.3	0.046532	9.9	0.045767	10.53	0.046699	0.001026, 2.2%
20.74	0.049597	21.63	0.050643	21.92	0.049643	21.43	0.049961	0.000591, 1.18%
30.15	0.051192	30.5	0.056641	30.47	0.057215	30.37	0.055016	0.003324, 6.04%
5.2.01 - 14% MC		5.2.02 - 14% MC		5.2.03 - 13% MC		5.2 Average – 13%MC		
-9.56	0.045631	-11.01	0.043158	-10.67	0.045207	-10.41	0.044665	0.001322, 2.96%
1.67	0.048009	1.52	0.046454	1.56	0.0465	1.58	0.046988	0.000885, 1.88%
10.32	0.049895	11.64	0.050843	10.56	0.051577	10.44	0.050736	0.000843, 1.66%
21.4	0.057459	20.51	0.058356	21.9	0.056596	21.65	0.057028	0.00088, 1.54%
30.06	0.057624	31.94	0.063526	30.46	0.063827	31.20	0.063677	0.003498, 5.49%
5.2.01 - 18% MC		5.2.02 - 17% MC		5.2.03 - 17% MC		5.2 Average – 17%MC		
-11.05	0.049999	-10.91	0.049845	-11.08	0.049715	-11.01	0.049853	0.000142, 0.29%
0.82	0.052378	1.38	0.050055	1.36	0.04968	1.19	0.050704	0.001462, 2.88%
9.41	0.05652	9.97	0.054787	9.94	0.053973	9.77	0.055093	0.001301, 2.36%
21.63	0.067421	21.81	0.067197	21.57	0.064283	21.67	0.066300	0.001751, 2.64%
31.04	0.077847	30.69	0.077682	30.55	0.078104	30.76	0.077878	0.000213, 0.27%

Table H.14 - Chamber Temperature and Relative Humidity Data for Specimens 5.2.01, 5.2.02, 5.2.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
5.2.01	23.37	0.49, 2.14%	30.25%	1.83%, 6.17%
5.2.02	23.34	0.41, 1.78%	29.17%	1.6%, 5.55%
5.2.03	23.34	0.41, 1.77%	28.56%	1.3%, 4.57%
5.2.01	23.62	0.23, 0.96%	53.40%	1.33%, 2.5%
5.2.02	23.63	0.23, 0.97%	53.98%	1.33%, 2.47%
5.2.03	23.62	0.23, 0.97%	54.67%	1.27%, 2.32%
5.2.01	23.95	0.76, 3.23%	80.39%	6.62%, 8.13%
5.2.02	23.88	0.63, 2.68%	79.38%	6.03%, 7.45%
5.2.03	24.09	0.73, 3.05%	82.05%	1.93%, 2.34%
5.2.01	23.86	0.48, 2.03%	95.04%	1.96%, 2.06%
5.2.02	23.92	0.5, 2.11%	95.10%	2%, 2.11%
5.2.03	23.88	0.55, 2.33%	95.10%	1.87%, 1.97%

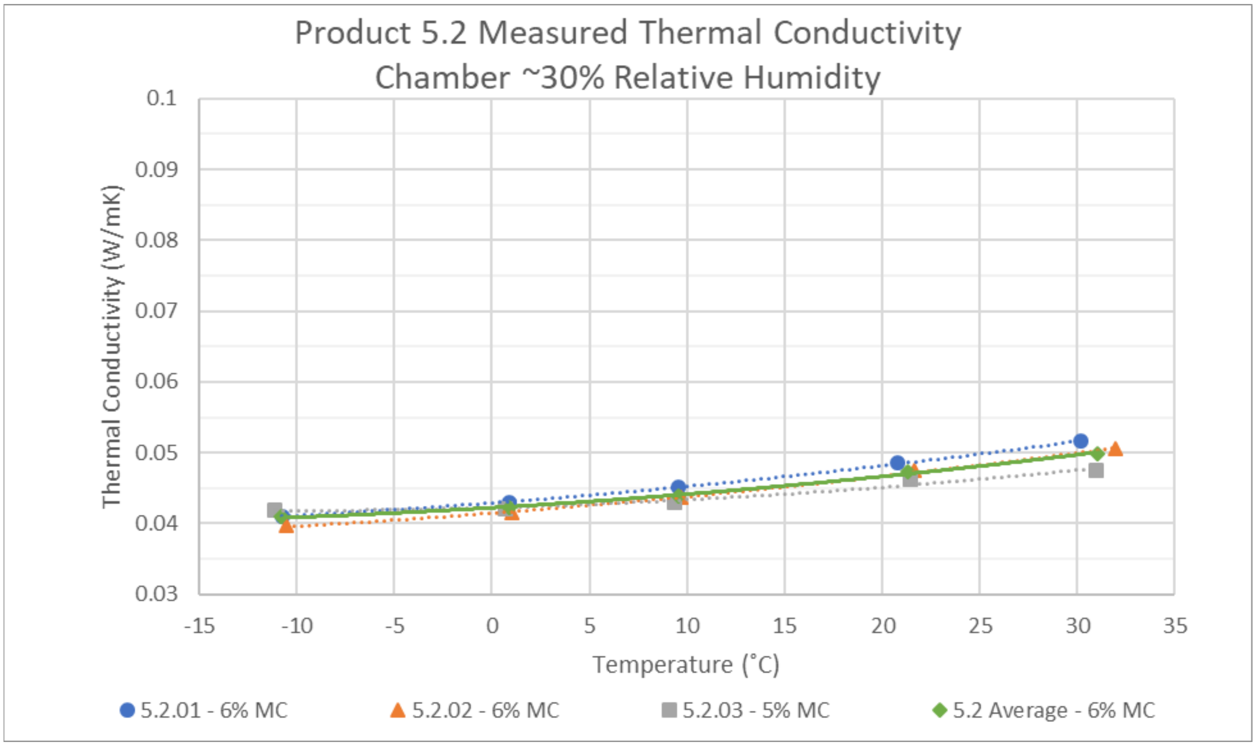


Figure H.31 – Thermal Conductivities for Product 5.2 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

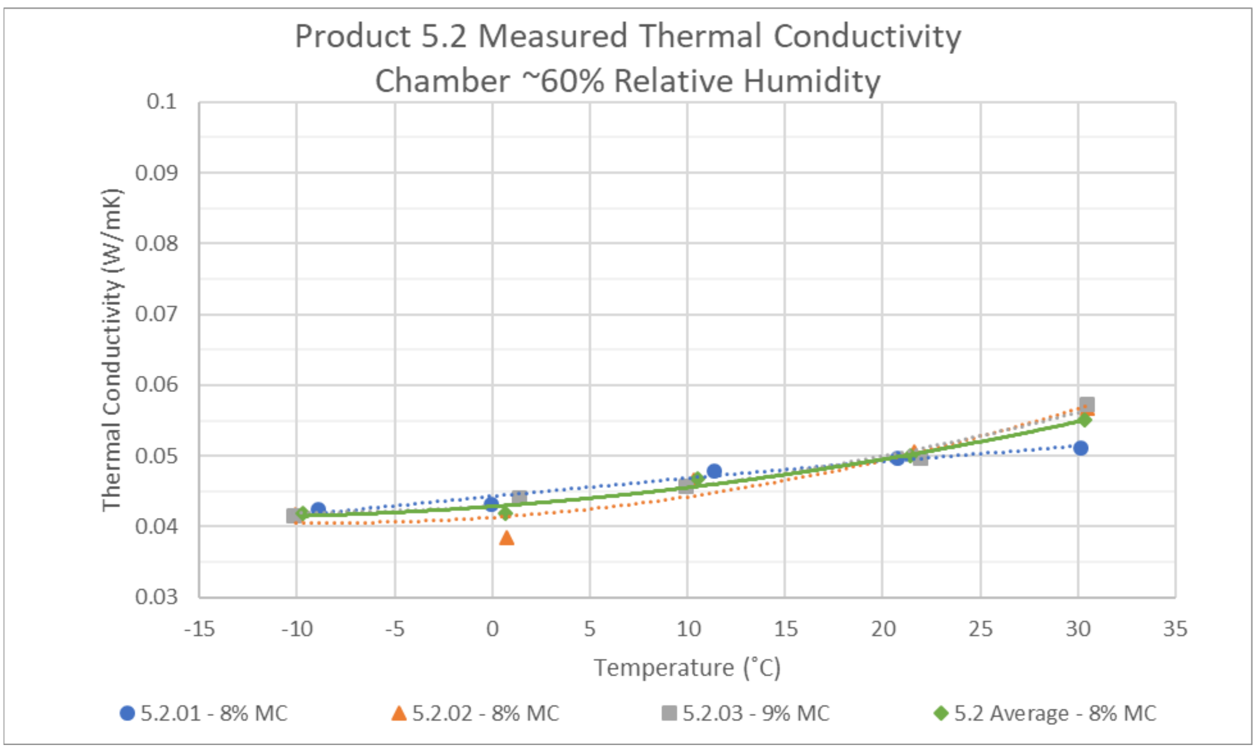


Figure H.32 – Thermal Conductivities for Product 5.2 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

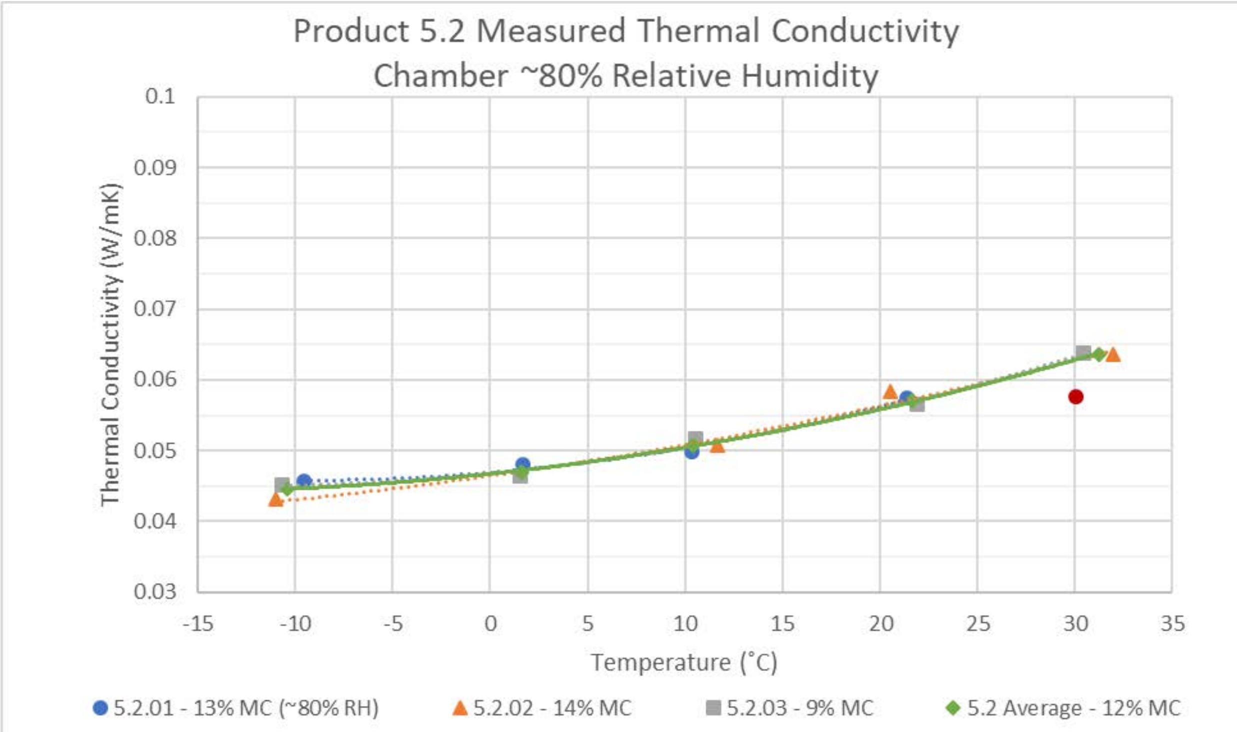


Figure H.33 – Thermal Conductivities for Product 5.2 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

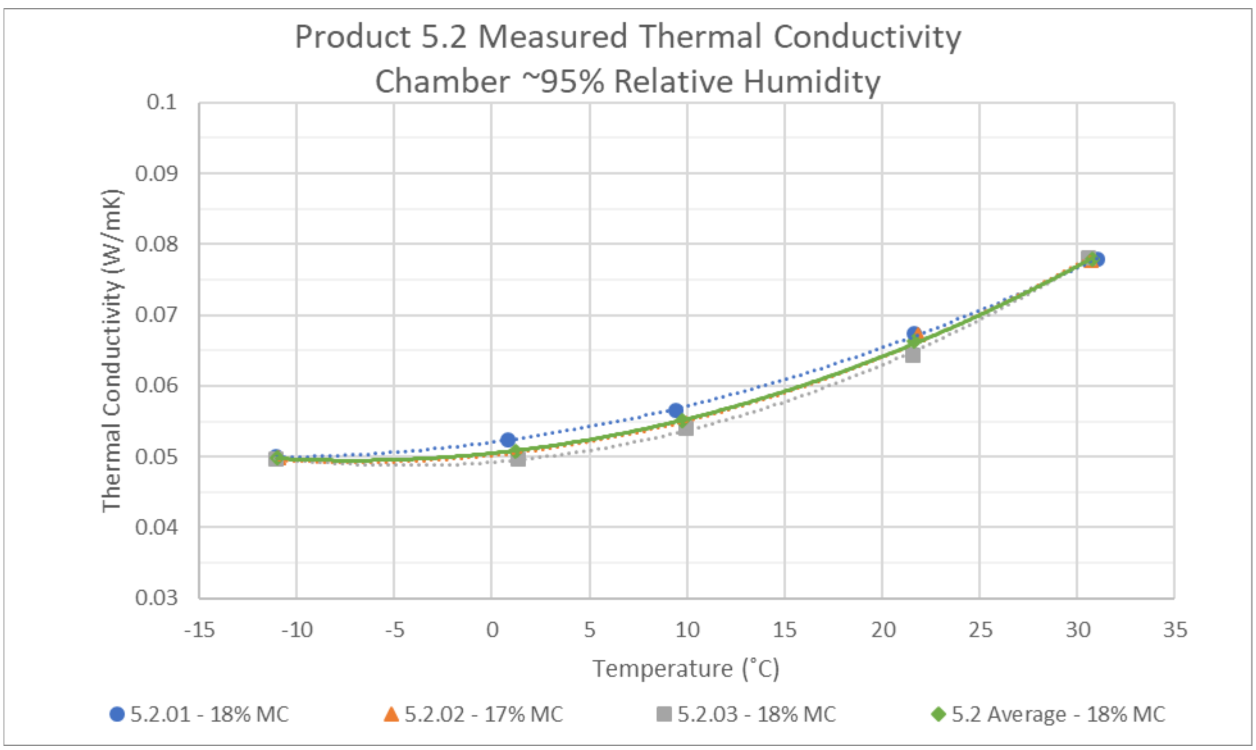


Figure H.34 – Thermal Conductivities for Product 5.2 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

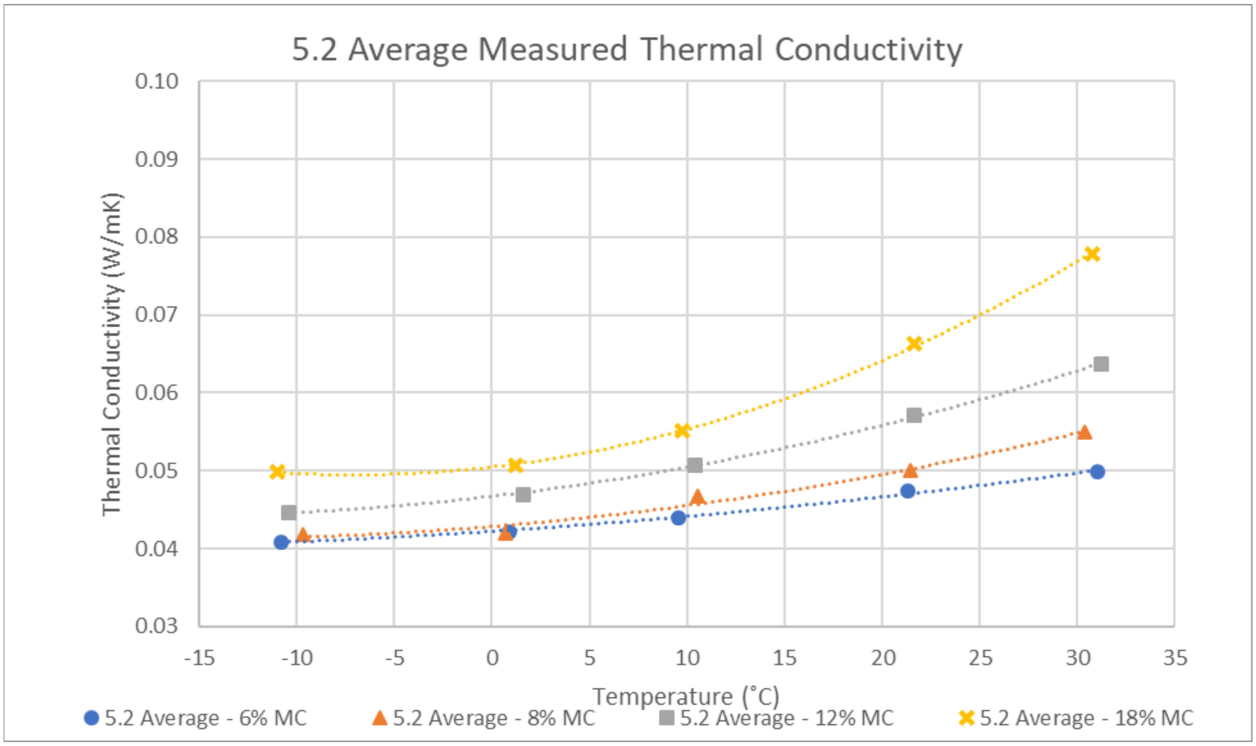


Figure H.35 – Thermal Conductivities for Product 5.2 over Full Temperature Range and Relative Humidity Range.

Table H.15 - Thermal Conductivities for Specimens 5.3.01, 5.3.02, 5.3.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
5.3.01 - 7% MC		5.3.02 - 7% MC		5.3.03 - 7% MC		5.3 Average – 7%MC		
-11.75	0.04249	-10.77	0.042867	-11.81	0.042171	-11.44	0.042509	0.000348, 0.82%
-0.18	0.043112	1.05	0.042392	-0.29	0.043322	0.19	0.042942	0.000488, 1.14%
10.658	0.044812	9.6	0.044829	10.26	0.046207	10.17	0.045283	0.000801, 1.77%
21.71	0.048475	21.38	0.047938	21.86	0.049478	21.65	0.048630	0.000782, 1.61%
31.5	0.053182	30.7	0.051059	31.3	0.053876	31.17	0.052706	0.001468, 2.78%
5.3.01 - 9% MC		5.3.02 - 9% MC		5.3.03 - 9% MC		5.3 Average – 9%MC		
-11.45	0.046111	-11.56	0.04811	-11.85	0.047161	-11.62	0.047127	0.001, 2.12%
-0.07	0.046174	0.35	0.043908	-0.58	0.048498	-0.10	0.046193	0.002295, 4.97%
10.59	0.04851	11.19	0.047808	11.15	0.052554	10.98	0.049624	0.002562, 5.16%
21.83	0.053656	20.61	0.052718	20.57	0.055723	21.00	0.054032	0.001537, 2.85%
31.78	0.061003	29.94	0.057071	31.88	0.062956	31.20	0.060343	0.002997, 4.97%
5.3.01 - 16% MC		5.3.02 - 16% MC		5.3.03 - 17% MC		5.3 Average – 17%MC		
-11.46	0.051102	-11.09	0.075579	-11.37	0.050491	-11.42	0.050797	0.000432, 0.85%
0.54	0.051803	-0.63	0.051189	-0.68	0.051757	-0.26	0.051583	0.000342, 0.66%
11.42	0.057284	11.15	0.051557	10.97	0.056342	11.20	0.056813	0.003071, 5.41%
21.31	0.061566	20.52	0.058475	20.71	0.058872	21.01	0.060219	0.001682, 2.79%
31.34	0.074816	30.76	0.070369	31.54	0.07186	31.15	0.071115	0.002263, 3.18%
5.3.01 - 24% MC		5.3.02 - 24% MC		5.3.03 - 25% MC		5.3 Average – 24%MC		
-11.56	0.049553	-11.19	0.052913	-11.73	0.053813	-11.49	0.052093	0.002245, 4.31%
0.55	0.050894	0.41	0.050847	0.43	0.049983	0.46	0.050575	0.000513, 1.01%
8.77	0.058735	8.97	0.055869	8.63	0.059197	8.79	0.057934	0.001803, 3.11%
21.51	0.068361	19.25	0.076694	21.15	0.066789	20.64	0.070615	0.005323, 7.54%
31.14	0.08656	31.49	0.079466	31.78	0.080492	31.47	0.082173	0.003834, 4.67%

Table H.16 - Chamber Temperature and Relative Humidity Data for Specimens 5.3.01, 5.3.02, 5.3.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
5.3.01	23.32	0.36, 1.57%	26.56%	1.63%, 5.84%
5.3.02	23.33	0.36, 1.55%	26.84	1.62%, 5.97%
5.3.03	23.32	0.38, 1.64%	26.65%	1.1%, 4.06%
5.3.01	23.65	0.28, 1.19%	55.71%	1.4%, 2.52%
5.3.02	23.62	0.28, 1.17%	56.36%	1.51%, 2.69%
5.3.03	23.46	0.45, 1.95%	63.84%	1.79%, 2.8%
5.3.01	24.03	0.77, 3.25%	80.81%	6.96%, 8.55%
5.3.02	24.25	0.87, 3.59%	81.43%	7.33%, 8.76%
5.3.03	24.17	0.72, 2.98%	81.75%	1.95%, 2.37%
5.3.01	23.82	0.29, 1.2%	95.05%	1.06%, 1.12%
5.3.02	23.83	0.33, 1.39%	94.97%	1.43%, 1.51%
5.3.03	23.78	0.35, 1.46%	94.59%	1.36%, 1.43%

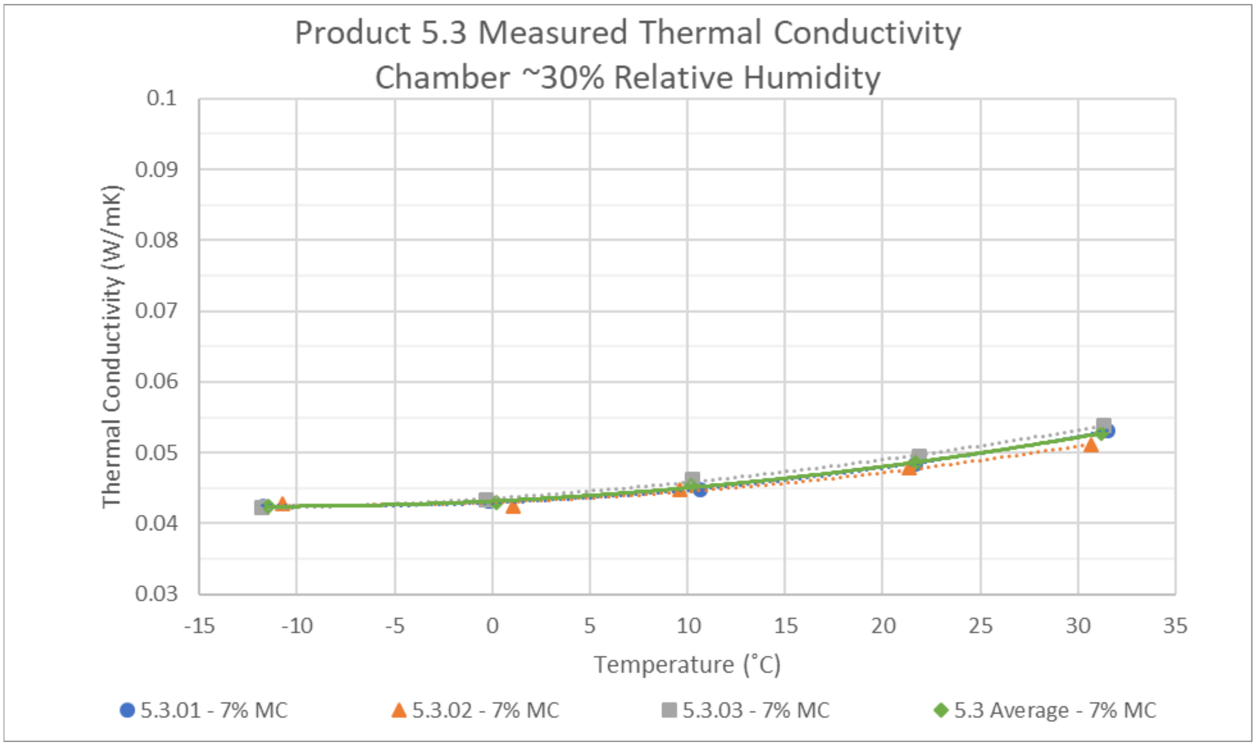


Figure H.36 – Thermal Conductivities for Product 5.3 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

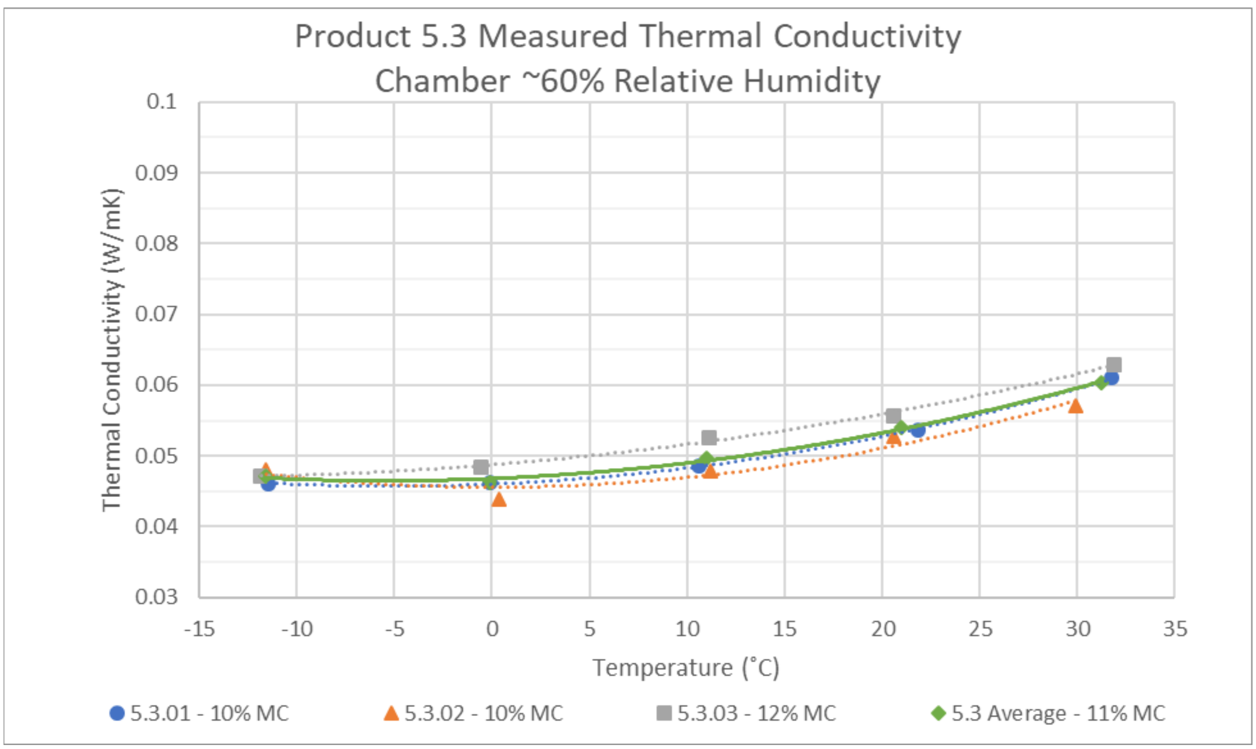


Figure H.37 – Thermal Conductivities for Product 5.3 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

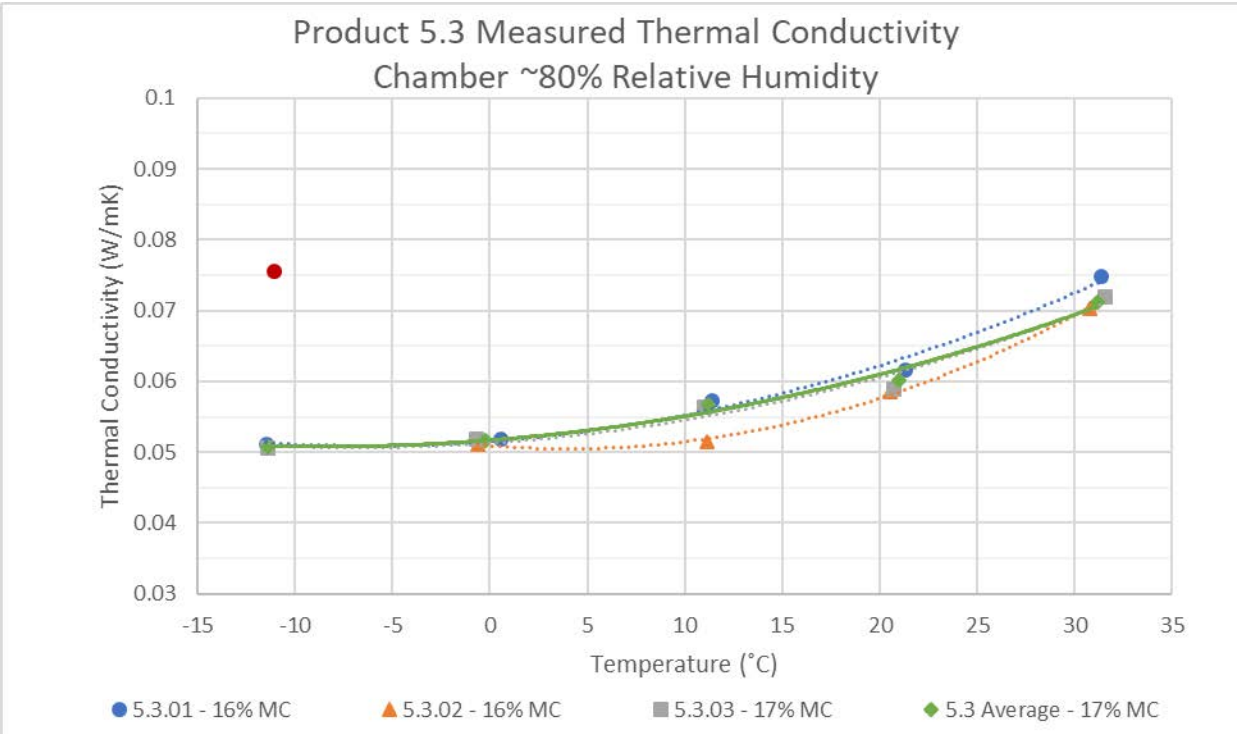


Figure H.38 – Thermal Conductivities for Product 5.3 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

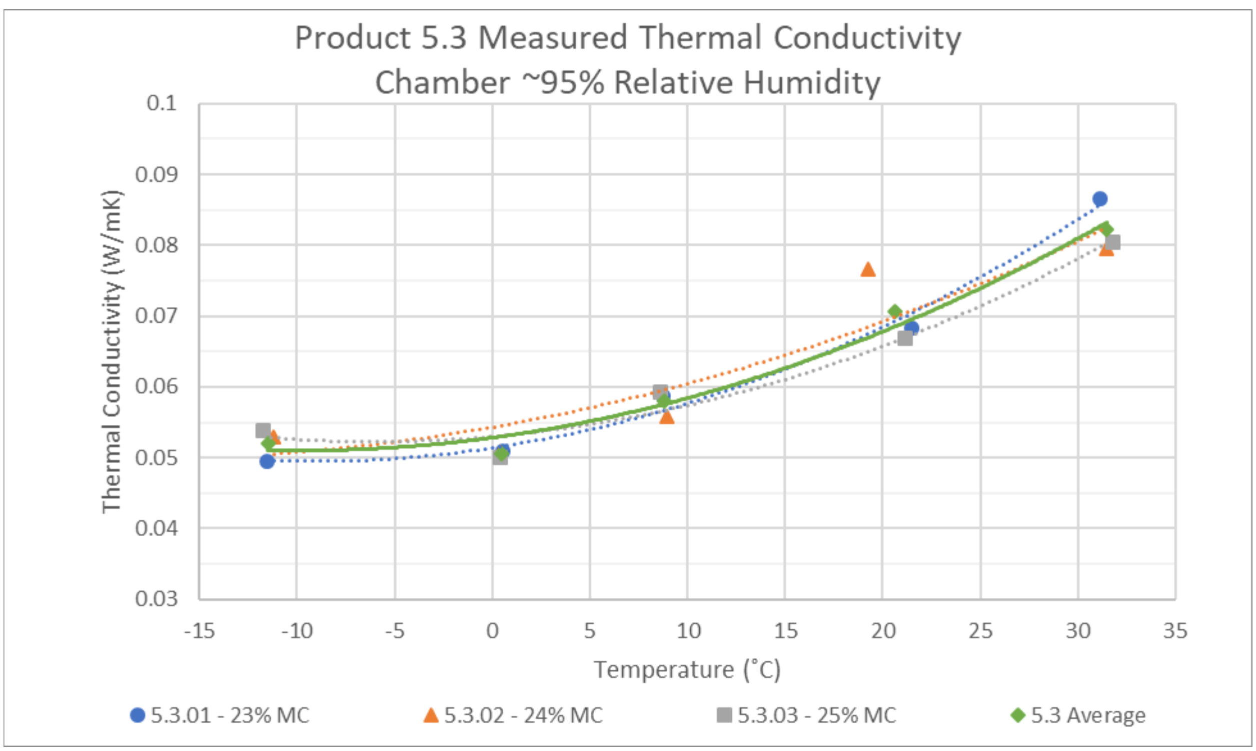


Figure H.39 – Thermal Conductivities for Product 5.3 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

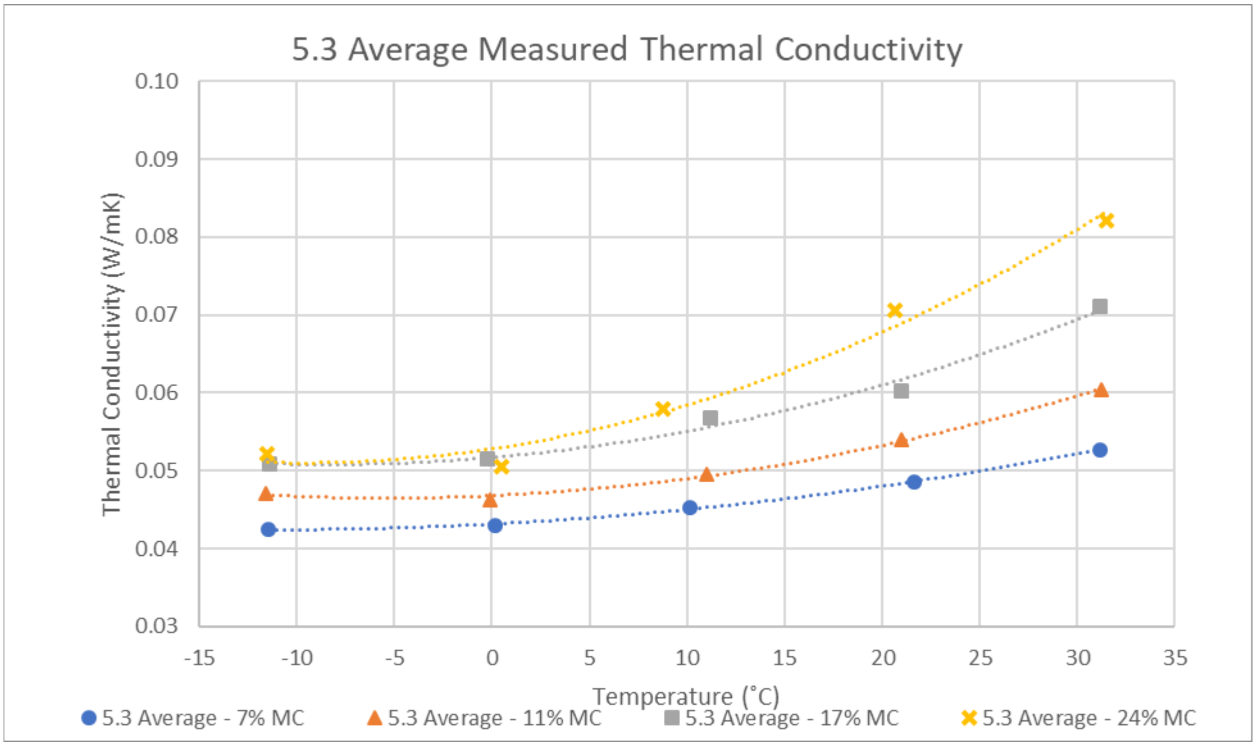


Figure H.40 – Thermal Conductivities for Product 5.3 over Full Temperature Range and Relative Humidity Range.

Table H.17 - Thermal Conductivities for Specimens 6.2.01, 6.2.02, 6.2.03, and Average.

Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	Temp (˚C)	k (W/mK)	SD, CV%
6.2.01 - 7% MC		6.2.02 - 6% MC		6.2.03 - 6% MC		6.2 Average – 6%MC		
-10.35	0.041989	-10.27	0.042794	-10.8	0.040579	-10.47	0.041787	0.001121, 2.68%
0.64	0.035619	1.57	0.043433	-1.2	0.042777	0.19	0.043105	0.000464, 1.08%
10.29	0.044422	10.39	0.044889	8.91	0.045634	9.86	0.044982	0.000611, 1.36%
19.7	0.047072	19.74	0.047222	21.65	0.053225	20.36	0.049173	0.00351, 7.14%
31.65	0.050048	31.67	0.05068	30.5	0.058972	31.27	0.053233	0.00498, 9.35%
6.2.01 - 9% MC		6.2.02 - 9% MC		6.2.03 - 9% MC		6.2 Average – 9%MC		
-9.78	0.045588	-9.1	0.044049	-10.89	0.042149	-9.92	0.043929	0.001723, 3.92%
1.55	0.043676	1.85	0.049564	2.01	0.047895	1.80	0.047045	0.003035, 6.45%
10.14	0.044949	11.17	0.051329	10.18	0.053124	10.50	0.049801	0.004296, 8.63%
19.56	0.049957	21.87	0.058824	21.06	0.056425	20.83	0.055069	0.004586, 8.33%
31.62	0.051453	30.96	0.063038	31.87	0.067434	31.48	0.060642	0.008256, 13.61%
6.2.01 - 14% MC		6.2.02 - 14% MC		6.2.03 - 14 MC		6.2 Average – 14%MC		
-10.34	0.048074	-10.62	0.051458	-11.22	0.041566	-10.73	0.047033	0.005028, 10.69%
1.42	0.045804	1.34	0.046717	0.72	0.048907	1.16	0.047143	0.001595, 3.38%
10.13	0.050712	9.97	0.050955	10.91	0.053674	10.34	0.051780	0.001644, 3.18%
21.9	0.056127	21.64	0.056157	21.67	0.063624	21.74	0.058636	0.00432, 7.37%
30.37	0.063934	31.1	0.062136	31.14	0.074258	30.87	0.066776	0.006542, 9.8%
6.2.01 - 19% MC		6.2.02 - 19% MC		6.2.03 - 19% MC		6.2 Average – 19%MC		
-10.78	0.048021	-11.26	0.046116	-11.18	0.04701	-11.07	0.047049	0.000953, 2.03%
1.76	0.051156	2.03	0.050667	0.75	0.049874	1.51	0.050566	0.000647, 1.28%
9.98	0.05798	10.86	0.056738	9.16	0.054619	10.00	0.056446	0.001699, 3.01%
22.04	0.070425	20.38	0.068268	21.31	0.068017	21.24	0.068903	0.001324, 1.92%
31.32	0.082852	29.69	0.083211	30.75	0.084751	30.59	0.083605	0.001009, 1.21%

Table H.18 - Chamber Temperature and Relative Humidity Data for Specimens 6.2.01, 6.2.02, 6.2.03

Specimen	Temp (˚C)	SD, CV%	RH (%)	SD, CV%
6.2.01	23.83	0.43, 1.81%	30.17%	0.43, 1.81%
6.2.02	23.54	0.52, 2.22%	30.30%	0.52, 2.22%
6.2.03	23.55	0.52, 2.22%	30.32%	0.52, 2.22%
6.2.01	26.32	0.11, 0.4%	61.52%	3.01%, 4.94%
6.2.02	26.32	0.11, 0.4%	61.51%	3.03%, 4.97%
6.2.03	26.07	0.11, 0.43%	61.90%	2.6%, 4.25%
6.2.01	23.75	0.68, 2.89%	81.70%	2.87%, 3.46%
6.2.02	23.96	0.85, 3.58%	81.15%	3.03%, 3.69%
6.2.03	24.34	1.2, 5.02%	79.95%	3.91%, 4.85%
6.2.01	24.06	0.89, 3.74%	94.75%	2.73%, 2.88%
6.2.02	23.90	0.52, 2.16%	95.68%	2.58%, 2.69%
6.2.03	23.78	0.42, 1.75%	95.97%	1.99%, 2.07%

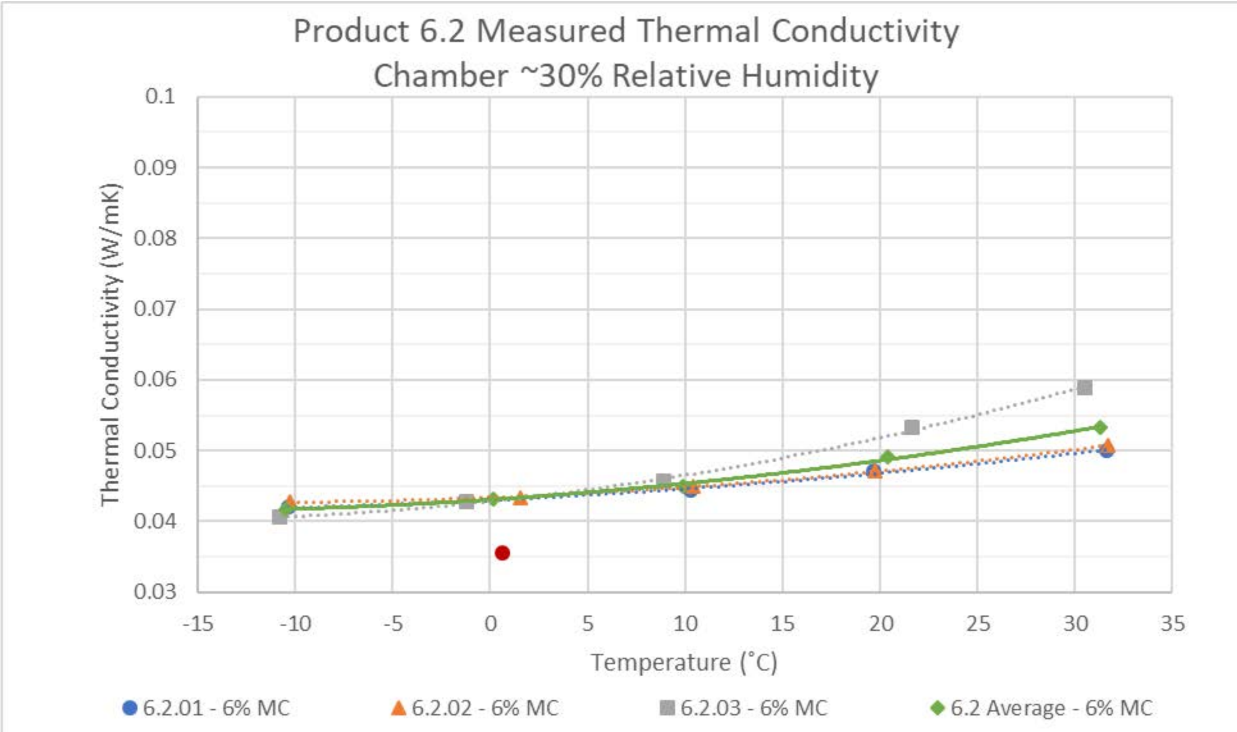


Figure H.41 – Thermal Conductivities for Product 6.2 over Full Temperature Range at 30% Relative Humidity Chamber Conditions.

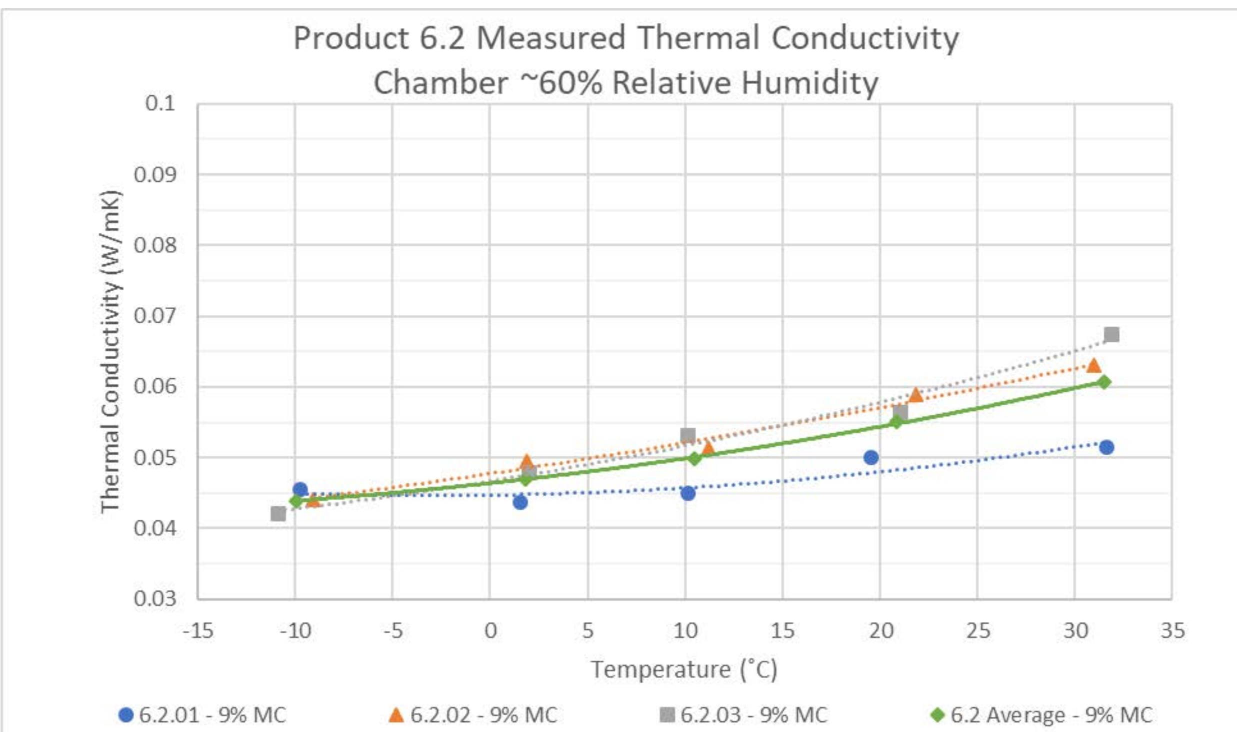


Figure H.42 – Thermal Conductivities for Product 6.2 over Full Temperature Range at 60% Relative Humidity Chamber Conditions.

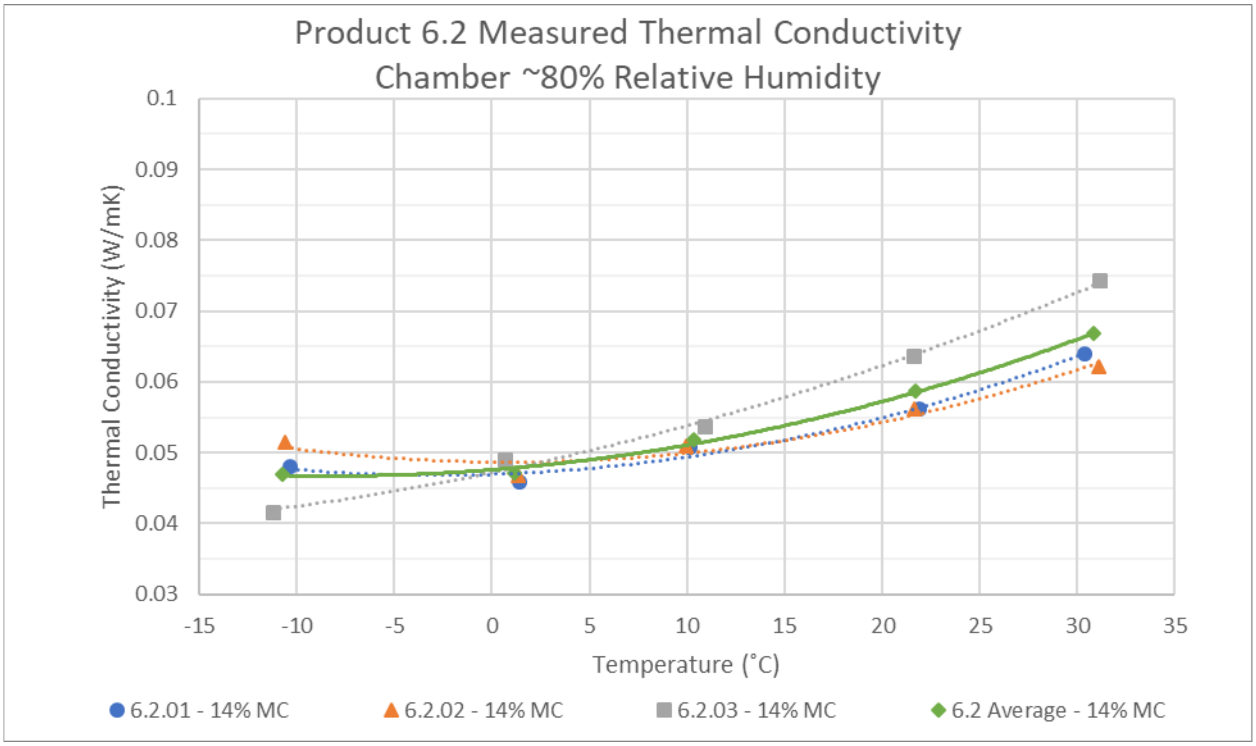


Figure H.43 – Thermal Conductivities for Product 6.2 over Full Temperature Range at 80% Relative Humidity Chamber Conditions.

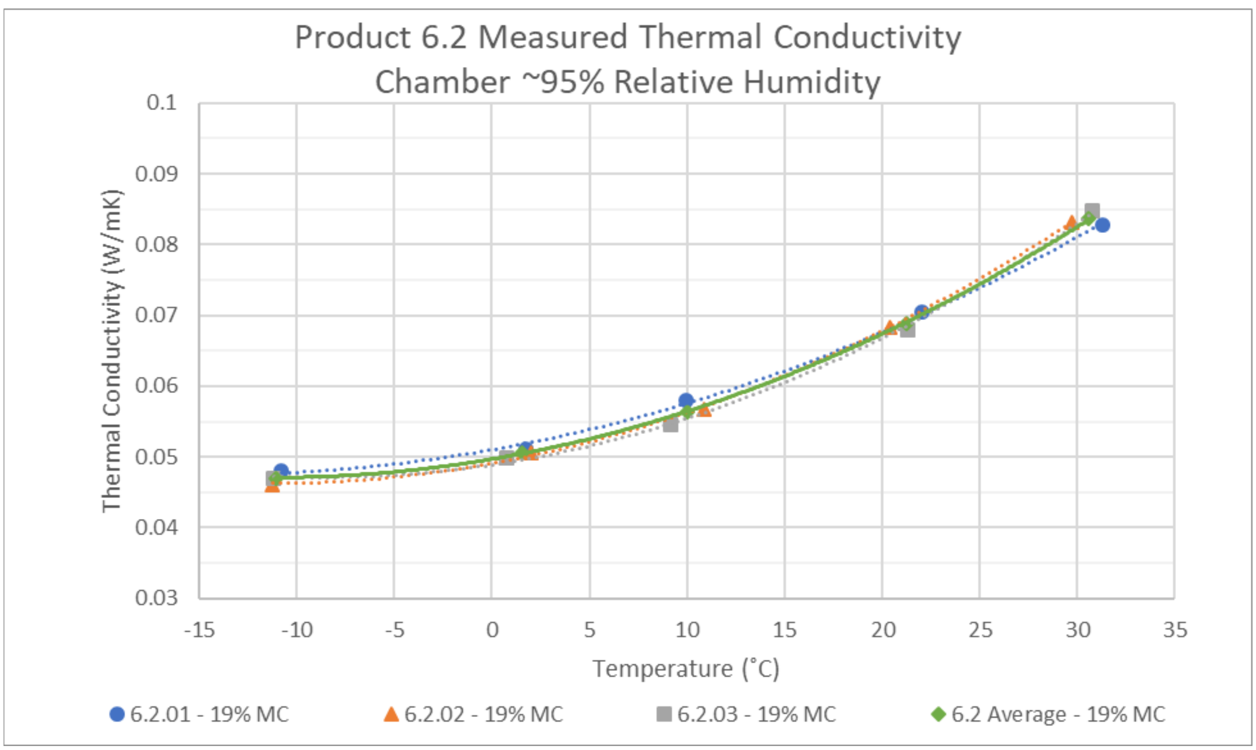


Figure H.44 – Thermal Conductivities for Product 6.2 over Full Temperature Range at 95% Relative Humidity Chamber Conditions.

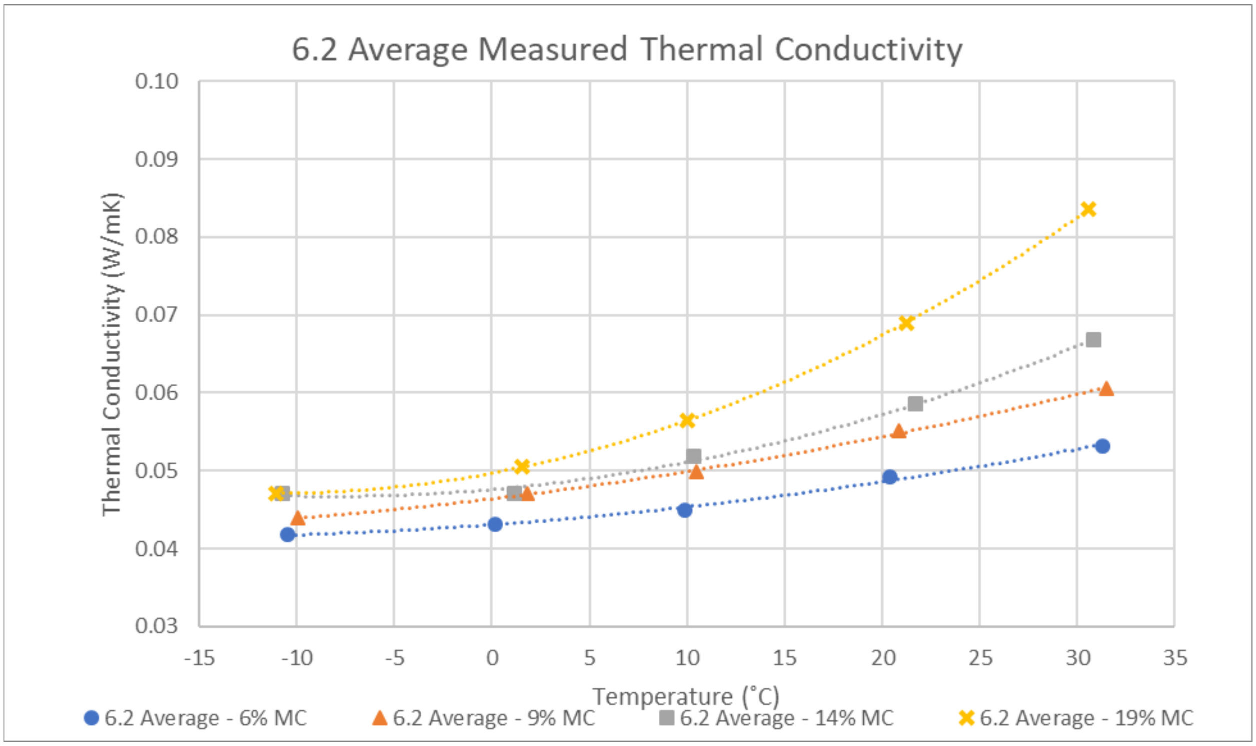


Figure H.45 – Thermal Conductivities for Product 6.2 over Full Temperature Range and Relative Humidity Range.

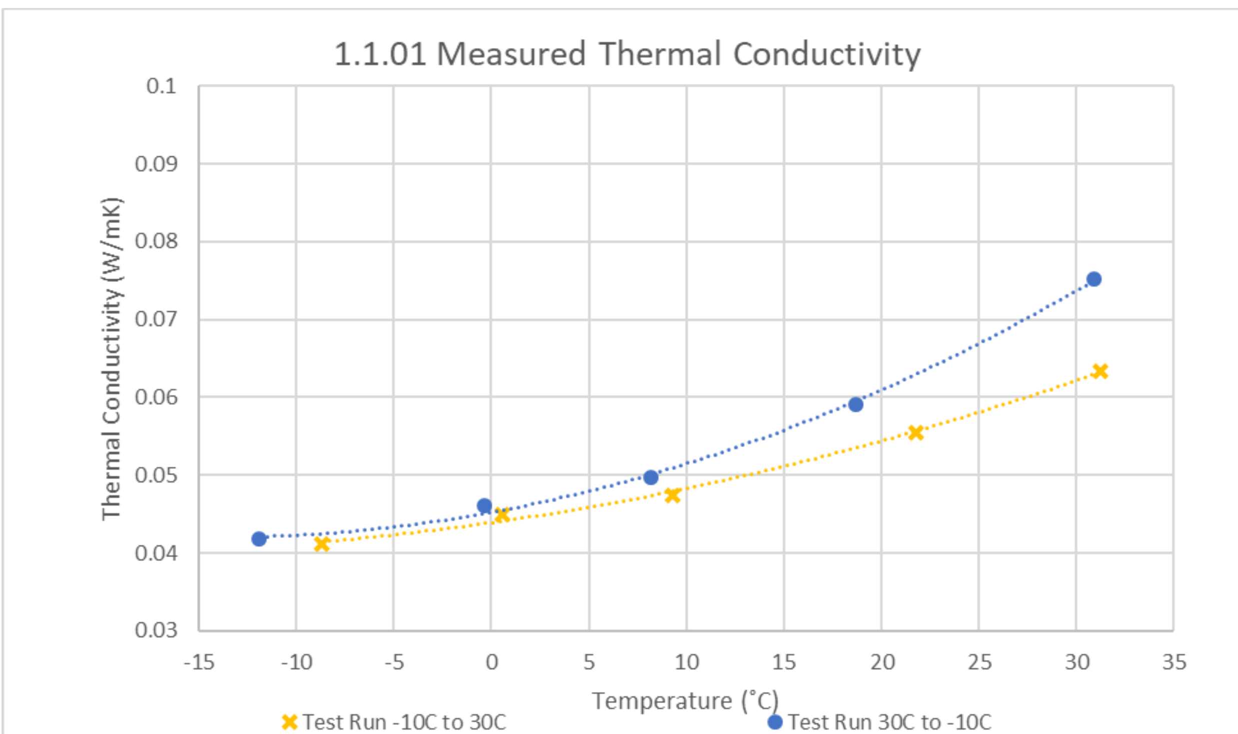


Figure H.46 – Thermal Conductivities for Specimen 1.1.01 at 95% Relative Humidity Chamber Conditions.

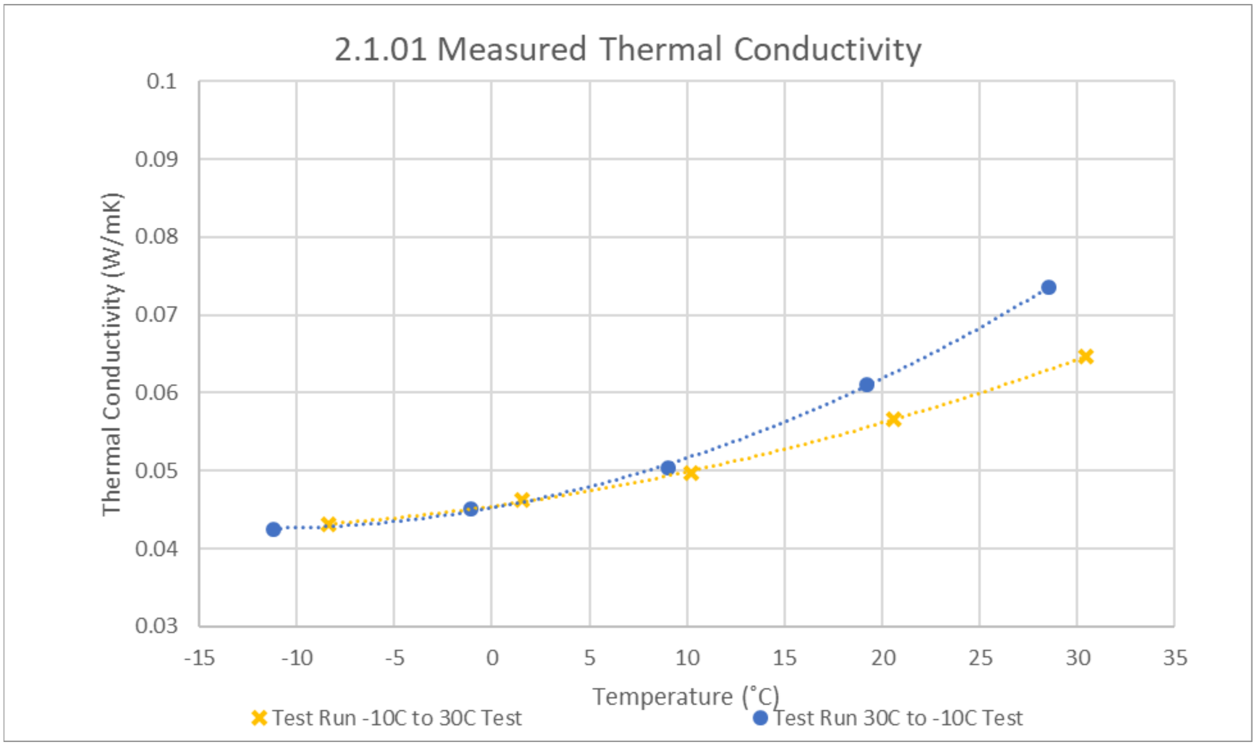


Figure H.47 – Thermal Conductivities for Specimen 2.1.01 at 95% Relative Humidity Chamber Conditions.

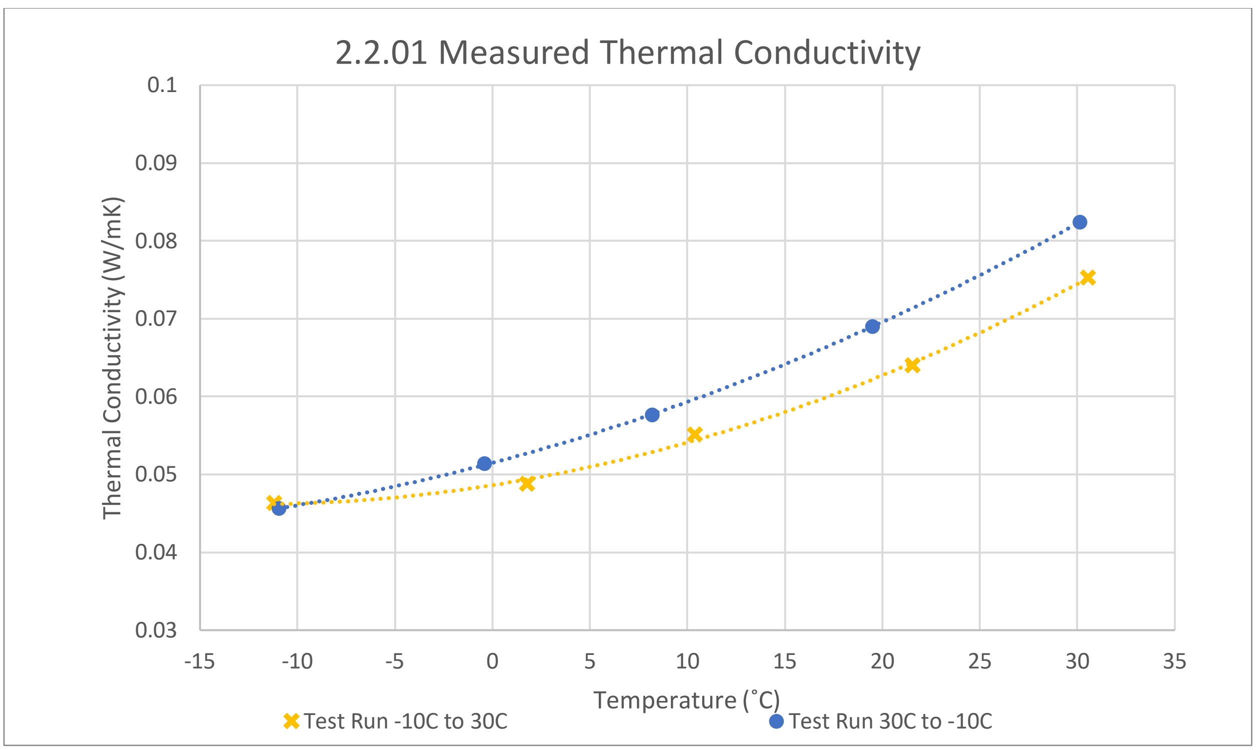


Figure H.48 – Thermal Conductivities for Specimen 2.2.01 at 95% Relative Humidity Chamber Conditions.

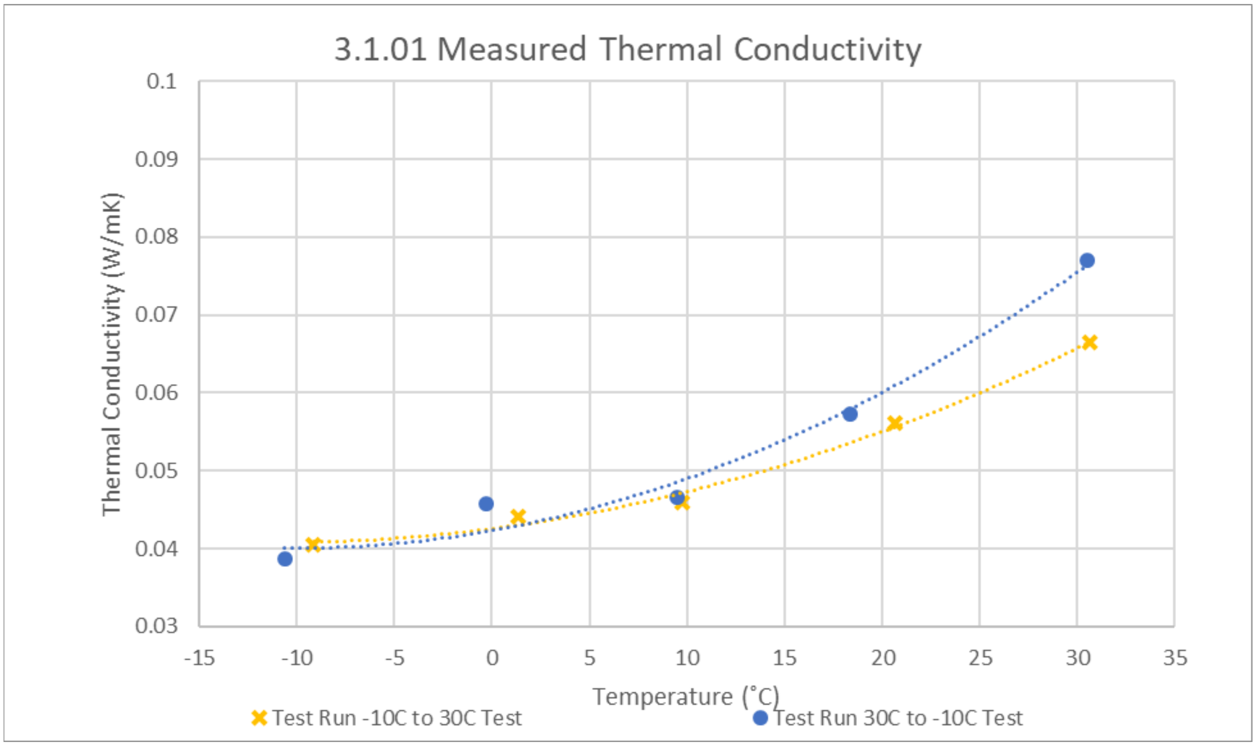


Figure H.49 – Thermal Conductivities for Specimen 3.1.01 at 95% Relative Humidity Chamber Conditions.

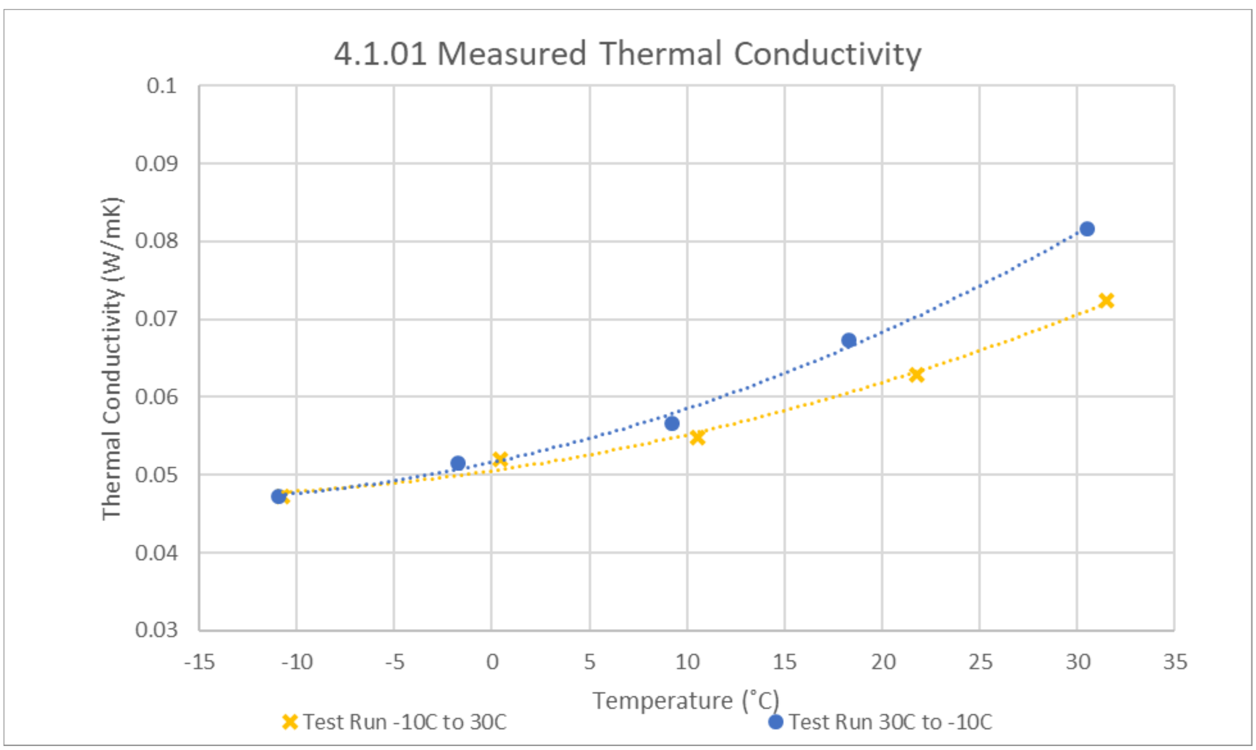


Figure H.50 – Thermal Conductivities for Specimen 4.1.01 at 95% Relative Humidity Chamber Conditions.

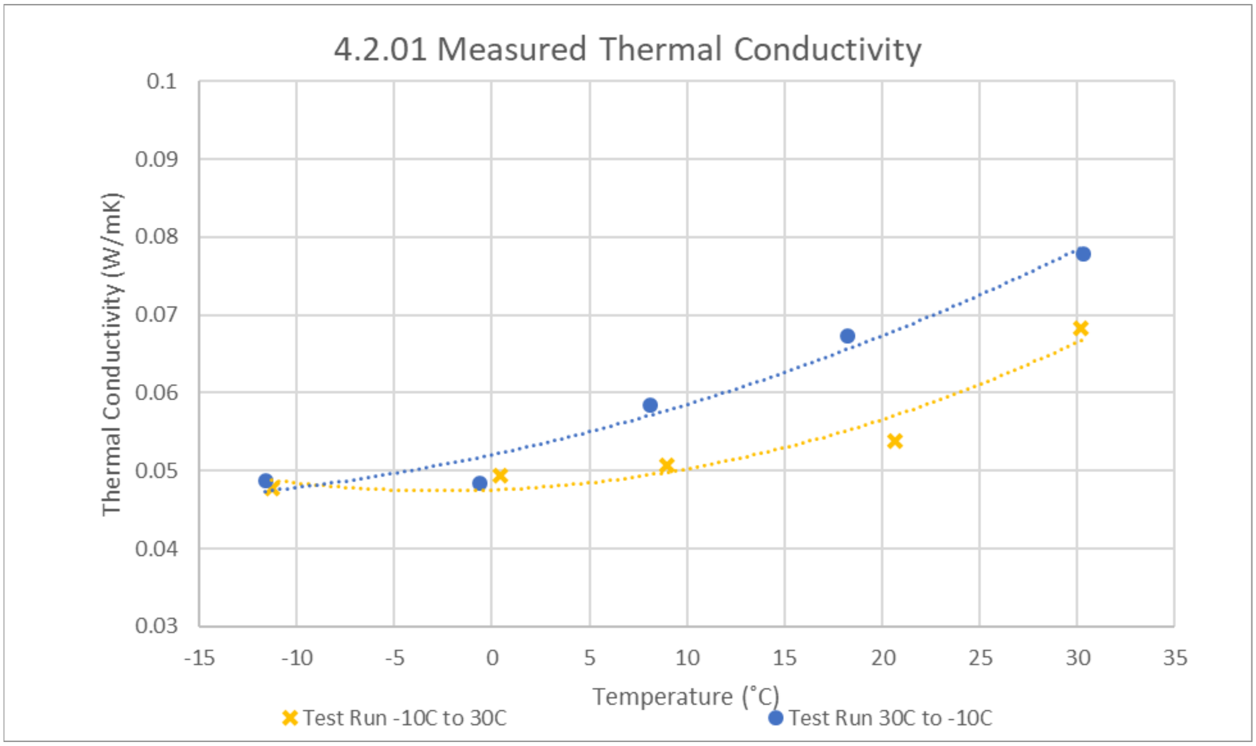


Figure H.51 – Thermal Conductivities for Specimen 4.2.01 at 95% Relative Humidity Chamber Conditions.

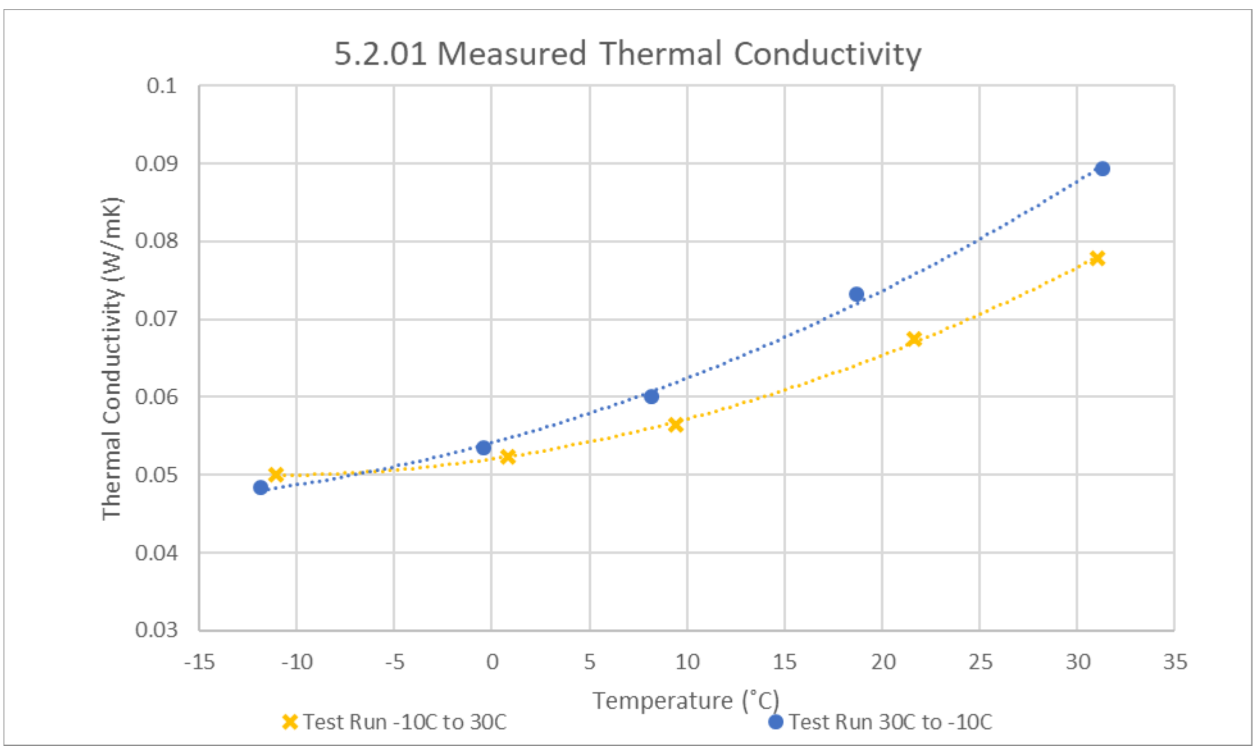


Figure H.52 – Thermal Conductivities for Specimen 5.2.01 at 95% Relative Humidity Chamber Conditions.

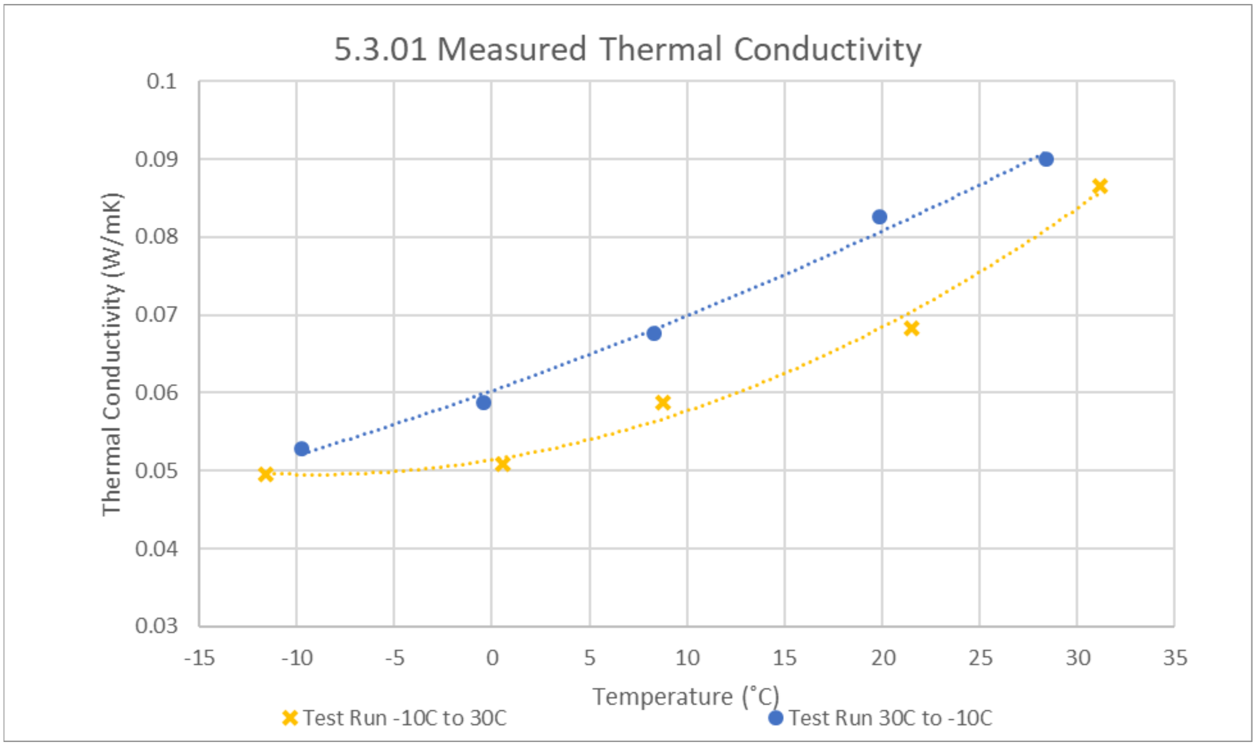


Figure H.53 – Thermal Conductivities for Specimen 5.3.01 at 95% Relative Humidity Chamber Conditions.

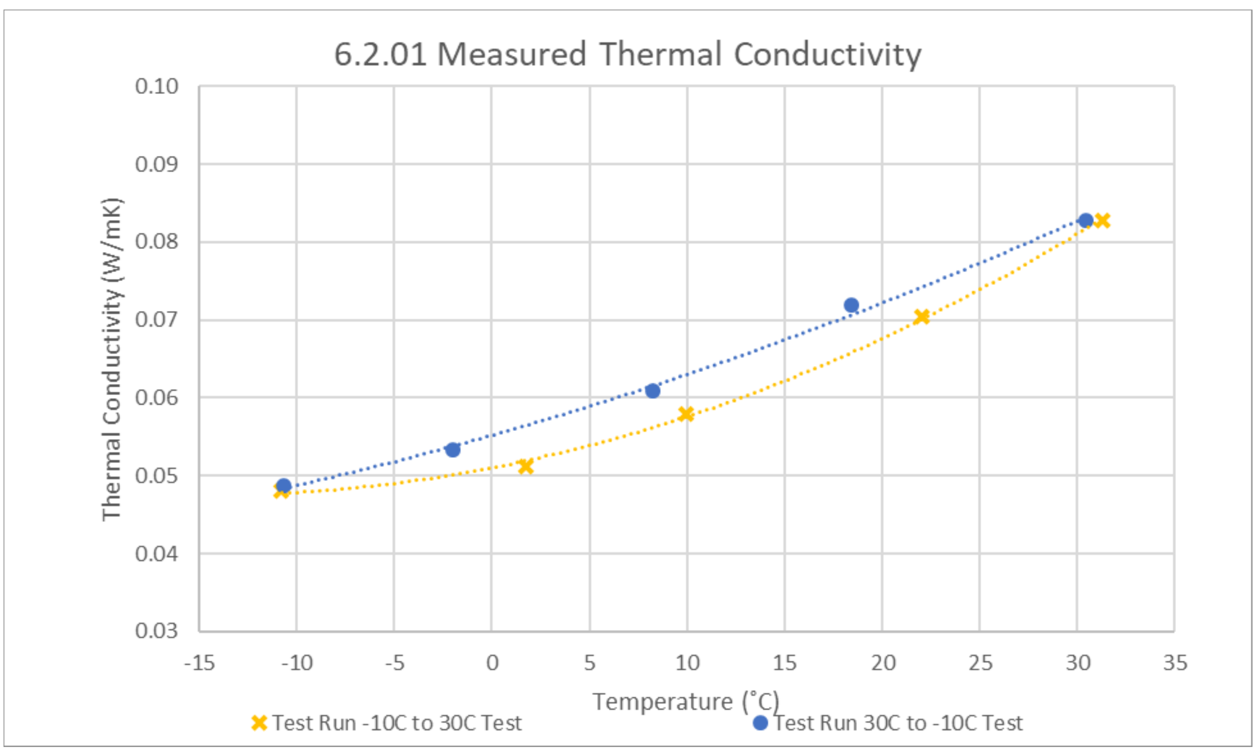


Figure H.54 – Thermal Conductivities for Specimen 6.2.01 at 95% Relative Humidity Chamber Conditions.

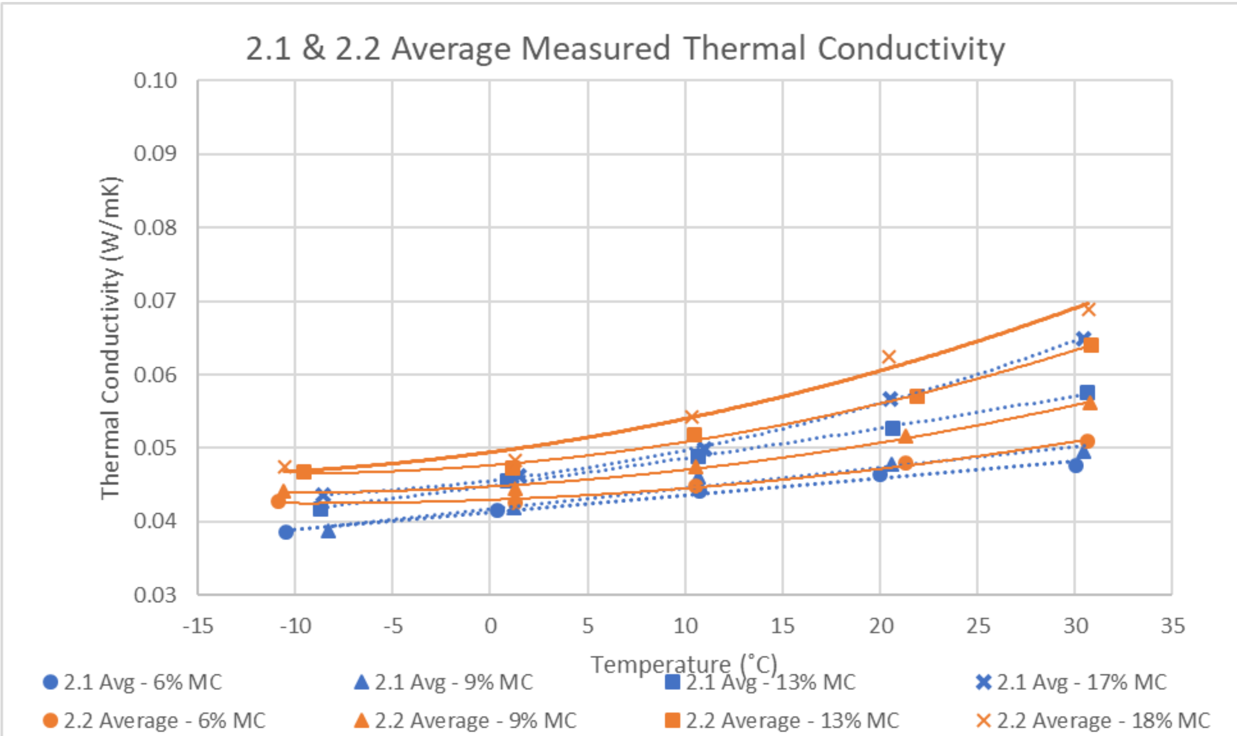


Figure H.55 – Thermal Conductivities for Product 2.1 & 2.2 for Full Temperature and Relative Humidity Range..

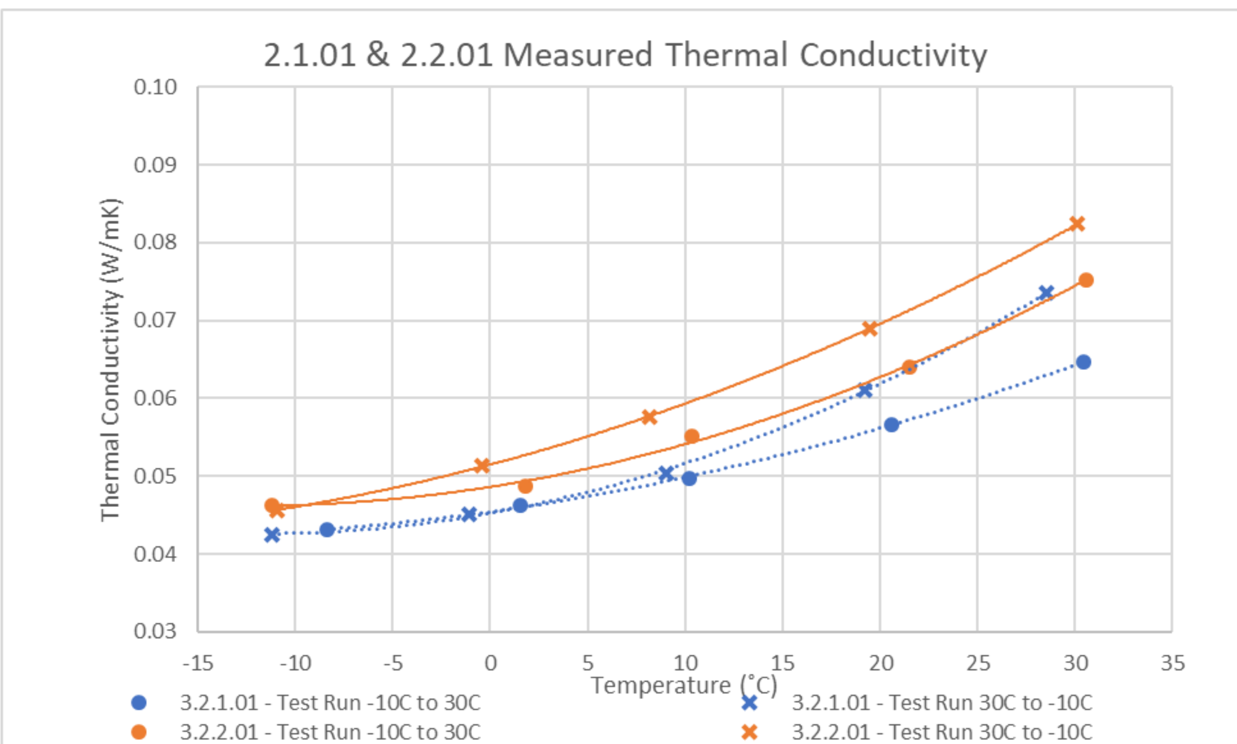


Figure H.56 – Thermal Conductivities for Specimen 2.1.01 & 2.2.01 at 95% Relative Humidity Chamber Conditions.

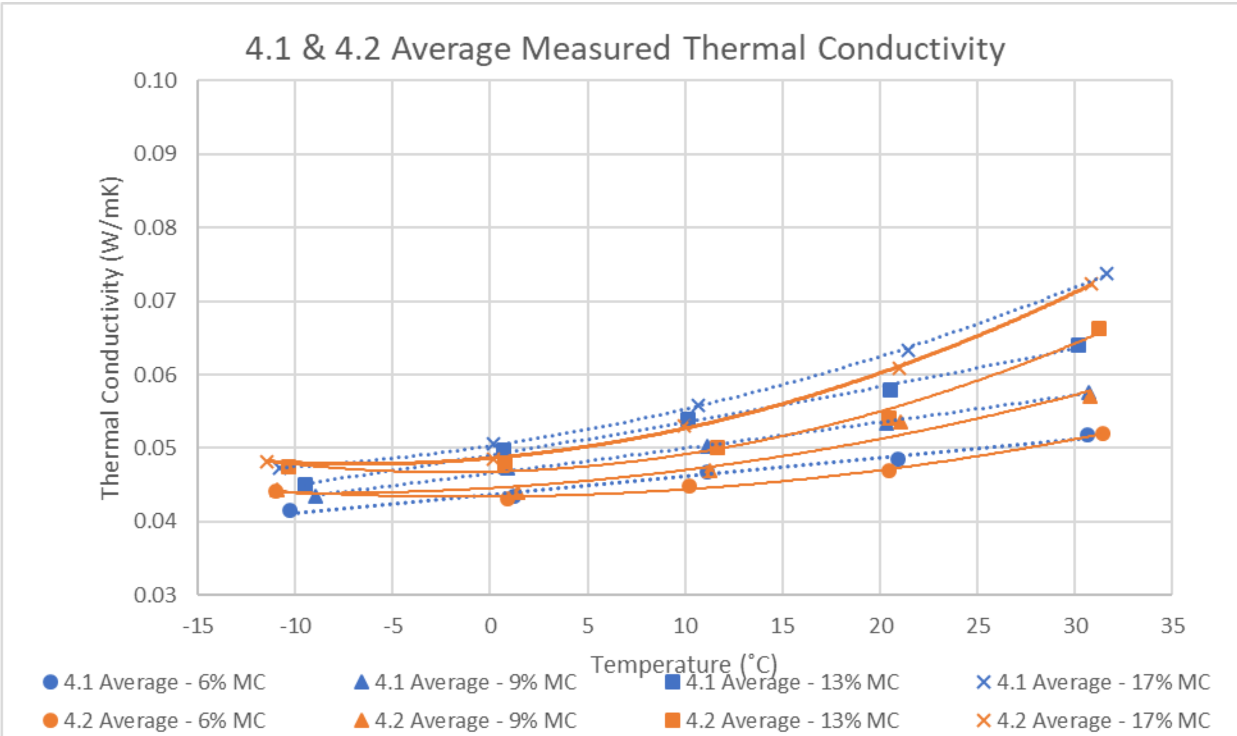


Figure H.57 – Thermal Conductivities for Product 4.1 & 4.2 for Full Temperature and Relative Humidity Range..

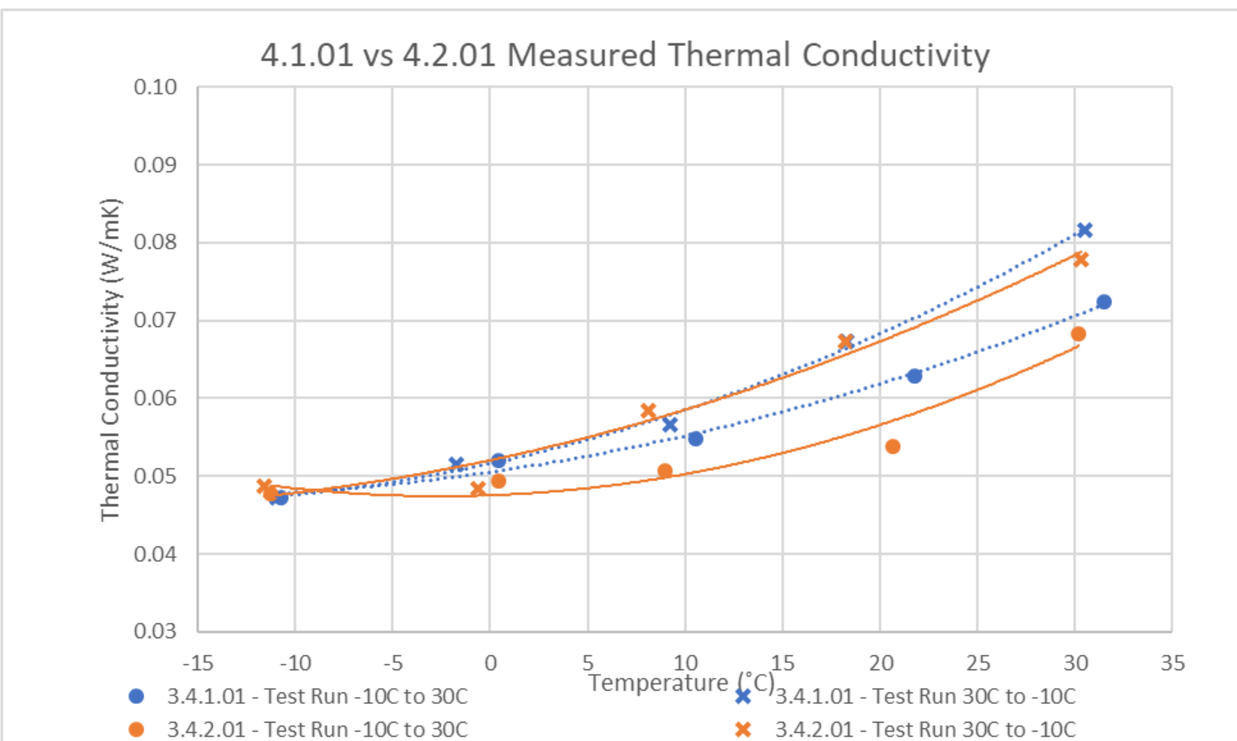


Figure H.58 – Thermal Conductivities for Specimen 4.1.01 & 4.2.01 at 95% Relative Humidity Chamber Conditions.

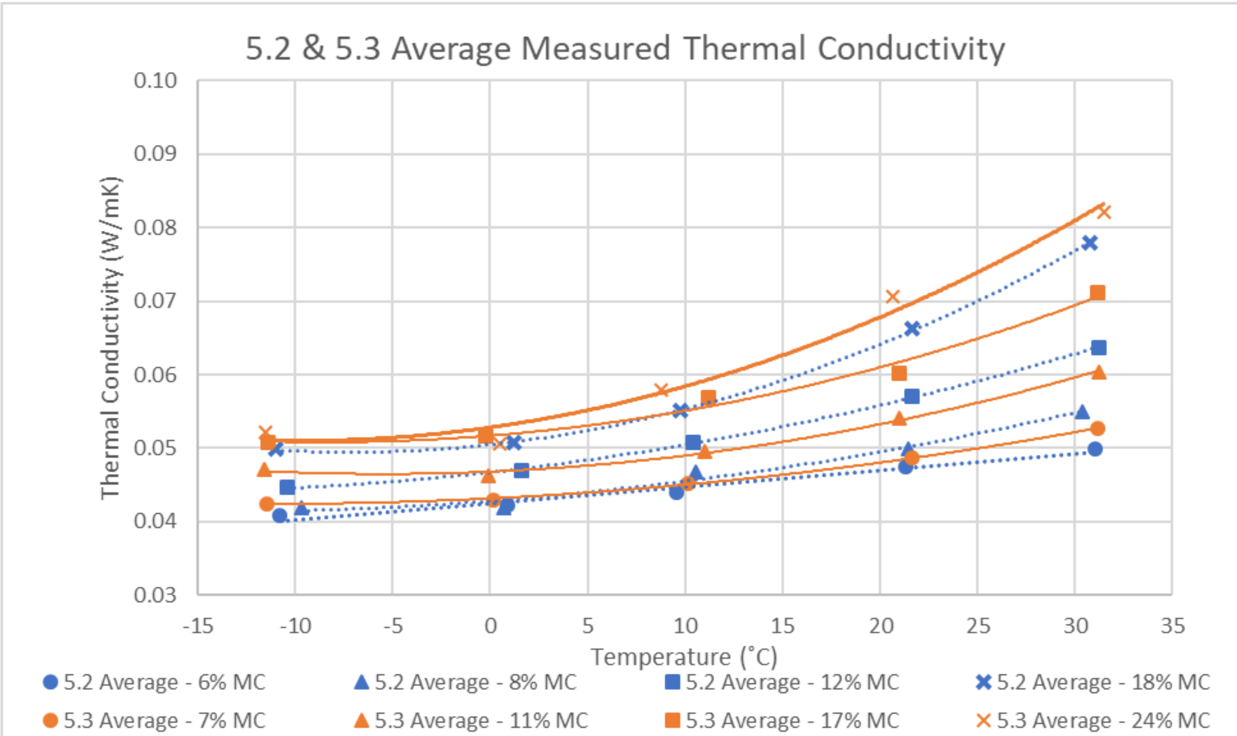


Figure H.59 – Thermal Conductivities for Product 5.2 & 5.3 for Full Temperature and Relative Humidity Range..

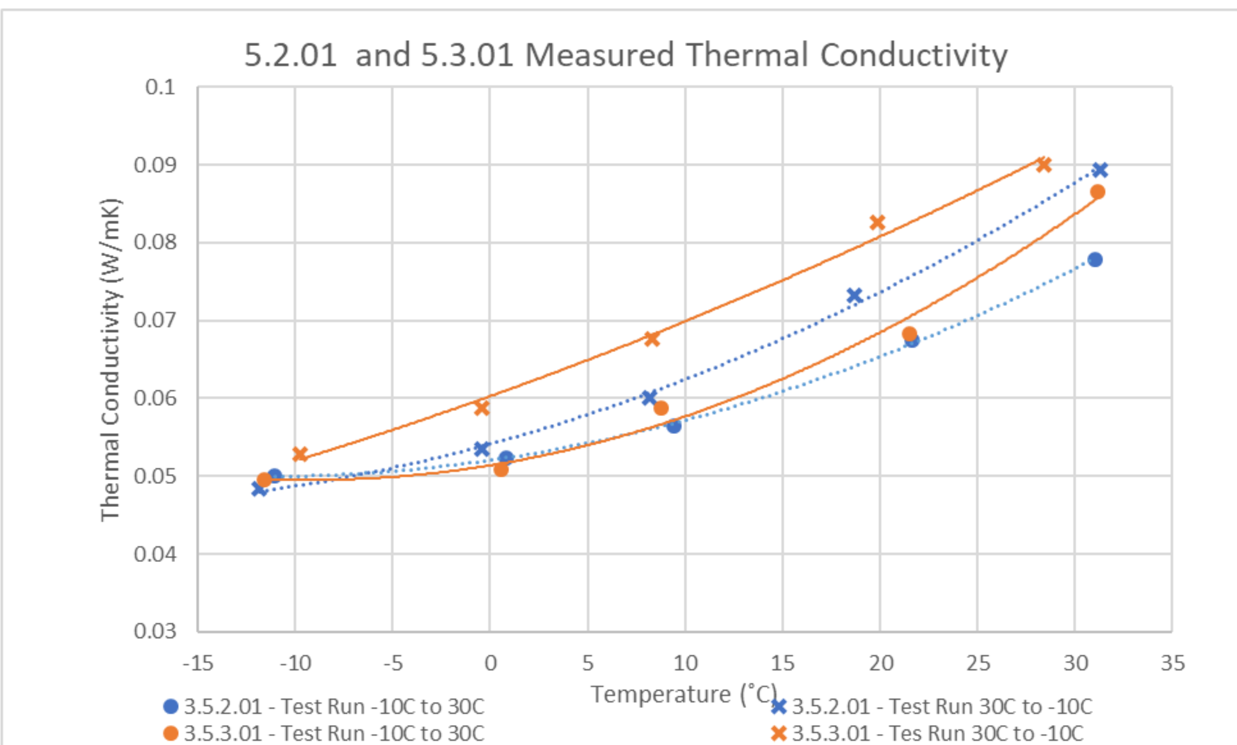


Figure H.60 – Thermal Conductivities for Specimen 5.2.01 & 5.3.01 at 95% Relative Humidity Chamber Conditions.

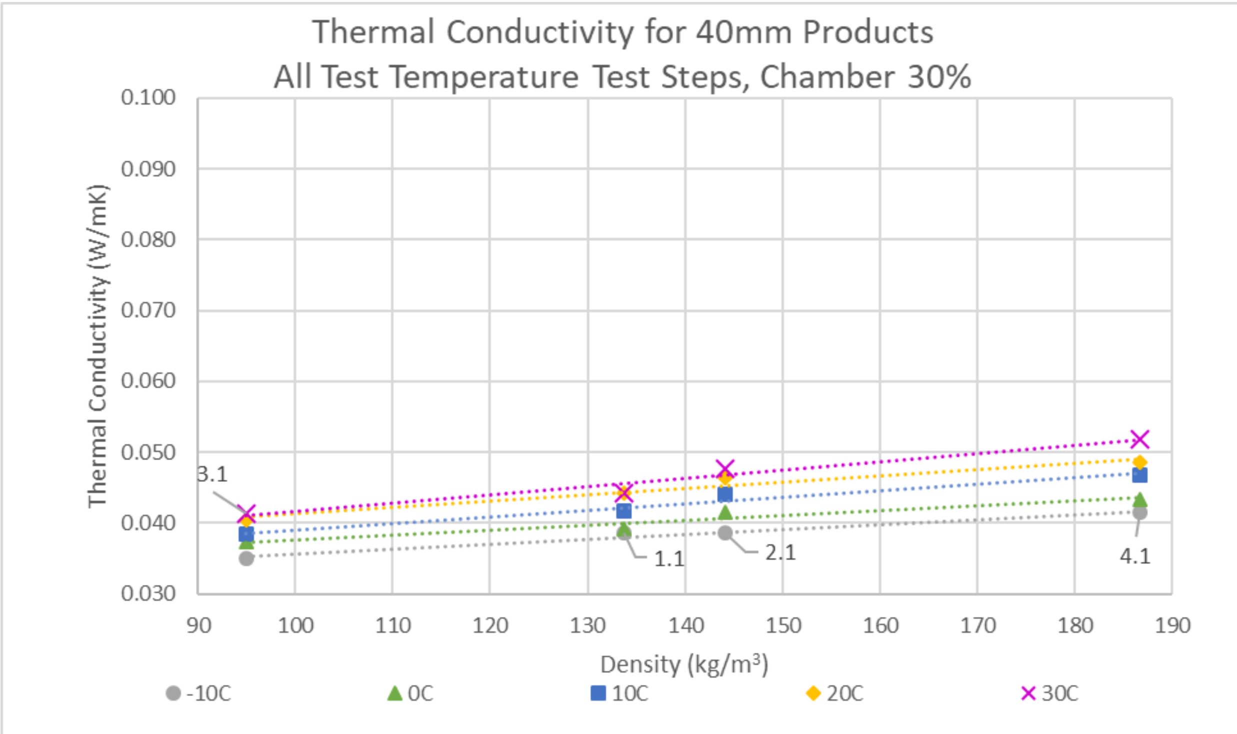


Figure H.61 – *Thermal conductivity vs Density for 40mm Products Pre-Conditioned at 30% Relative Humidity.*

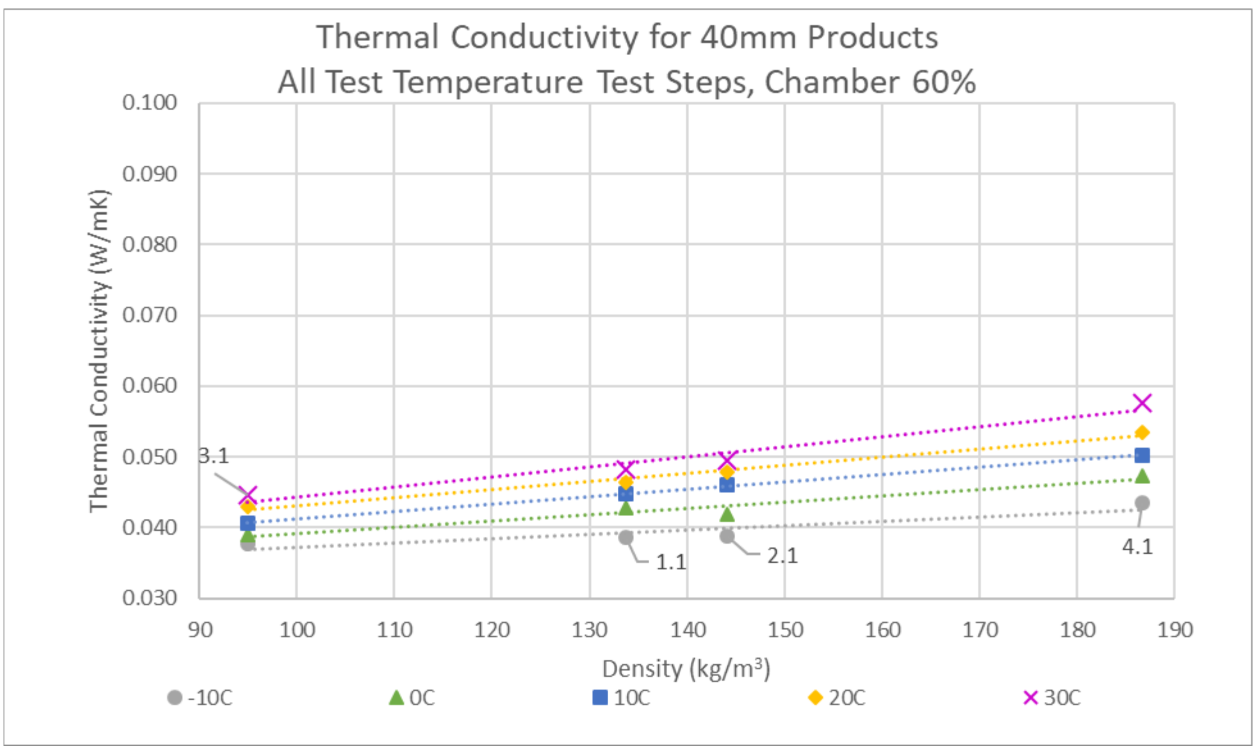


Figure H.62 – *Thermal conductivity vs Density for 40mm Products Pre-Conditioned at 60% Relative Humidity.*

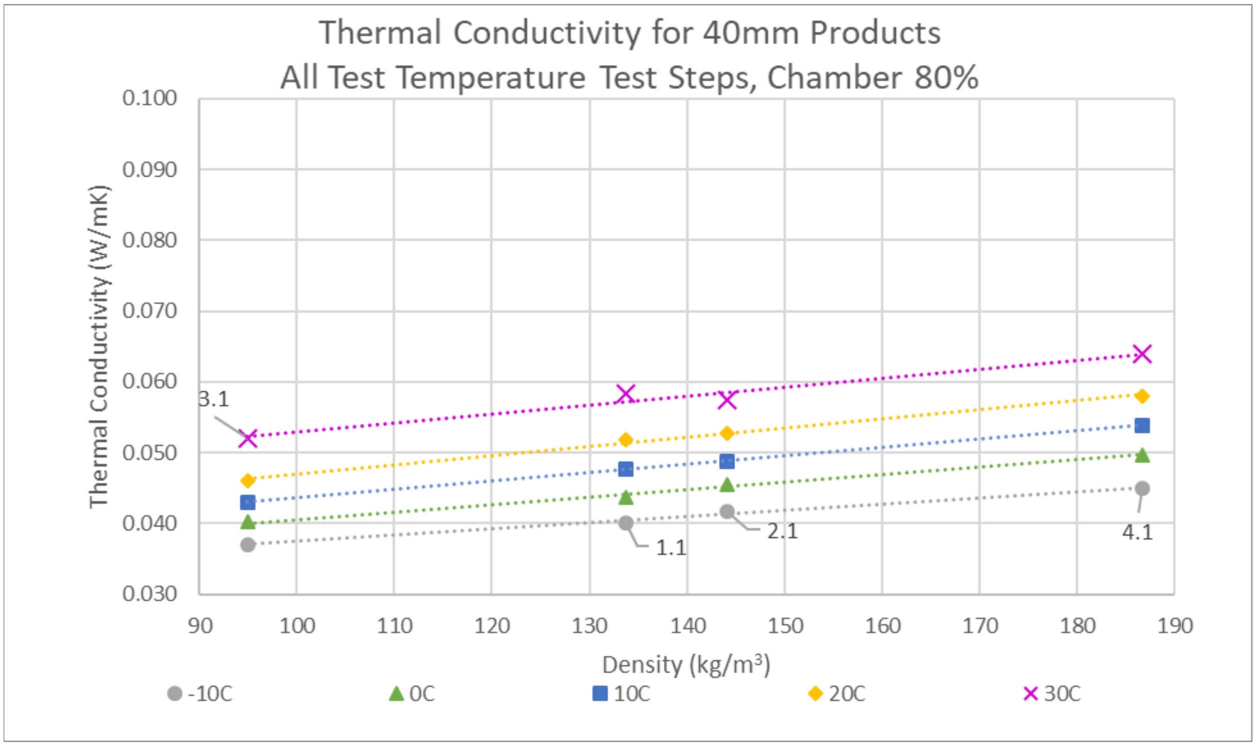


Figure H.63 – *Thermal conductivity vs Density for 40mm Products Pre-Conditioned at 80% Relative Humidity.*

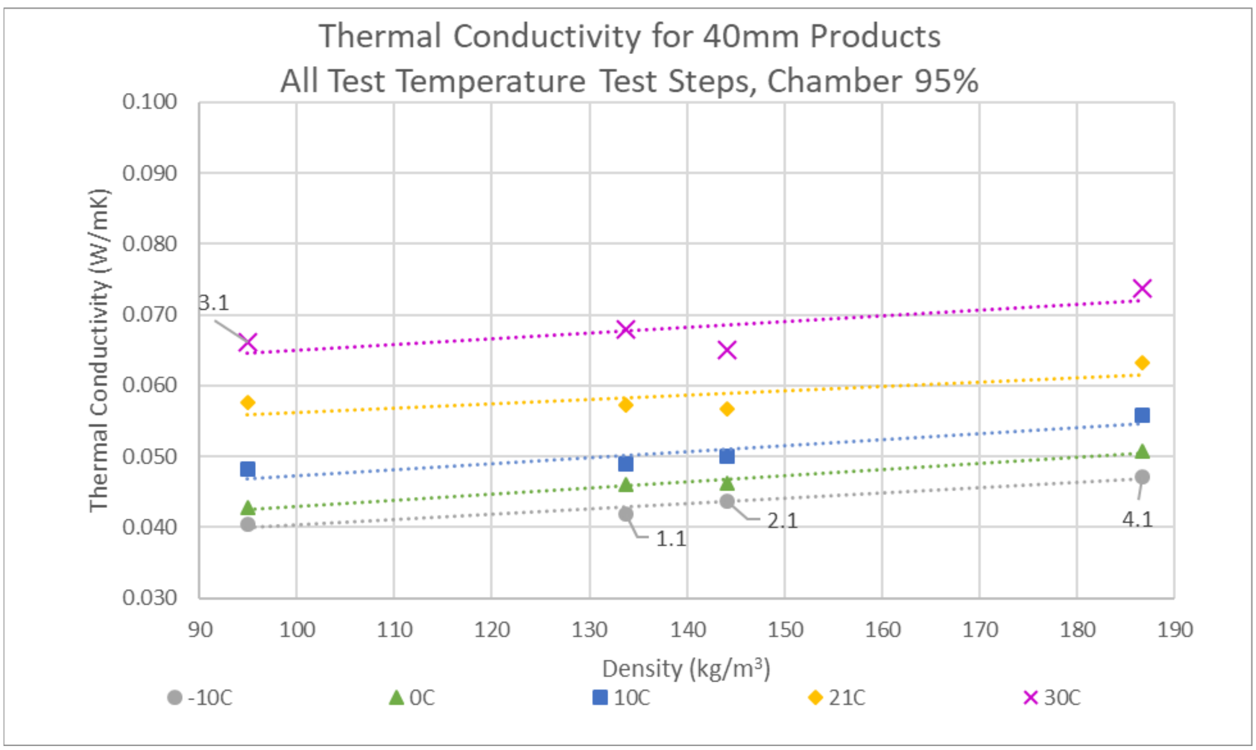


Figure H.64 – *Thermal conductivity vs Density for 40mm Products Pre-Conditioned at 95% Relative Humidity.*

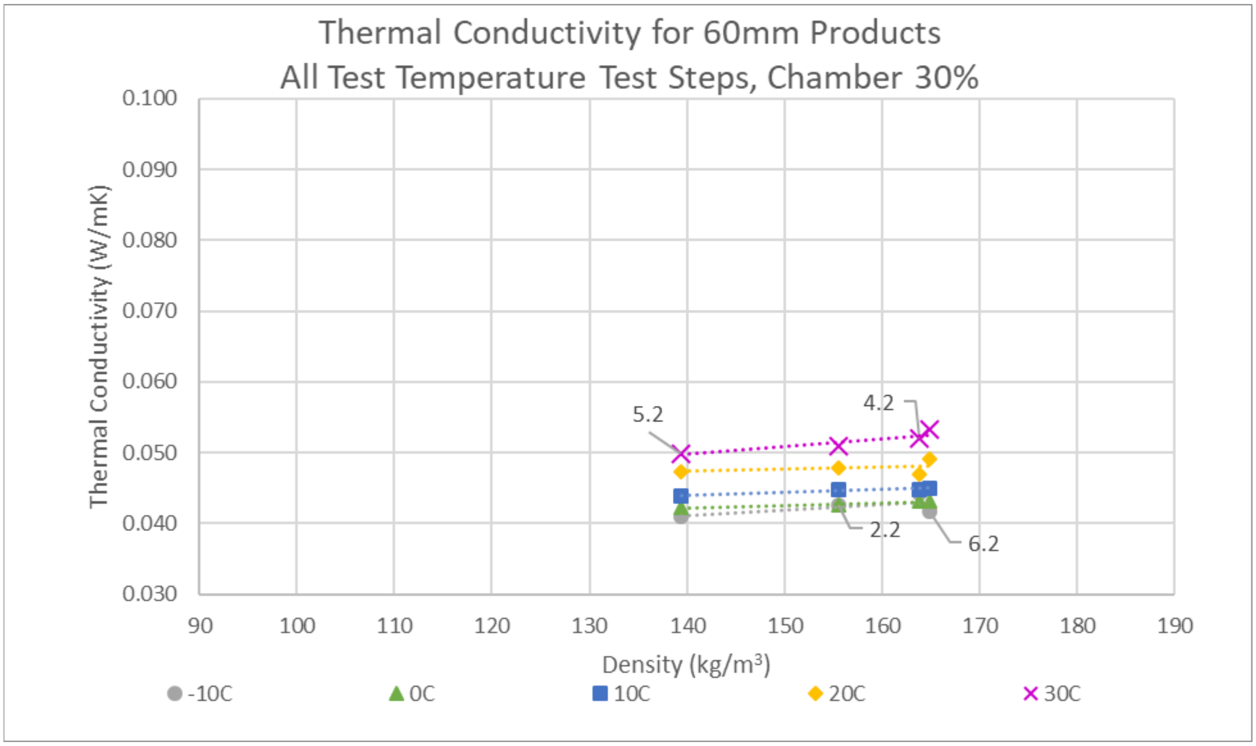


Figure H.65 – *Thermal conductivity vs Density for 60mm Products Pre-Conditioned at 30% Relative Humidity.*

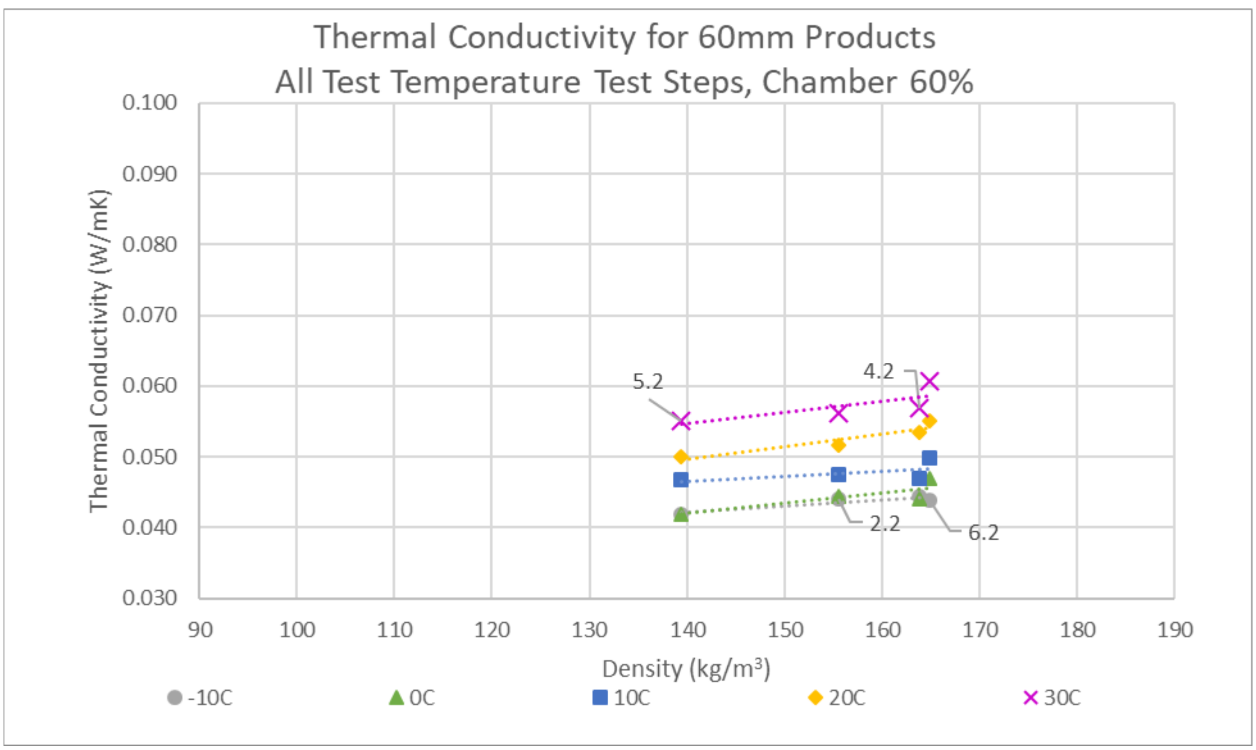


Figure H.66 – *Thermal conductivity vs Density for 60mm Products Pre-Conditioned at 60% Relative Humidity.*

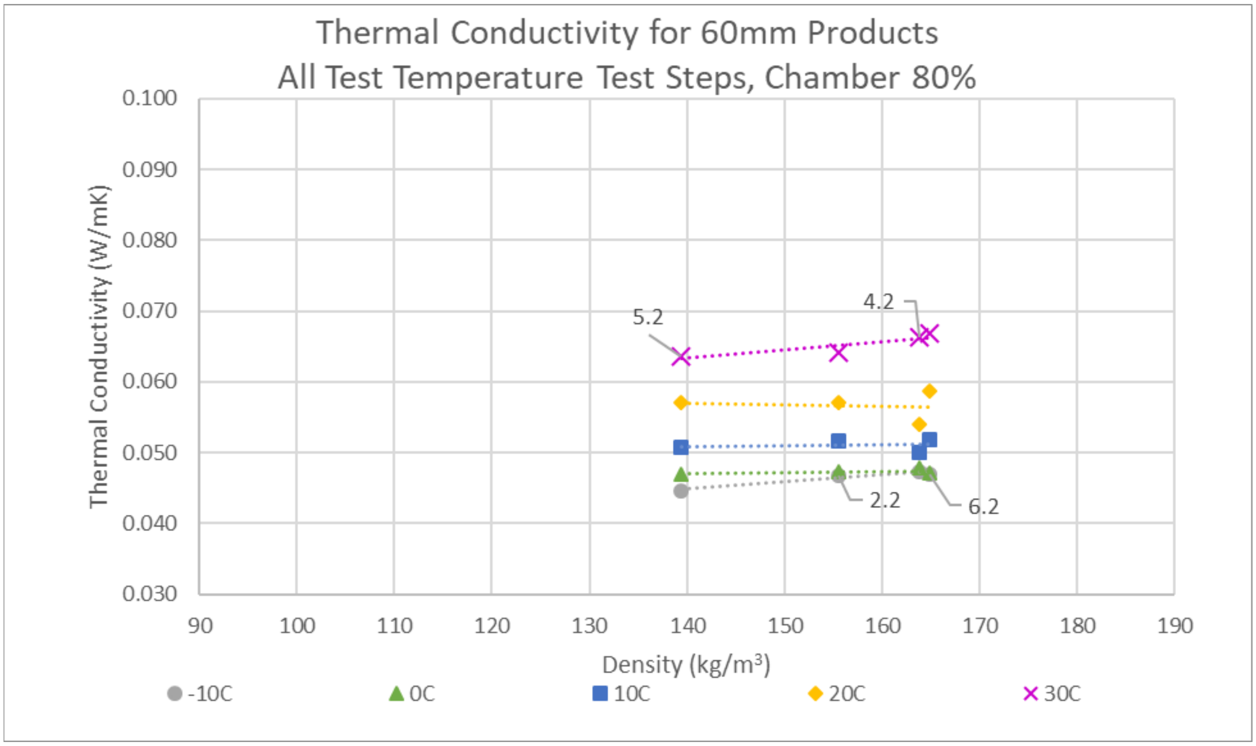


Figure H.67 – *Thermal conductivity vs Density for 60mm Products Pre-Conditioned at 80% Relative Humidity.*

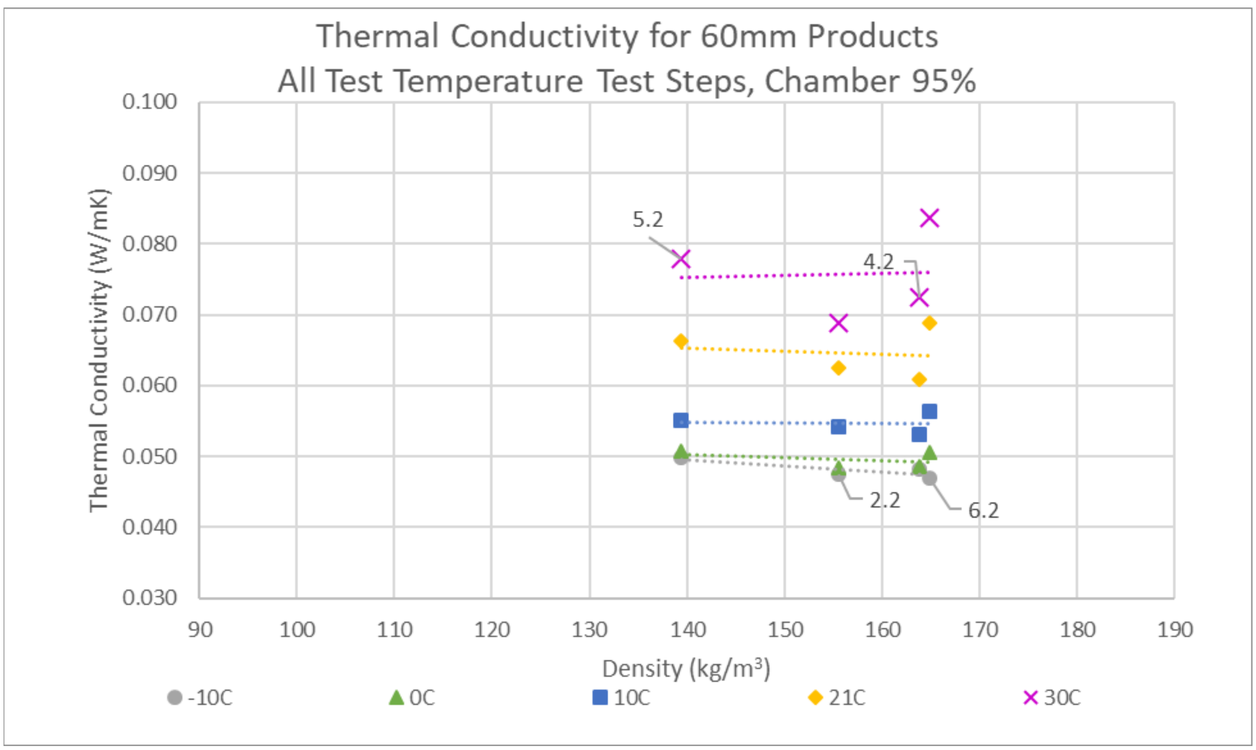


Figure H.68 – *Thermal conductivity vs Density for 60mm Products Pre-Conditioned at 95% Relative Humidity*

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