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The Impact of Aging on the Effective Thermal Conductivity of Foam Insulation: A Simulation Investigation Using Laboratory Characterization Data

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Abstract: *The thermal conductivity of the insulating materials is fundamental in designing high performance building envelopes. This property is often advertised using a single value that is implied to be constant, though research shows that most insulating materials have an effective conductivity that may change over a range of environmental parameters, such as temperature and moisture levels. In this research project, various polyurethane and polyisocyanurate materials are analyzed in order to determine how the effective conductivity is altered by accelerated aging, obtained through exposure to high temperature, moisture, and freeze-thaw cycling. The measured results are used in hygrothermal simulations to determine the assumed and actual performance of insulating materials in the context of high performance wall and roof assemblies in cold climates. Results show that the effects of aging and environmental temperature have a higher impact on the performance of polyisocyanurate materials than polyurethane materials. Additionally, high moisture levels contribute to lower performance in all foam materials, with open cell materials experiencing the greatest performance reduction.*

Keywords: *thermal conductivity, foam insulation, aging, hygrothermal modelling, cold climate*

INTRODUCTION

Effective Conductivity

In building envelopes, the insulation layer plays an important role for limiting the heat flux exchange. The performance of insulation is quantified by thermal conductivity, a property that indicates the rate of heat transfer through a given material thickness. Advertised thermal conductivities of insulating materials are determined through laboratory tests according to codified procedures, such as the ASTM C518 standard test method for steady-state thermal transmission properties using a heat flow meter apparatus (ASTM C518, 2015). This methodology requires that materials are tested at a mean temperature of roughly 24°C using a temperature delta of 20°C in a one-dimensional heat flow meter. However, research has shown that the thermal conductivity results obtained through the ASTM C518 may be misleading for determining the actual performance of building insulating materials in realistic environments. (Berardi & Naldi, 2017). Although the ASTM C518 standard only requires measurements at one average temperature, it is often reported that at lower temperatures, the conductivity reduces. Other standards have suggested that the reported thermal properties of materials should be measured under conditions closer to the final applications (ASTM C1058).

Temperature dependent conductivity can be explained through basic state of matter laws in physics: as the temperature of a material increases, the molecules of the material vibrate and move faster, allowing for increased rates of heat transfer through conduction. While further research suggested that most fibrous insulation materials have a linear relationship between their conductivities and the temperature, it has been found in some foam insulation materials, such as polyisocyanurate, the conductivity has a non-linear relationship with environmental temperature and may experience increased thermal conductivity at cold temperatures (Berardi & Naldi, 2017). This effect occurs due to the condensation of certain blowing agents within the foam cells, such as the pentane found within polyisocyanurate (Berardi, 2017). Research shows that insulating materials also have moisture content dependent conductivities due to the relatively high conductivity of water compared to the conductivity of foam insulations (Muller-Steinhagen & Ochs, 2005).

Aging Effects (Environmental Exposure)

Over time, foam insulation materials experience three stages throughout their aging process. Early in the life cycle, the conductivity of a foam insulation material increases at a relatively high rate, which slows down to a lower rate for most of its life until the conductivity eventually plateaus. This aging model is often considered to be driven by the blowing agents escaping from the cells in the foam material (Bhattacharjee et al., 1994).

The effect of aging in foam materials is seen in both closed cell polyurethane and polyisocyanurate materials. One of the most impactful aging effects on the thermal conductivity is the diffusion of the highly insulating blowing agents, and the infusion of air from the environment which may carry moisture into the material. These two effects begin to occur immediately after the manufacturing process, but the rate at which the gas

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movement occurs is much faster for the infusion of outside air than for the diffusion of blowing agent gasses. It is suggested that the infiltration of exterior air takes place over the first 1-2 years of the material life cycle, while the diffusion of blowing agent gasses take place over 10-20 years (Shukla, 2017). This sheds light on the model presented in Fig. 1, where initially the conductivity of a foam material increases rapidly (the effect of air infiltration), and then slowly plateaus (the effect of blowing agent gasses diffusing expires).

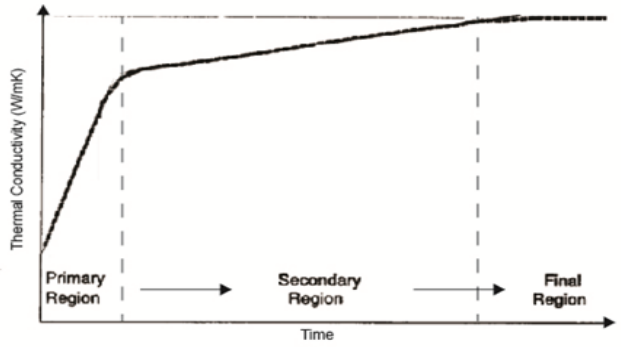

Figure 1: Typical Aging Curve of Insulating Plastic Foam (Bhattacharjee et al., 1994)

In foam materials, the blowing agents have evolved over time (Ross, 2005). Development of blowing agents have been pushed by environmental regulations such as the Montreal Protocol of 1987. CFC (chlorofluorocarbons) and HCFC (hydrochlorofluorocarbons) blowing agents were banned due to issues with ozone layer depletion. Non-ozone depleting HFCs (hydrofluorocarbons) are widely used today in polyurethanes while Pentane gases are used in polyisocyanurates. Plans to phase out and replace HFCs with HFOs (hydrofluoroolefins), which have a lower global warming potential, are being initiated. As blowing agents evolve, it is important to revisit how the new materials behave as a result of aging effects, as investigations of newer foam materials are lacking.

As the effects of material aging are explored, the final effective conductivity becomes more important. Currently, the long-term thermal resistance rating (LTTR) is the Canadian standard value used for advertising the long term thermal conductivity value of foam insulations. The LTTR of a material is described in the CAN/ULC-S770 (2015) standard as the conductivity of the material after 5-year storage in a laboratory setting. The LTTR value is assumed to be close to the conductivity in the final region in the aging curve. The CAN/ULC-S770 (2015) standard also provides the framework for determining the LTTR of a closed cell foam insulation sample at an accelerated rate, through the thin slice stack method. Due to the progressively reduced thickness of the material samples, and consequently, to the higher surface area to volume ratio, the insulating blowing agent gasses are able to escape at a faster rate, and a higher percentage of the original blowing agent molecules are replaced with air. This allows the samples to undergo a simulated aging of five or more years over the course of a few months.

A major issue with the LTTR method is that it assumes only diffusion of the blowing agent gasses have an effect on the aged thermal conductivity of the material, and disregards environmental conditions that materials would be exposed to outside of a laboratory environment, such as varying moisture levels and temperature ranges, as well as polymer degradation over time which is not reflected in the thin slice method. In particular, the polymer degradation could be simulated through heat exposition, rather than reducing material thickness through the thin slice method (Ludwick et al, 2008).

It has also been found that as polyurethane foam materials undergo freeze-thaw cycling, more moisture is absorbed into the material when submerged (Garber-Slaght, 2012). This research suggested that a foam material undergoes more freeze-thaw cycles, the polymers degrade and allow the cells to absorb more moisture. As the conductivity of a material will increase as the water content rises, the effect that freeze-thaw cycles have on a foam materials ability to absorb and store moisture may hence be very important.

Objectives

This study explores the effects of environmental weathering and aging, through exposure to high temperature, moisture, and freeze/thaw cycles, on the temperature and humidity dependent conductivity of foam insulating materials. Using this information, hygrothermal models are developed to assess how insulation materials perform over the life cycle of a building under real environmental conditions.

Two major outputs are developed in this research. The first major output takes the measurements that indicate conductivity of the materials over a range of temperatures and moisture levels, and determines the effect that the various aging processes have on the temperature and humidity dependent conductivities. This data is then used for further analysis of the materials within the context of a building envelope. The second output will be the results of hygrothermal simulations for each material simulated in various wall and roof assemblies in Canadian climates. This output allows for further analysis regarding which materials are better suited to be used under certain environmental conditions or assembly designs. The results of this study will allow designers to further understand the dynamic nature of the foam insulation materials that were analyzed and how their performances may change over

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the life-cycle of a building. Valuable information regarding the true thermal performance of insulating materials under specific environmental conditions can lead to more accurately designed wall assemblies that aim to meet a certain R-value within the envelope.

TEST METHODOLOGY

Material Samples

The material samples used in the test methodology include various types of polyurethane (labelled as PU-x) and polyisocyanurate (labelled as PI-x). For the purposes of the test methodologies, all samples were cut to a thickness of 50mm, except for PI-A which was only available in 25mm thick sheets. The assortment of materials was chosen to span over the range of commonly used insulations types. The two closed-cell polyurethane materials (PU-A and PU-B) from separate manufacturers are similar in their thermal performance and density, and reflect standard medium-high density polyurethane. The two open cell polyurethane materials are very different from each other. PU-C reflects standard low density open-cell foam insulation, while the PU-D material is novel open cell foam that is advertised to act as a vapour permeable exterior insulated sheathing membrane which has a relatively high density for open cell foams. While open cell foams theoretically avoid some of the aging effects due to the escape of blowing agent gasses, it will still be important to investigate how the aging affects these samples. The polyisocyanurate sample PI-A is a high performance aluminium faced material designed to perform in assemblies with thickness limitations, and for this reason it is manufactured in sheet 25mm thick. Material PI-B reflects a standard polyisocyanurate, with a cardboard facing available in 50mm sheets. Table 1 reports the advertised conductivity and density of the selected materials.

Table 1: Tested Materials

	Material	Conductivity [W/ m K]	Density [kg / m^3]
Polyiso | Polyurethane	**PU-A (Closed Cell) 50mm**	0.0233	28.9
	PU-B (Closed Cell) 50mm	0.025	35.0
	PU-C (Open Cell) 50mm	0.0378	6.83
	PU-D (Open Cell) 50mm	0.0333	17.2
	PI-A (Closed Cell) 25mm	0.0173	32.0
	PI-B (Closed Cell) 50mm	0.0248	32.0

Conductivity Measurements

For each material sample, the initial step involved testing its thermal conductivity in a heat flow meter. According to the CAN/ULC-S770-15 “Standard Test Method for Determination of Long-Term Thermal Resistance of Closed-Cell Thermal Insulating Foams”, materials should be tested in accordance with ASTM C518.

In order to gain a full understanding of the material performance in a Canadian climate the samples were also tested at a range of mean temperatures from -10°C to 30°C, in order to determine the temperature dependent conductivity. Due to limitations with the cooling power of the testing equipment, the tests at a mean temperature below 0 ° C ran with a temperature delta between the two plates of the device reduced to 10 ° C down from 20°C used for higher temperatures.

These measurements allowed to indicate how each of the samples perform over a range of temperatures typically found in a Canadian climate, and aimed to know if samples had a thermal conductivity linearly dependent from the temperature or if the material experienced unusual conductivity trends as some research suggested.

Elevated Temperature

The most important aspect of the simulated aging method is not just to determine a single conductivity value such as the LTTR, but to understand how the effective conductivity over a range of temperatures is affected over the aging process. Through accelerated aging, the material samples can move through an aging curve within much shorter periods. A low temperature oven at 60°C was used in this study and samples were aged for 4 months, while their conductivity was measured monthly in order to gain a better understanding of the effect on performance. These set points were determined in accordance to the methodology updated by Berardi & Nosrati (2017). Using the Arrhenius Equation, and material values such as activation energy (the minimum energy required for chemical reactions to occur in a given material), the time spent aging at 60°C can be equated to real time under realistic environmental conditions (Berardi & Nosrati, 2017).

Moisture Exposure

For the purpose of determining the moisture dependent conductivity of the materials, these were also exposed to a range of moisture levels, from being dried to being fully submerged. An environmental chamber has been designed and built in order to create a steady environment at a set temperature and humidity level. This chamber was used to expose the materials to environments of 40%, 80%, 90%,

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and 95% RH and a constant temperature of 30°C for at least seven days at each set point. In addition to these set points, the materials were also dried in a low temperature oven at 60°C, and fully submerged in water to determine the material properties at minimum water content and maximum saturation. After the materials have been acclimated to each set point, they were wrapped with a non-insulating, vapour impermeable wrapping in order to preserve the state of the material throughout the measurement in the heat flow meter.

As the water storage function of materials generally shows that foam materials absorb more water only at very high moisture levels, more set points above 80% RH were selected in order to observe the critical changes in the effective thermal conductivity and moisture content at high moisture levels, compared to the set points below 80% which are expected to see minimal differences in the material performance.

Freeze – Thaw Cycling

Research has suggested that undergoing many freeze-thaw cycles may increase the water storage capacity of foam materials due to degradation of the foam polymers. Consequently, the effect of freeze-thaw cycling was investigated on the materials regarding both their effective conductivity and moisture storage capacity. As the materials experienced many freeze-thaw cycles in a cold climate, this method provided insight as to how the materials were affected over time in a realistic setting. The test chamber cycled between 40° C and -30° C on a 12-hour loop. More details about the several aging tools used for the tests described in this paper are reported in Berardi and Nosrati (2018).

The materials were exposed to approximately 150 freeze-thaw cycles, and their thermal conductivity was measured after approximately 75 cycles, and again after 150 cycles at which point, the samples were also exposed to high moisture levels (80, 90, 95% RH and submerged) in order to determine the extent of increased moisture storage capacity caused by the freeze-thaw cycling.

RESULTS

In this section, the measured results for a selected set of materials after undergoing the test methodologies previously described is reported and discussed. As a consideration for space, redundant results of similar materials were omitted, with focus placed on one series of result for each of closed cell polyurethane, open cell polyurethane and closed cell polyisocyanurate for analysis and discussion.

Elevated Temperature Results

In Figs. 2-4, the results for material PU-A, PU-D and PI-B respectively are shown. Fig. 2 reflects the idea that closed cell polyurethane foam materials age faster early in the process and eventually reach a plateau. The change in the first month of aging is greater than the rate of change later in the process. It is also interesting to note that as this material ages, an increase in conductivity at low temperatures appears.

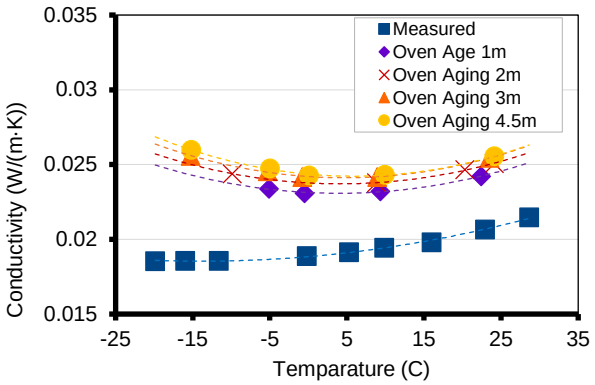

Figure 2: Effective Conductivity of Aged Closed Cell Polyurethane (PU-A).

In Fig.3, it can be seen that after aging, this effect is not seen in open cell polyurethane, indicating that there may be an issue with the blowing agent within the material after some aging has occurred. As expected, the change in performance of open cell polyurethane is very minimal over the process of accelerated aging. Since there is no blowing agent within the cells, the same effect shown in closed cell materials was not evident. While the effect of aging is minimal in these open cell materials, it is important to note that the starting conductivity is already much higher than that measured for the closed cell materials.

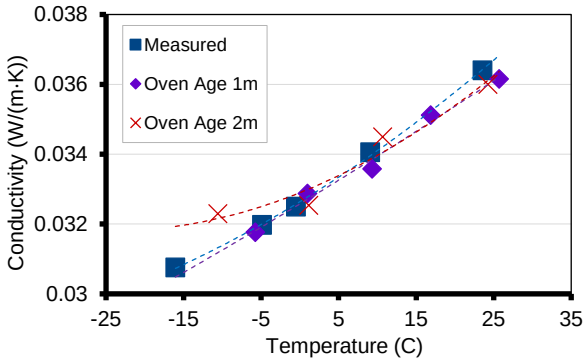

Figure 3: Effective Conductivity of Aged Open Cell Polyurethane (PU-D).

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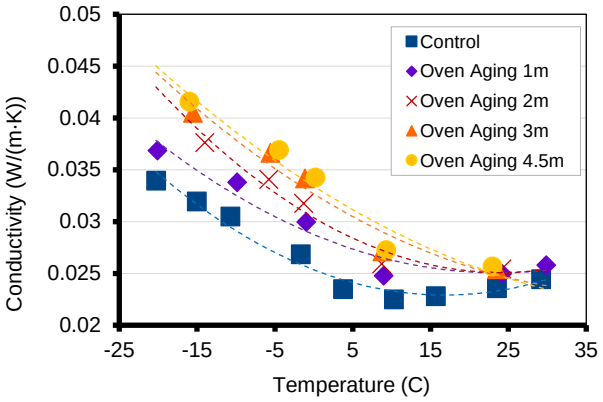

Figure 4: Effective Conductivity of Aged Closed Cell Polyisocyanurate (PI-B).

In the polyisocyanurate material (Fig. 4), it was observed that there is an evident increase in the conductivity at low temperatures in non-aged material. Interestingly, this effect appears to become even greater after aging has occurred. While logic may suggest that as the blowing agent which is causing the issue escapes, the effect of increased conductivity at low temperatures would actually be reduced, this does not appear to be the case. This may be due to the more rapid infiltration of air increasing the overall conductivity, while the blowing agent molecules that escape at a slower rate remain in cells of the material sample and continue to condense at low temperatures. An important note to take from the aging of polyisocyanurate is that the difference in performance between a pristine and aged sample when measured at 24°C in accordance with LTTR measurements is far smaller than the difference in performance after aging at 60°C.

Moisture Exposure Results

In Table 2, the mass of the samples measured after exposure to a range of moisture levels are reported.

Table 2: Material Mass (g) at Varying RH% Levels

Material	RH level				
	Dry	40%	80%	90%	95%
PU-A	116.7	117.5	118.5	119.3	122.6
PU-B	160.3	162.9	163.8	165.5	167.9
PU-C	25.8	26.3	26.8	27.68	36.5
PU-D	60.3	61.1	61.7	64.5	69.6
PI-A	80.7	81.3	82.8	83.9	85.6
PI-B	162.3	164.4	170.8	185.1	196.8

The water content between dry samples and 95%RH exposure are fairly significant, with the closed cell polyurethane materials both absorbing approximately 5% of their mass, open cell PU-C absorbing 44% of its mass, PU-D absorbing just over 15% of its mass, PI-A absorbing 6% of its mass, and PI-B absorbing up to ~21% of its mass, though the cardboard facing on the sample was responsible for absorbing a larger portion of the moisture. It is also clear that the majority of moisture storage begins to occur at 90%RH and higher.

At each of the moisture set points, the materials were also measured for conductivity across the same range of temperatures as previous measurements. These results are shown in figures 5-7 for PU-A, PU-D, and PI-B.

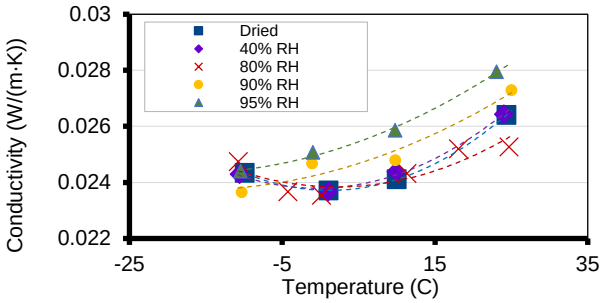

Figure 5: Effective Conductivity of Closed Cell Polyurethane across a range of moisture level (PU-A).

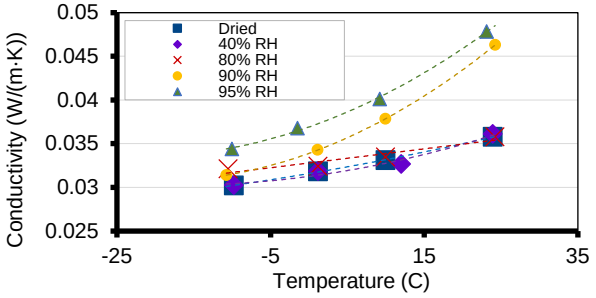

Figure 6: Effective Conductivity of Open Cell Polyurethane across a range of moisture level (PU-D).

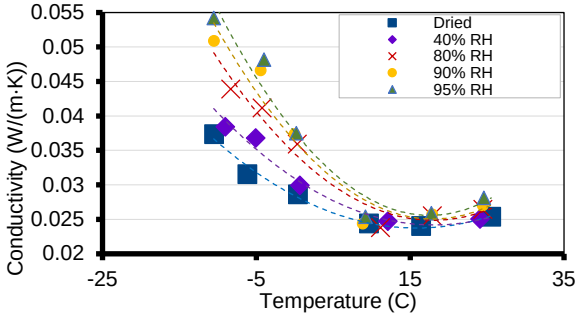

Figure 7: Effective Conductivity of Closed Cell Polyisocyanurate across a range of moisture level (PI-B).

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In Figs. 8-10, 3-axis graphics developed from the measured data in Fig. 5-7 respectively, display the phenomenon of changing effective conductivity over a range of temperature and humidity conditions. This type of representation will help bridge the gap between the practice of inaccurately simulating building envelopes through using a static material conductivity and the understanding that material conductivity is a function of the environmental conditions, and changes dynamically for temperatures and moisture levels.

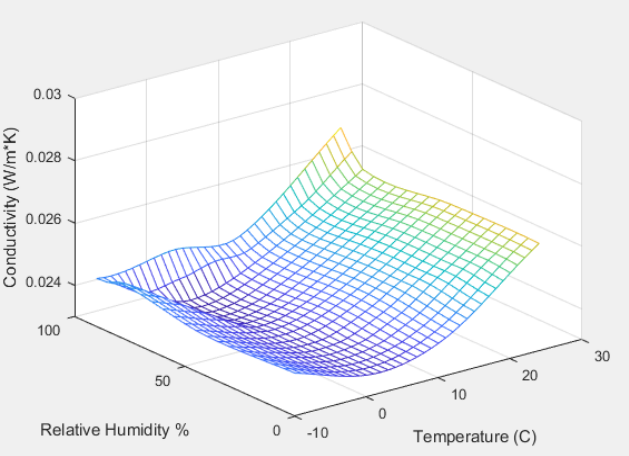

*Figure 8: Effective Conductivity (W/m*K) of Closed Cell Polyurethane across a range of moisture levels and temperatures (PU-A).*

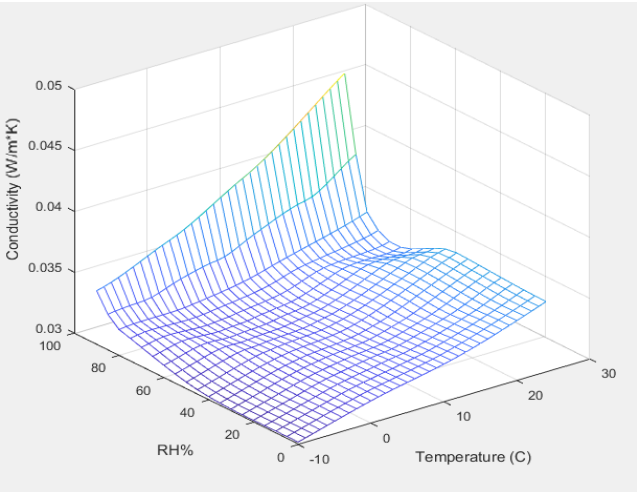

*Figure 9: Effective Conductivity (W/m*K) of Open Cell Polyurethane across a range of moisture levels and temperatures (PU-D).*

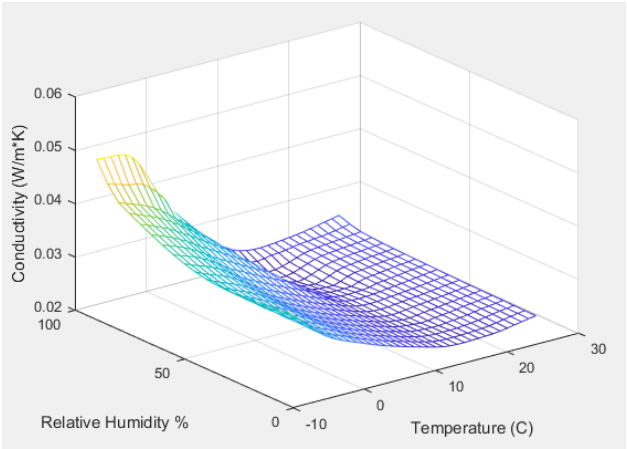

*Figure 10: Effective Conductivity (W/m*K) of Closed Cell Polyisocyanurate across a range of moisture levels and temperatures (PI-B).*

Through these graphics, it can be seen that in the three materials being explored, different relationships exist. In the closed cell polyurethane foam (Fig. 8), we see that the conductivity slightly increases as both temperature and humidity increase, and sees a slight increase in conductivity only at very low temperatures. The open cell polyurethane material (Fig. 9) has a similar relationship with environmental conditions, with the largest difference being the extent at which high moisture levels increase the conductivity. In the open cell material, the effect of high moisture dwarfs the effect of changing temperature.

For polyisocyanurate (Fig. 10), the material conductivity slightly increases with higher humidity, but also rapidly increases as the temperature decreases to lower values. An important distinction between the models can be seen in the z-axis scale, where it is shown that the effects of moisture and temperature are far greater in the polyisocyanurate material in figure 9. The model presented for polyurethane materials represents the expected result for most foam materials, as the increase in conductivity with both temperature and humidity is explained through basic material physics. In the result for polyisocyanurate, the reversed effect where conductivity increases at cold temperatures is due to the phenomenon previously discussed regarding the condensing of blowing agent gasses within the foam.

Freeze-Thaw Results

In the results measured before and after 150 freeze-thaw cycles, shown in Figs.11-13, the materials show results similar to what was seen in the heat accelerated aging results, though to a slightly lesser degree. In the two closed cell samples PU-A and PI-B, the material shows a slightly higher conductivity after the freeze-thaw cycles,

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while the open cell material has a relatively consistent conductivity over the freeze-thaw cycling. This indicates that similarly to heat accelerated aging, this aging method causes the foam polymers to degrade, allowing more of the insulating blowing agent to escape.

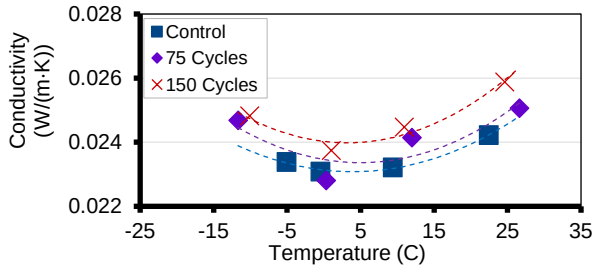

Figure 11: Effective Conductivity of Closed Cell Polyurethane after Freeze-Thaw Cycles (PU-A).

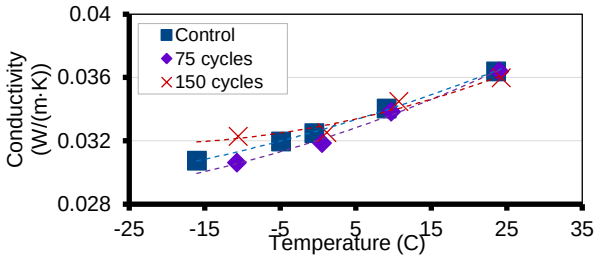

Figure 12: Effective Conductivity of Open Cell Polyurethane after Freeze-Thaw Cycles (PU-D).

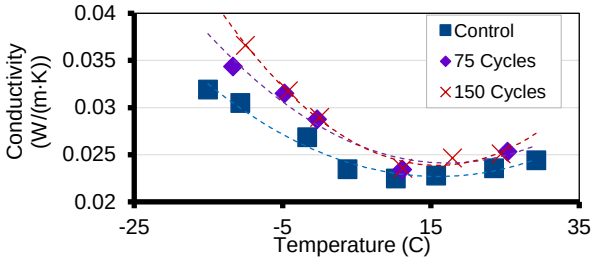

Figure 13: Effective Conductivity of Closed Cell Polyisocyanurate after Freeze-Thaw Cycles (PI-B).

HYGROTHERMAL SIMULATIONS

In order to determine the effect of temperature dependent conductivity on the performance of a building envelope under realistic conditions, the WUFI hygrothermal analysis software was used to perform hygrothermal simulations on wall assemblies using the tested materials.

Using the WUFI software, material files based on the results of the material investigations have been created. Each material incorporates the temperature and moisture dependent conductivity values found through measurements with the heat flow meter, as well as measured moisture storage function values, while other required material details were obtained through manufacturer technical data sheets. The simulations were conducted with a Toronto, ON. climate.

These materials were applied to basic wood frame construction assemblies shown In Figs. 13 and 14. Figure 13 is a standard stud wall assembly, typical to houses in a Toronto, ON climate. Figure 14 is the same assembly with an added layer of exterior insulation, typical of a wall renovation with the purpose of increasing the thermal resistance. In the simulations using Fig. 14, the investigated material was used as the exterior insulation layer only, in order to investigate the performance of each material with a mean temperature that is closer to the exterior environment. While in reality these wall assemblies have framing studs spaced throughout, in this 1-D investigation, only the portion of the wall section with insulation is considered. The simulations monitored the center of the investigated insulation layer, and outputs of the temperatures over the course of January and July at this location in the assembly were obtained. These temperatures were used with the temperature dependent conductivity curves developed through lab measurements in order to create a visualization of the dynamic effective conductivity over the duration of the simulation. These graphs reveal that when taking into account effective conductivity and aging, the thermal performance of a material varies based on the environmental conditions and the assembly design.

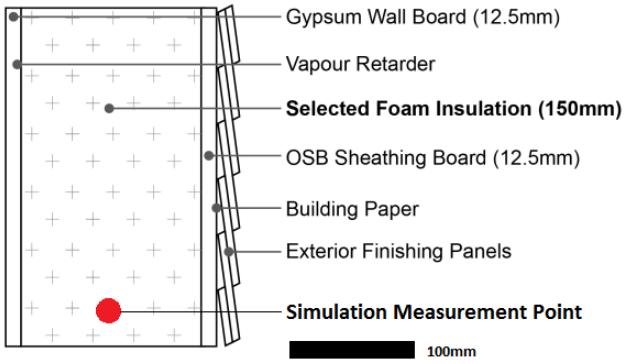

Figure 14: Standard Wood Frame Wall Assembly.

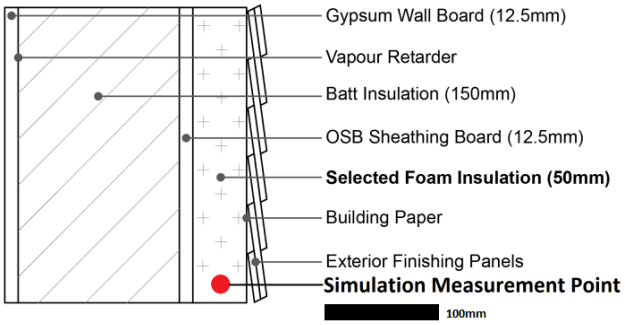

Figure 15: Exterior Insulated Wall Assembly.

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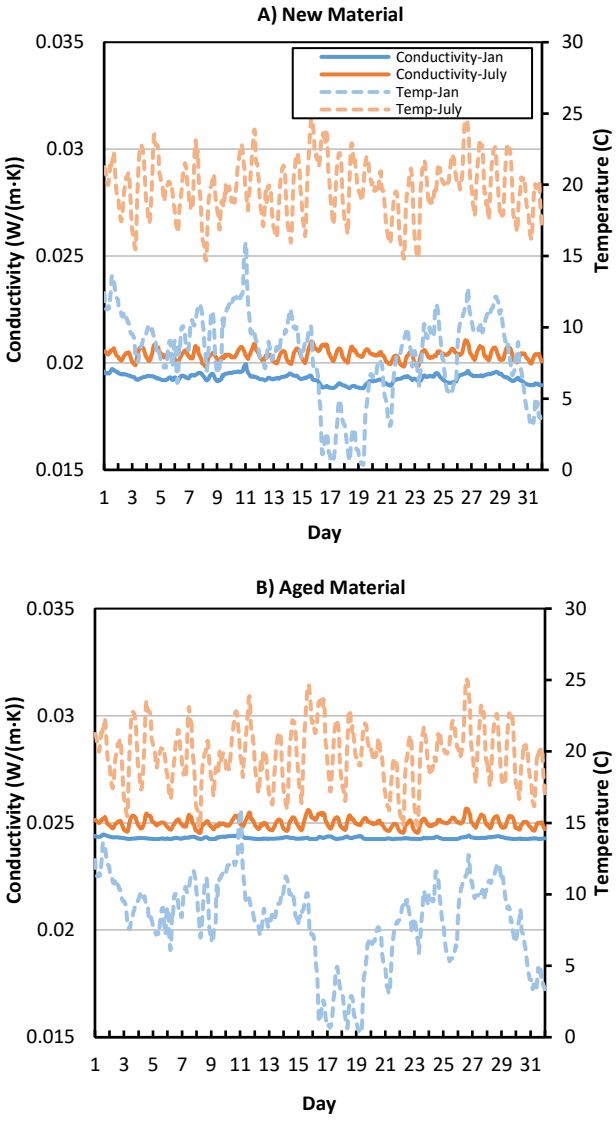

Figure 16: Effective Conductivity at Center of Interior Insulation Layer through January and July for New (Above) and Aged (Below) Material PU-A.

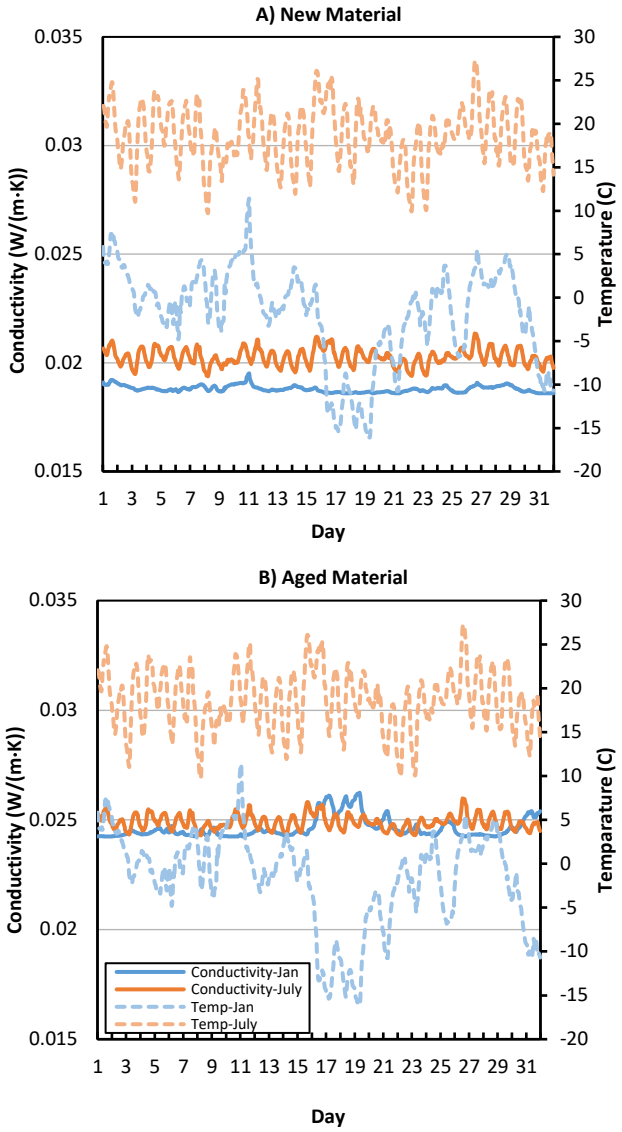

Figure 17: Effective Conductivity at Center of Exterior Insulation Layer through January and July for New (Above) and Aged (Below) Material PU-A.

The graph in Fig.16a displays the effective thermal conductivity of material PU-A within the wall assembly of Fig.14. It can be seen that over the course of both January and July, the material performance remains relatively consistent as it would be expected based on the unaged measurements of the material shown in Fig. 2. In Fig. 16b, the same wall assembly was simulated using the final aged values of PU-A. It can be seen that the effective conductivity remains consistent, though performs overall approximately 25% worse, as would be expected by the aging results in Fig.2.

In Fig. 17a, the material PU-A was simulated within the wall assembly of Fig. 15. The implication of monitoring this material when used as an exterior insulation layer is that the mean temperature within the material is closer to the exterior temperature. In Fig. 17b, this exterior insulation simulation was repeated using values of the final aged PU-A material. In Fig. 17, the results resemble what was found in Fig 16. Due to the relatively stable conductivity of PU-A over a range of temperatures, the performance is consistent wherever the material is used within the wall assembly.

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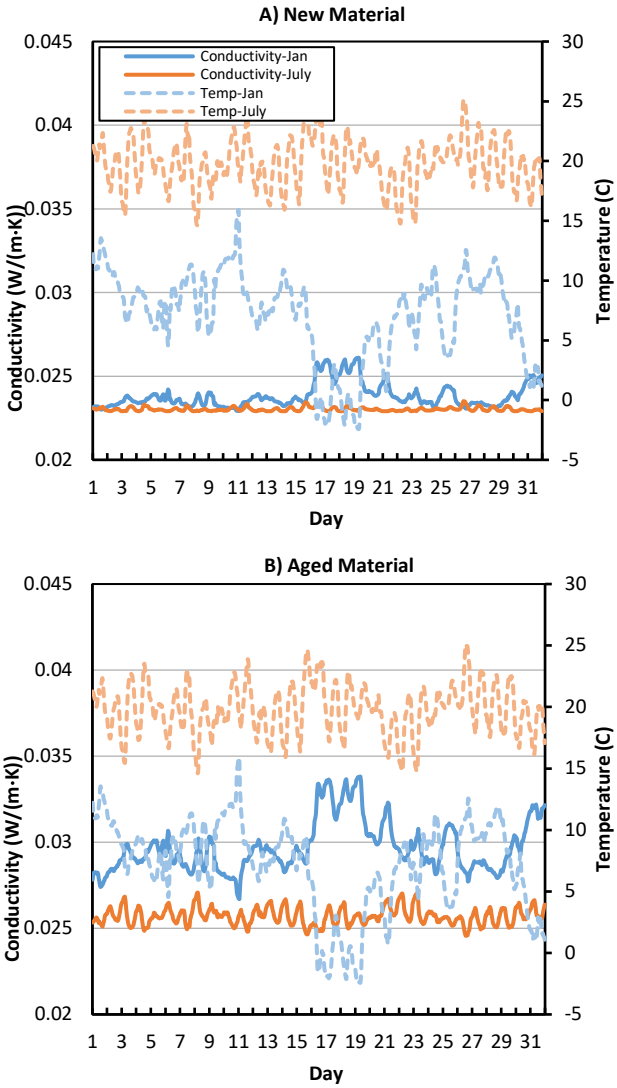

Figure 18: Effective Conductivity at Center of Interior Insulation Layer through January and July for Aged Material PI-B.

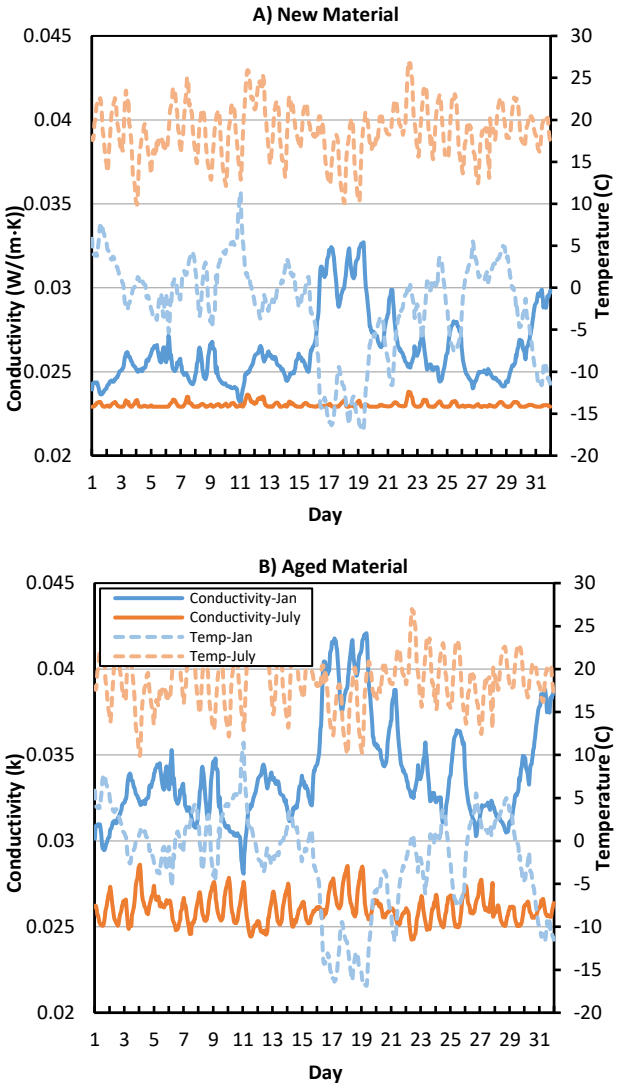

Figure 19: Effective Conductivity at Center of Exterior Insulation Layer through January and July for Aged Material PI-B.

In contrast to the results of PU-A, the material PI-B shows a very inconsistent temperature dependent conductivity, with major increases as the temperature is reduced and after aging. In Fig. 18, simulations using unaged and aged PI-B materials, reveal that the effective conductivity are less consistent during the coldest periods of January in both simulations, especially after aging (Fig. 18b). Additionally, when these simulations were repeated with the insulating material used as the exterior layer, the effective conductivity becomes even more variable over a range of temperatures. In Fig. 19, it can be seen that even before aging the PI-B material has massive swings in effective conductivity when used as an exterior insulation layer in the winter.

After aging (Fig. 19b), this effect becomes much worse, with nearly 40% reduction in performance during the coldest points of January, and significant inconsistency during July as well.

CONCLUSIONS

Constant conductivity values of insulating materials are typically used in building design and assessment. However, the thermal conductivity of insulating materials is affected by the operative conditions. Attention has focused on foam insulation such as polyurethane and polyisocyanurate, which exhibit less regular behavior, and larger changes in performance under varying conditions. Using constant thermal resistance values in design will

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result in actual building envelope performance that will vary from the calculated level, as it has been shown both trough experimental results and simulations. The results of these simulations have also shown the importance of understanding how a material performs within a given assembly, emphasizing the importance of simulating assemblies with accurate data for the purposes of high efficiency building, where decisions and calculations made during the design phase must accurately reflect material properties in order to have buildings performing at the expected level.

In the context of building simulation, the values presented in Figs. 8-10 can be far more accurate in determining the performance of a given envelope than if a singular value was given for a material conductivity. Through these findings, it can also be understood that there is no strict rule for how a given material will perform under a range of environmental conditions. Models developed through lab testing with one material cannot be used as a general rule applied to other materials. This emphasizes the idea that in simulations where a high degree of accuracy is required, software calculations must be carried out not only under the assumption of a changing effective conductivity, but that these models will differ between any given materials.

This paper aims to start a critical discussion about how the impact of temperature, moisture levels and material aging on the effective thermal conductivity affect (foam) insulation performance in building envelopes, and how issues that may arise from the changing effective conductivity may be mitigated in the design phase through the use of more accurate simulations taking into account extensive laboratory measured data.

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