THE EFFECTIVE THERMAL CONDUCTIVITY OF FOAM INSULATING MATERIALS CONSIDERING OPERATIVE TEMPERATURES AND MATERIAL AGING

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ABSTRACT

Constant thermal conductivity values of insulating materials are typically used in building design and assessment. However, the thermal conductivity of insulating materials is affected by their operative conditions. For example, it changes with temperature or moisture content levels. Linear temperature-dependent laws exist for many inorganic fibrous materials that exhibit a decreased thermal conductivity (better performance) at low temperatures. However, foam insulating materials such as the polyisocyanurates and the polyirethanes, exhibit less regular behavior. This study aims to understand the impact of temperature and material aging over the thermal conductivity of foam materials. Laboratory results for different materials are then used in hygrothermal simulations performed in order to assess the impact of considering the effective thermal conductivity in the context of Toronto.

INTRODUCTION

In building envelopes, the insulation layer plays an important role for limiting the heat flux exchange. The efficiency of the insulation layer is based on the material thermal conductivity, a property that indicates the rate of heat transfer through a given material thickness. The 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 difference between the two faces of the material of 20 °C using a heat flow meter that guarantees stationary one-directional heat exchanges. However, research has shown that the thermal conductivity results obtained following the ASTM C518 may be misleading for determining the actual performance of building insulating materials (Berardi and Naldi, 2017). For example, the effectiveness of foam insulating materials vary over the range of temperatures typically encountered in buildings (Lepage and Schumacher, 2013). Additionally, research also showed that insulating materials have moisture content dependent conductivities, as higher thermal conductivity at higher levels of moisture content will be due to the relatively high thermal conductivity of water vapor (Muller-Steinhagen and Ochs, 2005).

In addition to the performance of insulating materials varying over a range of temperatures and moisture content, foam insulation are often indicated to experience a reduction in performance over time, due to the effects of aging and environmental weathering time. In foam insulation, the main cause of reduced thermal performance is believed to be related to the escape of the blowing agent gasses from the foam cell structure (Stovall, 2009). Methods for accelerated aging have been developed in order to determine the long-term thermal resistance (LTTR) on a shorter timeline. For example, the CAN/ULC-S770 standard (2015) set a methodology in Canada for obtaining the LTTR of closed-cell thermal insulating foams after an aging period

of five years in a laboratory environment in less than three months.

While aging alone will have an effect on the performance of insulating materials, weathering due to the combined effects of hygrothermal exposure and UV radiation have been shown to contribute to the deterioration of polymer materials too (Ludwick et al., 2008). While Ludwick et al. focused on the structural performance of the foams, it is valuable to investigate the effects that aging has on their thermal conductivity too. In fact, the investigation into the performance of insulating materials over a range of temperatures and moisture content, as well as how those relationships are affected by the aging of the material will provide valuable insight into the expected performance of these materials in the built environment. As the building industry moves towards high efficiency design strategies, not only the level of performance, but also the accuracy at which the performance can be determined, is becoming highly important to match the assumptions done at the design stage with the final operative effective performance.

In this paper, the thermal conductivity of several foam materials over a range of temperatures and aging in an oven is measured. These data are then used for analysis of the foam materials within several building envelopes using WUFI simulations. The intent of this paper is to allow further analysis regarding which materials are better suited to be used under certain environmental conditions or assembly designs.

LITERATURE REVIEW

Foam insulations have been used in residential housing since the 1950s. Different varieties of foam insulation used in buildings exist among which expanded polystyrene (EPS), extruded polystyrene (XPS), one-part polyurethane foam, polyisocyanurate, closed-cell spray polyurethane, and open-cell spray polyurethane. Each type of foam has different thermal and moisture properties. Additionally, the foam chemistry for most of these products has significantly changed over the past 30 years and has adapted to mitigate the environmental implications of their products. Since the use of the first-generation of blowing agents known as chlorofluorocarbons, or CFCs, began in the mid-1900s, the global regulatory landscape has continually evolved. With a focus on protecting the ozone layer, second-generation blowing agents, known as hydrochlorofluorocarbons or HCFCs (for example, spraying systems formulated with HCFC-141b) were introduced. HCFCs were phased out in North America by third-generation blowing agents, called hydrofluorocarbons or HFCs. HFC foam blowing agents are considered non-ozone-depleting by the U.S. EPA and are commonly used worldwide nowadays. With continued regulatory pressure to reduce greenhouse gas emissions, fourth-generation blowing agents known as hydrofluoro-olefins, or HFOs, have been introduced recently to offer almost no global warming potentials. The U.S. EPA has announced phase-out dates for HFC blowing agents under its Significant New Alternatives Policy (SNAP) program through the two rules 20 and 21 published in 2015 and 2016. For spray polyurethane foam, the current SNAP rules ban the use of HFCs in high pressure two-component foam and low pressure one-component foam. Moreover, in October 2016, delegates to The Montreal Protocol met Kigali (Rwanda) and agreed to an amendment that adds high-GWP HFCs to the Protocol ban, and establishes schedules for the final HFCs phase down. Canada supported that accord to accelerate the adoption of HFC substitutes. As a consequence of the rapid evolution of these products, newer foams are continuously introduced into the market, and these are expected to perform differently from the results obtained in previous decades about the effective thermal conductivity considering operative temperatures and material aging. Unfortunately, a lack of tests on newer foams exists.

In fact, a common misconception regarding insulation materials is that the conductivity of a given material is constant over a range of environmental conditions. Advertised conductivity values for insulation are based on testing in accordance with ASTM C518, and the advertised LTTR is determined under strictly controlled

laboratory settings such as the CAN/ULC-S770 (2015), commonly used for closed-cell foam insulation. Under the standards for determining the LTTR of a material, the thermal conductivity value is still based on measurements in accordance with the ASTM C518. Although this standard only requires measurements at one average temperature, it is often reported that at lower temperatures, the conductivity reduces (Grin et al., 2014). In Fig. 1, this change in conductivity is shown for various insulating materials. 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.

Similarly, diffusion into insulating materials due to humidity causes an increase in thermal conductivity as the moisture content increases (Muller-Steinhagen and Ochs, 2005). As shown in Fig. 2, as the level of moisture increases, the conductivity of the material also increases due to the relatively high conductivity of water (~0.6 W/mK) compared to the conductivity of dry foam insulation, which are generally advertised to perform in the range of ~0.02-0.04 W/mK. Figure 2 also shows that at higher temperatures, the rate at which the increasing moisture content affects the conductivity is higher. This testifies the need to test several environmental parameters in different combinations.

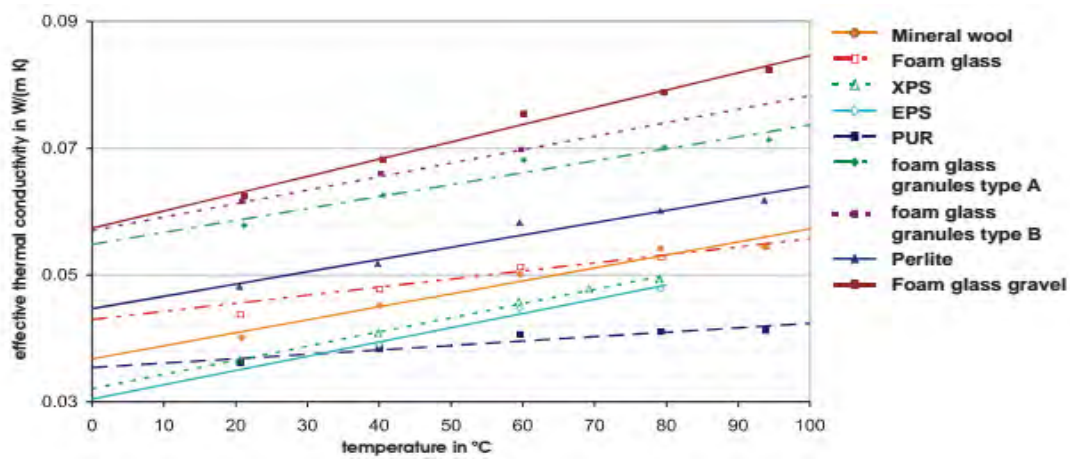


Figure 1: Thermal conductivity and material temperature (Muller-Steinhagen and Ochs, 2005).

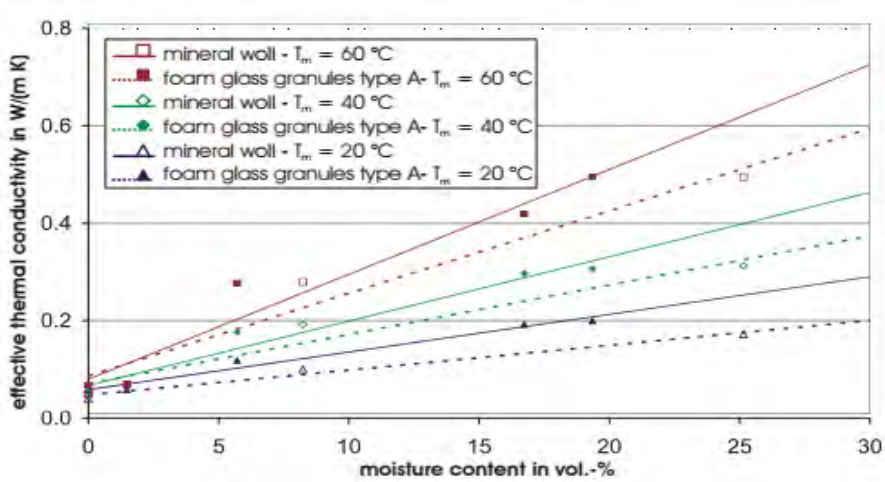


Figure 2: Thermal conductivity and moisture content (Muller-Steinhagen and Ochs, 2005).

In the late 1970s and early 1980s, a flurry of building science studies looked into the moisture characteristics of foam. In fact, moisture in foam insulations may even change the physical structure of the foam. Additionally, foam that has absorbed moisture can be susceptible to damage from freeze/thaw cycles, allowing for further absorption of moisture. Moisture absorption in foams is dependent on the type of foam but also on the environmental conditions. Simultaneous thermal and moisture gradients have shown detrimental effects on the thermal performance and dimensional stability of closed-cell foams (Schwartz et al., 1989). Freeze/thaw cycles affect polystyrenes more than polyurethanes, whereas polyurethanes are more susceptible to TMD than polystyrenes. Kaplar (1974) found that polyurethanes accumulate moisture over repeated freeze/thaw cycles. Similarly, research from the early 1990s summarized show that polyurethane foam samples increased 1.17 to 5.21% in mass after 168 freeze/thaw cycles.

Between the impact of temperature dependent and moisture content dependent conductivity, the overall thermal resistance of a building assembly that was designed under the assumption of a constant conductivity will perform differently from the expected, although modern hygrothermal simulations typically do not consider such a behavior. While an assumed linear temperature dependent conductivity does provide an adequate model for most materials, some materials do not follow a linear trend. Some recent foamed insulation products such as polyurethane and polyisocyanurate have an unusual behavior (Lepage and Schumacher, 2013). Berardi and Naldi (2017) recently showed that the measured thermal conductivity of new polyisocyanurate compared to other traditional insulating materials shows an anomaly pattern with significant thermal conductivity increase at the temperatures below 15 ºC. Meanwhile, Grin et al. (2014) report that in simulations of a large flat roof taking into account the measured conductivity of a polyisocyanurate, the effective conductivity could be 32% to 58% higher in the heating season and 16% to 37% higher during the cooling season compared to it is advertised value. In a similar study, Lepage and Schumacher (2013) found similar results when assessing a range of polyisocyanurate materials.

A study of the temperature dependent thermal conductivity of polyurethane foam conducted by Tseng et al. (1997) provides deeper analysis at the material level regarding its unusual thermal behavior. In the study, the conductivity of polyurethane foam is explored both theoretically and through measurements from 20 K (-253 ºC) to 300 K (27 ºC). The report provides insight into the non-linear trend found in the temperature dependent conductivity. Tseng et al. explain what is happening within the material where this non-linear trend is occurring: as the temperature of the polyurethane foam decreased below 270K, the R141b gas within the material begins to condense, increasing the conductivity. At 230K, the gas is fully condensed, and the linear trend begins to occur again as the temperature reduces from there (Tseng et al., 1997). It is also mentioned, that due to the uncertainties in the processing conditions, blowing agents, and gasses used in polyurethane manufacturing, this trend may occur differently in any given sample.

In modern production, the R141b gas is no longer used as it was discontinued in favor of the current HFC blowing agents in polyurethanes and pentane gasses in polyisocyanurate foams. Although some recent studies have confirmed that foam insulating materials may still experiencing the effect of increased conductivity at low temperatures, there is a clear demand for studies using new products. This study focuses on foam based insulating materials. Commonly used foam insulating materials include polyurethane and polyisocyanurate. Each of these materials is studied in order to discover why they may react to changing environmental conditions and aging effects differently.

FOAM INSULATION MATERIALS

Polyurethane foam is a versatile material, used for many purposes from insulation to padding. There are two

major types of polyurethane foam, open and closed cell. Within each of these categories, there are further distinctions within the types of material and their functions. The two types of insulating polyurethane that will be assessed are a low density semi-rigid open cell foam, and a high density, rigid closed cell foam.

In open cell polyurethane, the foam is expanded using CO_2 as a blowing agent, as the foam expands, bubbles within the foam develop open connections to each other allowing the CO_2 to escape and be replaced by air, this means that the foam is permeable to both air and vapor. Open-cell insulation is often referred to as low-density foam and generally is produced to be 0.5lbs/cu.ft (8kg/m^3), and has a firm cushion structure. A low-density open cell polyurethane foam generally provides ~3 R/inch (20.7mK/W). Closed cell polyurethane is expanded using a blowing agent such as an HFC (hydrofluorocarbon). Through the nature of the foam expansion with the blowing agent, a more dense foam is created and bubbles are prevented from developing open connections, leaving the gas trapped within the foam bubbles. This creates a material that has a higher thermal resistance value than an open cell foam, and is impermeable to air after 2.5 cm of thickness as well as to vapor above 5 cm of thickness. Generally, closed cell insulations are referred to as medium or high-density foam: medium density foams usually have a density of 2 lbs/cu.ft (32 kg/m^3) and provide a thermal resistance value of ~6 R/inch (41.4 mK/W). High-density foams are generally only used where greater compressive strength is required, and can be produced with a density greater than 3 lbs/cu.ft (48 kg/m^3).

The Canadian Urethane Foam Contractors Association (CUFCA) and many national and international laboratories have often indicated a correlation between the overall thickness of the spray foam insulation and its long-term thermal conductivity. They describe that the effects of off gassing and aging generally occur on the surface of the material, meaning that the thicker that the material is sprayed, the higher the overall thermal resistance over time. With the material in the center of the foam being less affected by aging, so that portion of the foam holds a higher thermal resistance for longer.

Similar in nature to polyurethane foam, polyisocyanurate is a versatile foam capable of performing as a high efficiency insulator. Polyisocyanurate products are all relatively high density closed-cell products which are manufactured similarly to polyurethane, using blowing agents to expand the polymer material into foam, currently making use of various pentane gas mixtures (Letts et. al, 2016). Polyisocyanurate is most commonly used in roofing applications for cold climates, as well as exterior insulation of an existing wall. Generally being advertised as the highest thermal resistance rating per material thickness among insulating materials, since some of the high efficiency varieties have conductivities advertised to be 0.02 W/mK. A major difference between polyurethane and polyisocyanurate is that polyisocyanurate is generally manufactured into boards, where most polyurethanes are sprayed in place.

Blowing agents are used in the manufacturing process of foam insulation to expand the foam material through chemical reaction, provide thermal resistance within closed cell foams, and have a large impact on the end product of the material. Historically, CFC and HCFC gasses were once used as blowing agents. These blowing agents were phased out after the ODP Reduction Montreal Protocol. Currently, HFC gas is used as the blowing agent for most polyurethane foam insulation. After the phase out of HCFCs, most polyisocyanurate manufacturers moved toward pentane gas mixtures as blowing agents. As evidenced by recent research carried out by Grin et al. (2014) and Letts et al. (2016), polyisocyanurate do not conform to the assumed linear trend in temperature dependent conductivity. While polyurethane materials have shown this effect in past studies (Tseng et al., 1997), recent investigations reveal that the occurrence is more prevalent in polyisocyanurate samples. Research suggests that this may be related to the changes in blowing agents used between the date of Tseng's 1997 investigation and the investigations by Grin et al., in the last

five years, while polyurethanes moved towards HFC and Polyisocyanurates moved to Pentane gasses.

The CAN/ULC-S770 provides the framework for determining the long-term thermal resistance of a closed cell foam insulation sample through the thin slice stack method. The thin slice stack method, carried out in accordance with ASTM C1303 allows the foam material to age at an accelerated pace by creating thin slices of a foam material from the original sample. When these thin slices have been aged and the conductivity has been re-measured after the aging period, the rate of accelerated aging on the thin slices be equated to the actual pace of aging for the full sized sample in a laboratory setting using the following scaling equation: $(t_1/t_2) = (L_1/L_2)^2$, where t_1 and L_1 are the duration of the test and the thickness of the thin slice, while t_2 and L_2 refer to the original sample. In order to determine the LTTR of the foam material, t_2 should be 5 years. When the value of L_1 and L_2 are measured, t_1 can be solved for, providing the scaled test duration for the thin slice. In order to ensure accuracy in the test method, the control (unaged) samples should have their conductivities verified prior to aging. The samples being prepared for thin slice aging should be sliced into four 10 mm slices, 2 face slices and 2 core slices. Prior to aging, it must be verified that the core slices when measured in a stack, have a conductivity within 12% of the core slices measured in a stack. After the thin slices have been aged for the scaled test duration, the surface and core slices will again be measured in separate stacks in order to determine the aging factor of the samples.

The effects of material aging show that in addition to having an inconsistent thermal conductivity in a range of environmental conditions as previously discussed, the thermal conductivity of closed-cell foam insulations increases over time. Several studies have found that the accuracy of the thin slice method provided a predicted LTTR value within a few percentage points of the actual value after being aged at full thickness for 2 years (Stovall, 2009). While the ASTM method for determining LTTR has been validated though lab testing, further studies have been carried out on polyurethane foams in order to determine the effects of accelerated aging on structural material properties after aging under high temperatures (Tcharkhtchi, 2014, Abdou and Budaiwi, 2014) as well as through UV exposure and moisture exposure (Ludwick et al., 2008).

The effect of material aging can have an impact on the insulating value of the material over time. The effects of aging occur slowly in most insulating materials, and in order to develop an understanding of the effect of aging on foam insulation, the aging process must be expedited. In a study on the aging of polyester materials, it was found that the temperature at which a material is store has a large impact on the aging process (Hunter et al., 2000). In fact, at higher temperatures, the rate of deterioration increases substantially.

As reported by Jelle (2014), accelerated aging through various mechanisms such as elevated temperature, high hygrothermal exposure and UV radiation can be used to affect building materials in different ways. Jelle (2014) also reported that the duration of the expedited aging process can be correlated using the Arrhenius Equation to the time it takes for the material to age similarly in standard environmental conditions. Knowing this, foam insulation samples can be stored at higher than standard temperature levels for an extended period of time, and later it can be determined the equivalent age in a standard environment, allowing conclusions to be drawn regarding the effect of long term aging performance.

METHODOLOGY

In the initial phase of testing, tests on various foam insulation were performed. The specific information sets that were determined including the temperature dependent conductivity, moisture dependent conductivity, and the effects of aging on the previous qualities. Only a portion of these results are reported in this paper. For each type of testing, a new sample was used in order to prevent issues with lasting effects of previous

tests. The materials that were tested include the following samples:

- Polyurethanes: (A) medium density (33.6 kg/m^3) closed cell - RSI (50mm thick) 2.55 m^2*K/W; (B) medium density (28.9 kg/m^3) closed cell - RSI (50mm thick) 2.14 m^2*K/W;
- Polyisocyanurates: (A) medium density (32.04 kg/m^3) closed cell - RSI (25mm thick) 1.44 m^2*K/W, aluminum faced; (B) medium density (32.04 kg/m^3) closed cell - RSI (50mm thick) 2.01 m^2*K/W, cardstock faced; (C) medium density (32.04 kg/m^3) closed cell - RSI (50mm thick) 2.01 m^2*K/W, cardstock faced.

In order to gain a full understanding of the performance in the Canadian climate, the samples were tested in range from -20 °C to 30 °C. In addition to the standardized test at 24 °C, the samples were tested at a range of average temperatures of 30, 20, 10, 0, -5, -10, -15, and -20 °C. Due to potential limitations with the cooling power of the testing equipment, at the tests at mean temperature -15 and -20 °C, the temperature difference across the samples was reduced to 10 °C instead that the 20 °C used at other average temperatures.

RESULTS

The five types of material samples (two polyurethane foams and three polyisocyanurate foams) were tested in the initial measurement phase in order to determine the temperature dependent conductivity of those materials. The results are plotted against the assumed constant value of the manufacturers advertised conductivity (Figs.3 and 4).

The results in the first material test for Polyurethane A reveal that contrary to what some research suggests (Tseng, 1997), this polyurethane does not appear to have a major increase in conductivity below 0 ° C, though the value towards -20 does very slightly increase. This may indicate that at even colder temperatures the effect of increasing conductivity may be seen, though for the purposes of construction in Canada, it may not be relevant. At higher temperatures, the conductivity seems to increase at a relatively linear rate, which is consistent with general research regarding temperature-dependent conductivity of any other insulating products (Grin et al., 2014). The results of Polyurethane B reveal a similar trend to the previous polyurethane sample, though in this material, the conductivity increases relatively linearly towards 30 °C, without the slight increase in conductivity around -20 °C.

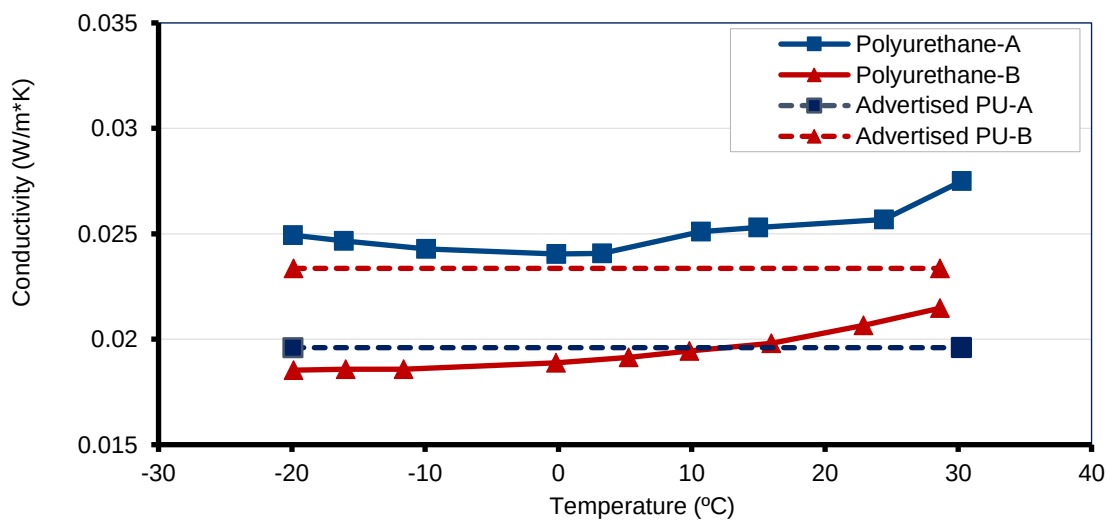


Figure 3: Temperature dependency of the thermal conductivity for the polyurethanes considered in this paper.

Based on the results of the two polyurethanes, it seems that polyurethanes do not experience the negative effects of increasing conductivity below 0 ° C. The lack of this effect being observed could be explained by differences in the blowing agents used in polyurethane foam insulations compared to when Tseng et al. conducted their tests. While the exact nature of the blowing agents used has not been disclosed by the manufacturers, it is evident that with the regulations introduced after the Montreal Protocol and other similar protocols, the new blowing agents have also improved the low temperature performance.

The test result of Polyisocyanurate samples A, indicates a negative effect of temperature increasing the conductivity at temperatures below 0° C (Fig.4). Below 5° C, the conductivity appears to increase, where it begins to plateau. According to research by Grin et al., 2014, it can likely be expected that past -20 °C, the conductivity will level out and begin to reduce again. Given the opportunity, it would be important to continue to explore the effects of cold temperature on the conductivity of this material below -20 °C as well in order to gain a full understanding of when it can be expected that the conductivity returns to the assumed linear correlation of reducing as temperature decreases. Finally, there is ~18% increase in conductivity from the lowest value measured at 5 °C compared to the highest at -20 °C.

Contrary to the plateau in conductivity below -15 °C in sample A, polyisocyanurate samples B and C experience a continued increase in conductivity at a much higher rate. Between the lowest and highest conductivity measured for sample B, there is 33% reduction in performance at -20 °C compared to the lowest measured value at 10 °C, while in sample C there is a 29% reduction in performance between the highest measured value at -20 °C and the lowest at 10 °C. While both Polyisocyanurate B and C follow very similar temperature dependent conductivity curves, the sample B appears to be increasing linearly at a slightly higher rate as the temperature decreases below 0 °C.

An important observation that was made looking at all material test results is the inconsistencies between the advertised value and the measured value of materials. In order to gain a better understanding of this difference, more samples of each material should be tested in order to find an average temperature-dependent conductivity, as there are likely to be inconsistencies between different samples of the same materials. Looking at the current result, the measurements suggest that in a scenario where an assembly is designed with a specific U-value, the wall may perform much differently than the advertised value suggests, even without taking temperature-dependent conductivities into account.

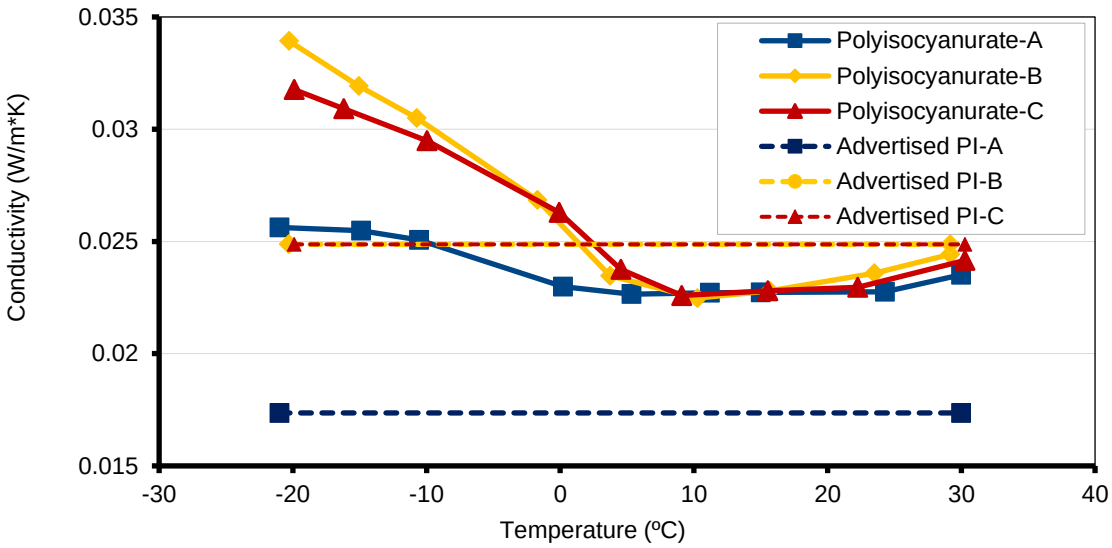


Figure 4: Temperature dependency of the thermal conductivity for the polyisocyanurates considered in this paper**.**

From the previous discussion it emerges that there is over 15% difference between the highest and lowest values in all materials, in the Polyisocyanurate samples B and C, this range is greatly increased to 33% and 29% respectively. Additionally, and most importantly, the temperature at which the lowest and highest conductivities are experienced are different for different material. In the polyurethanes, both material samples experience their lowest conductivity at temperatures below water freezing, while at those temperatures, the polyisocyanurate are experiencing their highest conductivity values.

These measurements reveal that the effects of condensing blowing agents causing an increase in conductivity at low temperatures are only seen in the polyisocyanurate materials. The exact nature of the blowing agents used have not been disclosed by the manufacturers, but through research by Lett et al. in 2016, it can be assumed that the Polyisocyanurate samples that were tested make use of Pentane blowing agents, while the current HFC gasses used in polyurethane foams do not encounter the same effect.

The material were then aged in an oven at 60 °C for different periods for each sample. Through this high temperature aging, notable decreases in performance were found across all of the samples tested (Fig.5), and especially for polyisocyanurates which showed clear reduction in their thermal performance already after 30 days (1months).

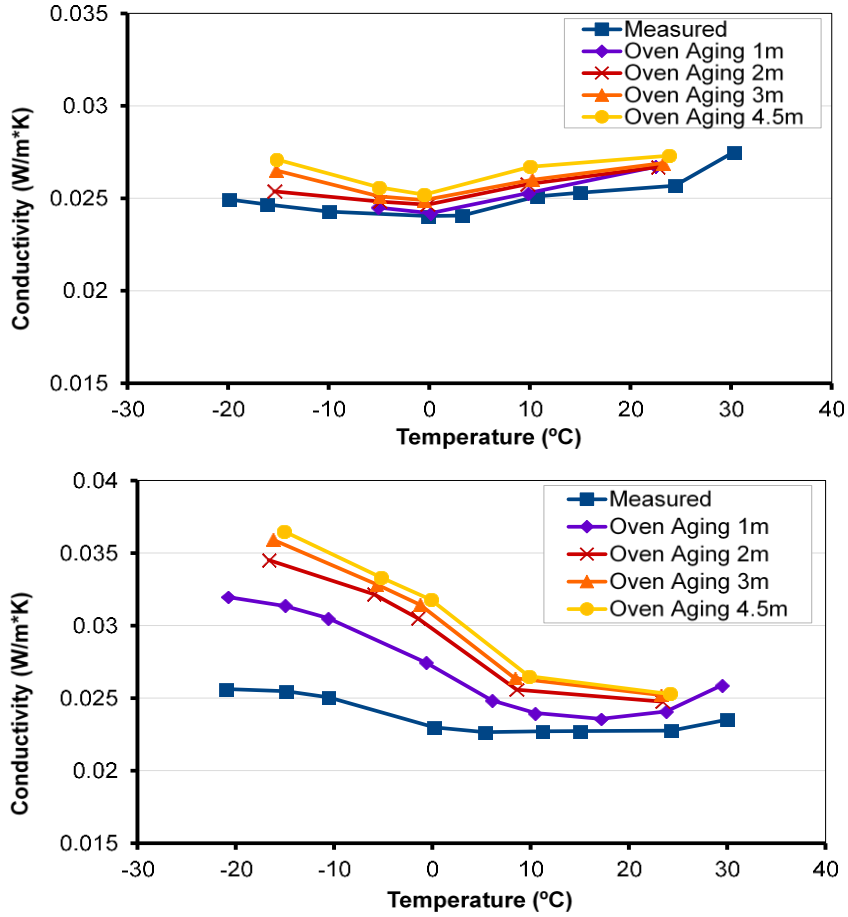


Figure 5: Thermal conductivity of the polyisocyanurate after high temperature exposition for different periods (expressed in months; i.e. 1m: 1 month) in an oven for different periods for polyurethanes (above) and polyisocyanurates below.

DISCUSSION

In order to determine the effect of temperature dependent conductivity on the performance of a building envelope under realistic conditions, WUFI hygrothermal analysis software was used in order 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 dependent conductivity values found through measurements with the heat flow meter, while other required material details were obtained through manufacturer technical data sheets. Additionally, material files that use a consistent thermal conductivity based on the advertised conductivity, as well as the measured conductivity at 24 °C was created in order to compare between the advertised and measured results in a wall assembly simulation. These materials were applied to basic wood frame construction assemblies (Fig.6), replacing the specified insulation with an equivalent amount of each of the tested materials.

Through the results of WUFI simulations, two datasets were obtained to be used in the analysis of thermal performance. By observing the monitored temperature at the center of the insulation layer, which is assumed to be the mean temperature in the insulation, the effective U-Value at any point throughout the simulation was assumed as the mean insulation temperature.

In order to observe the effect of the insulations dynamic conductivity with the most clarity, a basic wood stud wall assembly with OSB and gypsum board on either side was simulated filled with each insulating material.

This type of wall assembly achieved nearly all of its effective U-value through the insulation alone.

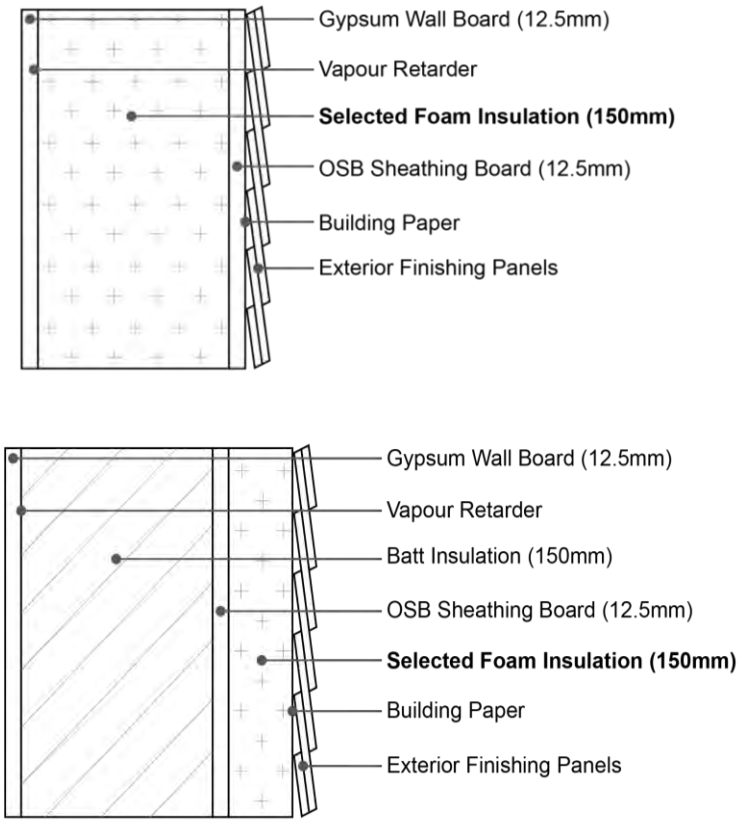
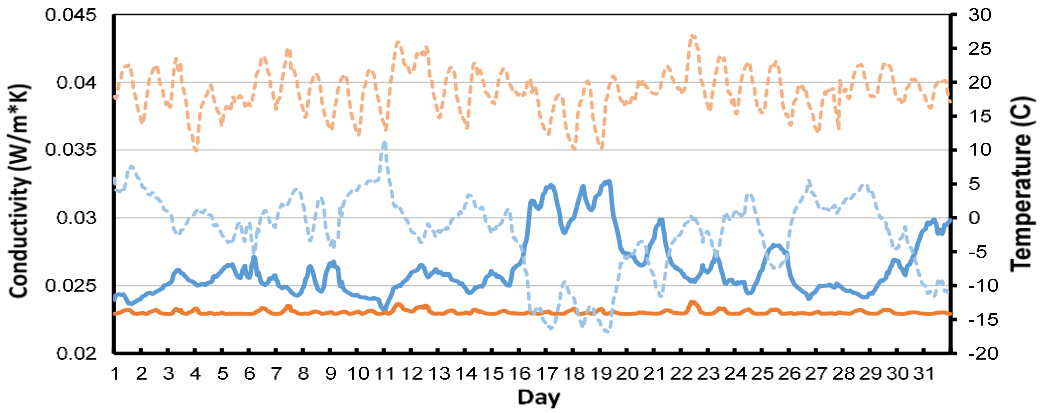
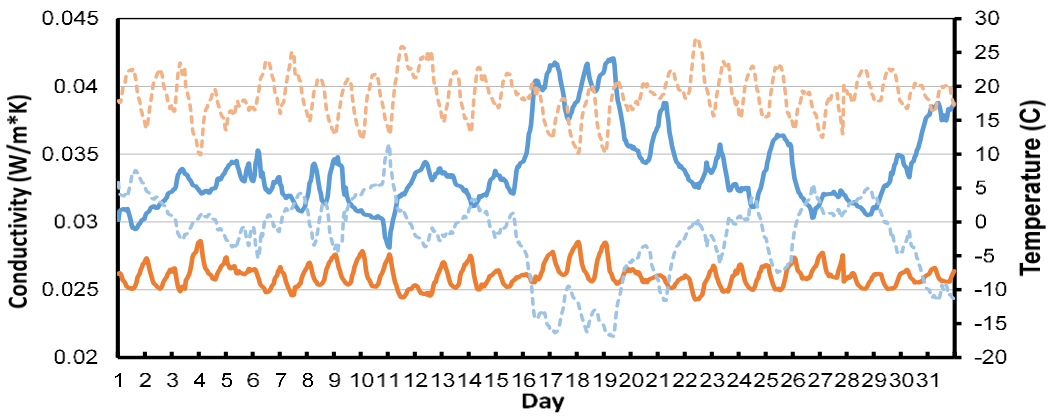


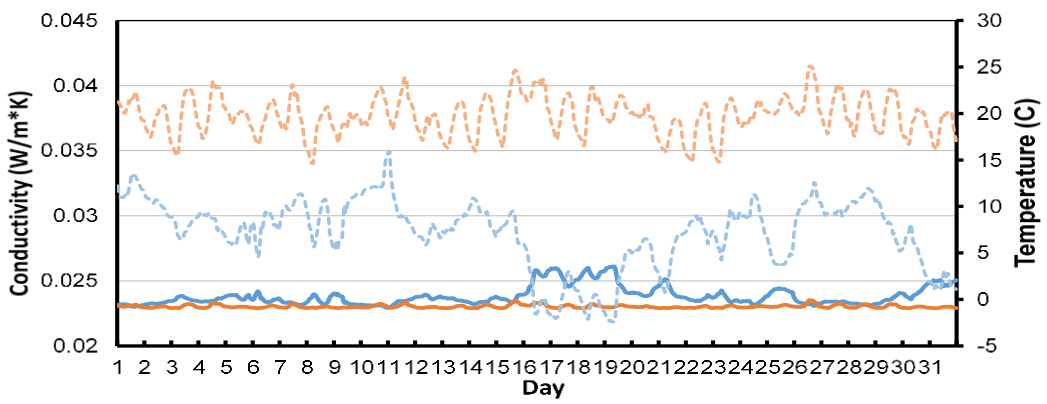
Figure 6: Wall assemblies for interior application simulation and interior and exterior applications



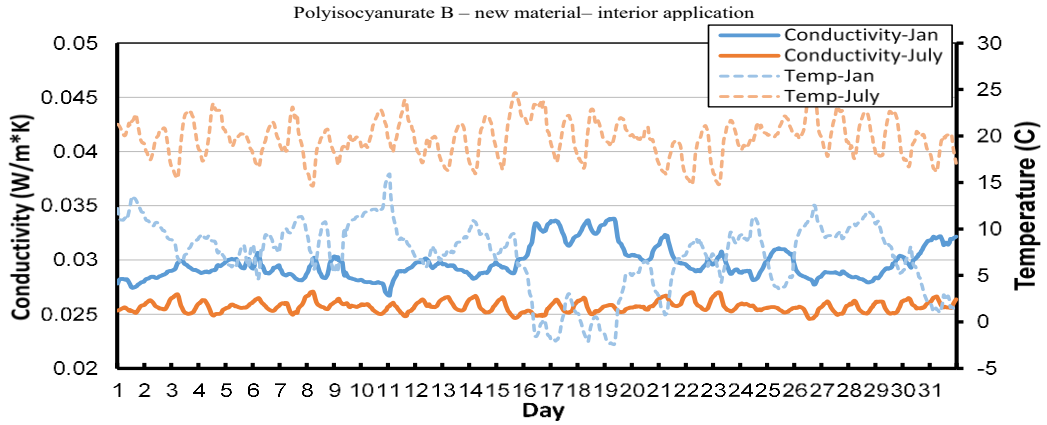
Polyisocyanurate B – new material– exterior application



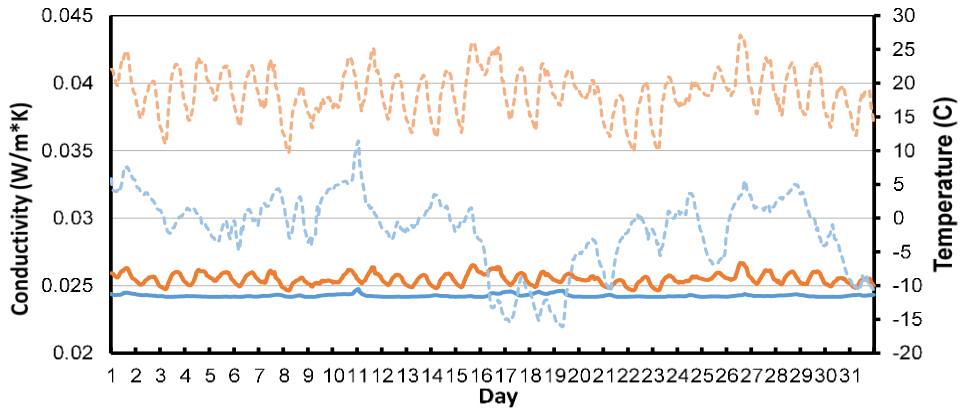
Polyisocyanurate B – aged material– exterior application



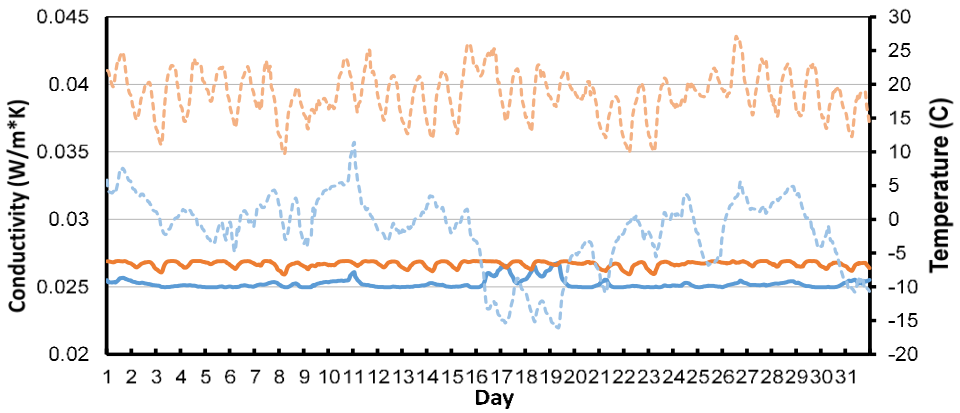
Polyisocyanurate B – new material– interior application



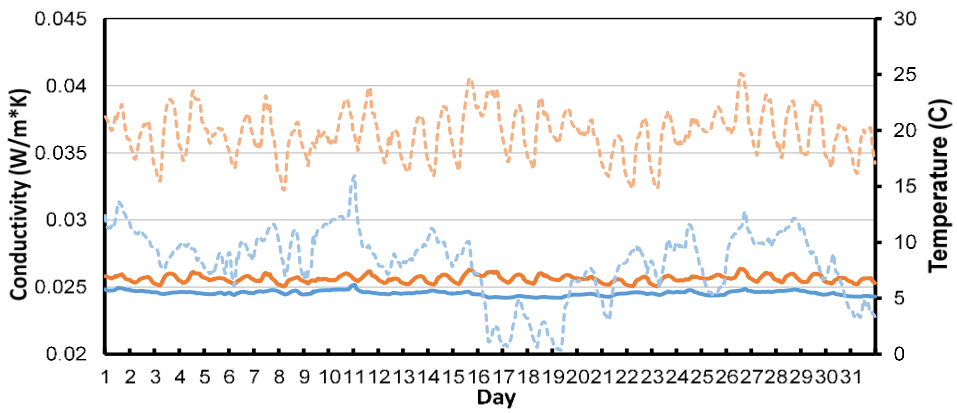
Polyisocyanurate B – aged material– interior application



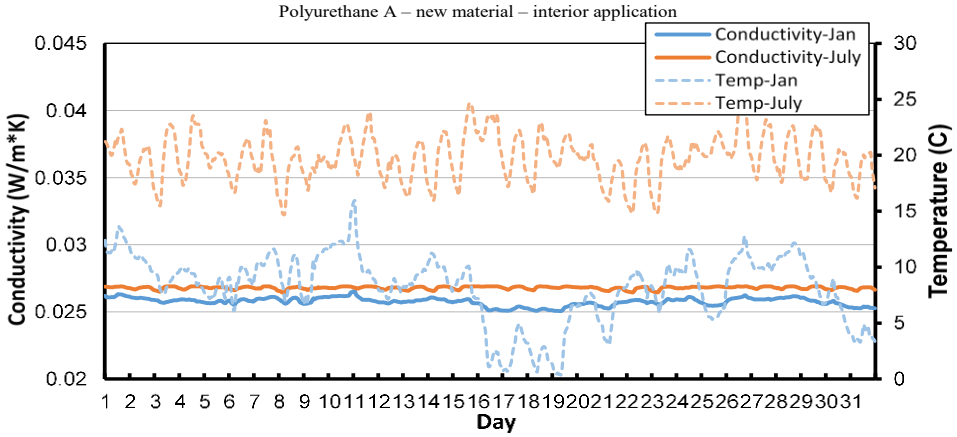
Polyurethane A – new material – exterior application



Polyurethane A – aged material – exterior application



Polyurethane A – new material – interior application



Polyurethane A –aged material – interior application

Figure 7: Hygrothermal results of the effective thermal conductivity under realistic conditions as result of WUFI simulations.

In Fig.7, the results of two representative months in the Toronto climate are shown. Contrary to what the temperature-dependent conductivity charts might suggest, the results of the simulations indicate that for the most part, the insulation performs better than the measured value at 24 °C year round, with the only exception being Polyisocyanurate B, which performs slightly worse in January and February, when the exterior environment is at its coldest.

Looking into the results from WUFI, it is shown that even in the coldest months of the year, when the exterior temperature reaches below -20 °C, due to the interior environment being simulated at a constant of 21 °C, the mean temperature within the insulation rarely drops below 0 °C. Among all the results, nearly all data points for the temperature at the mid-point of the insulation are between 0 and 20 °C.

The polyurethane samples results in an increase in performance throughout the cold winter months, due to the more linear decrease in conductivity as temperature is reduced, while the polyisocyanurate samples are shown to perform relatively consistently year round. According to the temperature-dependent conductivity charts, this can be explained by the relatively consistent conductivities measured between 0 and 20 °C in those materials. Looking only at these simulations, it could be concluded that, while the temperature-dependent conductivity of the insulating foams have a relatively large range, the negative effect on the actual performance of a building under realistic conditions is quite low in the polyisocyanurate, and in fact, in polyurethane samples, the material performs better than the assumed performance in the colder months.

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. The attention has focused on foamed insulation such as polyurethane and polyisocyanurate, which exhibit less regular behavior. Using constant thermal resistance values results in actual building envelope performance different from the design predictions as it has been shown both trough experimental results and simulations. This paper aims to start a more critical discussion about how the impact of temperature and material aging over the thermal conductivity affect foam insulation performance in building envelopes.

ACKNOWLEDGMENTS

The authors wish to thank the Ontario Center for Excellence through the OCE-VIP 1 Program, the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Ministry of Research, Innovation and Science through the Early Researcher Award program for their financial support, and the industry collaborators and partners, for their support.

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