Environmental Engineering and Management Journal November 2014, Vol.13, No. 11, 2881-2886
http://omicron.ch.tuiasi.ro/EEMJ/

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MEASUREMENTS OF THE THERMAL CONDUCTIVITIES OF SOME COMMONLY USED INSULATING MATERIALS AFTER WETTING

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Abstract

Currently, thermal insulation of buildings is required from both an energy savings perspective and a money savings perspective. Insulation is primarily installed on the outer surface of the buildings. Weather and other circumstances can produce humidity that can act on the building structure, e.g., by changing its heat capacity, the heat transfer coefficient and/or other factors. As a result, it is important to measure the sorption behaviors of the construction materials. To perform sorption measurements, we use a desiccator (Venticell 111 type) to dry the samples and a climatic chamber (Climacell 111 type) to wet the materials. With these two chambers, we can achieve the relevant moisture content of different humidity levels and create a sorption isotherm graph for the sample. During the measurements, four different types of insulations were used (a mineral wool, EPS30, graphite-doped EPS, and yellow colored Extruded Polystyrene).

Key words: climacell, holometrix, insulation materials, moisture sorption, venticell

Received: February, 2014; Revised final: October, 2014; Accepted: October, 2014

1. Introduction

Currently, energy savings is notably important; one method to achieve energy savings is the insulating of buildings. Adding insulation materials not only reduces the heat loss but also enables a greater amount of stored heat. The European Union has declared several directives to achieve a high energy efficiency rate, e.g., stricter requirements for the overall heat transfer coefficients are mandated (Kalmár, 2002; Kalmár and Kalmár, 2007; Lakatos, 2014).

As previously reported, the moisture content of the building materials not only changes the heat transfer coefficient but also change the heat capacity (Lakatos and Kalmár, 2013a, b). As a result, it is important to measure the sorption capability of the materials.

Building, structural and construction materials mostly have a porous structure; due to this property, the specific external surface is larger compared to materials with a smoother surface and of the same specific volume. Materials with a high porosity can absorb and store more water than those of low porosity (Babu et al., 2006, Zhang, 2014; Wilby, 2014). Therefore, when humidity has an effect on building materials, it primarily appears on the outer layer. Due to the pressure difference or to the capillarity, the moisture can spread into the entire volume. The sorption capability of a material can be represented by its sorption isotherm (Duskov, 1997; Gnip et al., 2006a, b; Kalmár and Csáky, 2011; Kalmár and Csáky, 2012; Vejelis and Vaitkus, 2006).

To perform measurements of the sorption isotherm, we used two apparatuses: a Venticell (111) type dryer and a Climacell (111) type climate chamber for wetting the samples.

In addition to these two apparatuses, a milligram precision balance is used to weigh the samples.

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2. Case studies

2.1. Wetness effect

Moisture in building materials can appear in several ways (Kalmár and Kalmár, 2012; Lakatos and Kalmár, 2013a). A slight quantity of the water can infiltrate into the material via the manufacturing process. Furthermore, moisture can be absorbed by the materials due to the outer weather conditions. Buildings under construction are particularly exposed to moisture stress. Precipitation has an impact on the building in different ways. A large moisture load can occur in the internal side due to the functioning of the room; these types of rooms are, e.g., pools and bathrooms, where significant water vaporization can be found. In addition, the use of technologies that produce a significant quantity of moisture can expose the surfaces and the internal surfaces of a room to a large moisture load. In such spaces, the prevention of vapor diffusion is not sufficient, and a dehumidification system is also required to reach a lower humidity concentration.

The physical properties of the building materials can be changed by the presence of the wetness. However, water vapor does not significantly change the heat transfer coefficient (U-value) or the density of the material. When the wetness in the material is in liquid form, it can increase the U-value and exert a corrosive effect on the surface of the material. Under strange conditions, mold can appear. When we are not careful about avoiding condensation and the exterior temperature is too low, the inner wetness can change from the liquid phase to the solid phase; when this change occurs, the volume of the moisture will increase and cause irreversible processes that can damage the structure.

2.2. Materials sorption

Building materials can be classified according to their outer layer. If the outer layer is a solid material, then the moisture can only establish chemical connection or adsorption on the outer surface. Metals have such properties in general, and they begin to corrode when exposed to moisture. Closed pores in the material can only adsorb moisture on the outer layer. Foamy materials, such as plastic foams (expanded polystyrene (EPS) and extruded polystyrene (XPS)) defines another category. These porous materials can be further classified by what combination can occur through the wetting process. For example, bitumen bonded insulations do not exhibit absorption, but capillarity and diffusion can occur; for fibrous materials, only diffusion occurs. However, for most of the building materials, such as bricks, all three phenomena occur: absorption, capillarity and diffusion.

For the saturation process, moisture flow is required. One of the primary drivers of this phenomenon is the partial pressure difference. If the partial pressure of the water vapor on the surface of the material is less than the partial pressure of the air, adsorption can occur. If the partial pressure of the moisture in the material (or on the surface) is greater than the water vapor in the atmosphere, drying can occur, which is called desorption.

3. Experimental

In the experiments, we examined the thermal conductivity of materials at different sorption levels. Four different types of insulations were measured: mineral wool, EPS30, graphite-doped EPS and a yellow Extruded Polystyrene. To define a minimal sorption level, we used a desiccating chamber, a Venticell (VC) device, which can ensure the homogenous desorption of the sample. Desiccation to a changeless weight was performed at 343 K temperature via hot air circulation. At this temperature, we prevented the samples from exhibiting any deformation and any physical changes; however, the temperature was high enough to ensure the relatively fast drying procedure, and the temperature is slightly under the lowest melting point of the materials studied.

To achieve the required wetness level, a climate-controlled chamber, ClimaCell (CLC) was used at 90% relative humidity and at 293 K temperature for 4, 8, 12, 16 and 20 hours. To avoid any natural desorption from the surface of the wetted samples, a foil layer was applied to each sample. The layering procedure was performed as soon as it was possible (Lakatos and Kalmár, 2013a, b).

3.1. Thermal conductivity measurements

The prepared samples, with 30 × 30 × 3-to-5 cm geometries, were positioned in a Holometrix 2000 type Heat Flow meter (HFM). This equipment is designed to determine the thermal conductivity of insulation materials in accordance with standard ASTM C518 and ISO 8301 protocols. The samples were placed in the test section between two plates, which are maintained at different temperatures (T_1 = 285 K and T_2 = 295 K, with T_{mean} = 290 K) during the experiment. After achieving thermal equilibrium and establishing a uniform temperature gradient throughout the sample, the thermal conductivity is determined (Lakatos and Kalmár, 2013a, b). To determine the average thermal conductivity of a sample at a given moisture level, ten individual samples were used.

The thermal conductivity of the analyzed material was taken as the mean value of the result of these ten measurements (Lakatos, 2014). With the thickness and the mass density of samples, the device can calculate the thermal conductivity. A description of the calculation method is as follows. First, the Fourier equation (Eq. 1) provides the relationship between the parameters of the test samples and the sections.

$$q=\lambda*A*\Delta T/\Delta x \qquad (1)$$

where: q and ΔT are the heat flow and temperature difference across the sample, respectively, A is the area through which the heat flows, Δx is the thickness and λ is the thermal conductivity of samples. During the measurement, the HFM provides a signal (in volts) to a transducer that represents the heat flow. Knowing these values are proportional, the heat flow is given by (Eq. 2):

$$q=N*V \quad (2)$$

where: N is a calibration factor and V is the voltage signal on the heat transducer.

The calibration factor was determined before the experimental series using a standard fibrous glass board sample ($\lambda_{calibration}$ = 0.05 W/mK). Using Eqs. 1-2, the thermal conductivity can be determined by Eq. (3) (Lakatos and Kalmár, 2013 a, b):

$$\lambda=N*V*\Delta x/\Delta T \quad (3)$$

3.2. Wetting of the samples

The moisture content of the samples can be calculated using the following equation (Eq. 4):

$$\omega\,(\%) = ((m_w-m_d)/m_d))*100 \quad (4)$$

where: m_d and m_w are the mass of the dried and the damped samples, respectively. The porosity of the material (ψ) is equal to the ratio of the volume of the pores (V_p) over the total volume (V_m) (Eq. 5).

$$\Psi=V_p/V_m \quad (5)$$

Here, the saturated pore ratio (ψ_w) can be defined as the ratio of the volume of the moisture and the volume of the pores in the material (Eq. 6).

$$\Psi_w=V_w/V_p \quad (6)$$

The thermal conductivity of a wetted material depends on the moisture content of the material. Usually, thermal conductivity will be based on heat conduction through the solid and through the gas phase; however, if the pore size is “great” enough, convection of the filling gas can occur (Lakatos and Kalmár, 2013a). Due to the inhomogeneous structure of the materials, theoretically it is very difficult to calculate the moisture effect on the materials (Fekete, 1985). Several models are available to describe the influence of the water content on the thermal conductivity of materials.

For the building materials under the given conditions, the thermal conductivity values can be determined as follows (Eq. 7):

$$\lambda_W=\lambda_0*A*t*\omega*exp\,(-B\omega) \quad (7)$$

where: λ_W and λ_0 are the thermal conductivity of the wet sample and the dried sample, respectively, furthermore, A and B are constants for the material that can be determined from the experiments, t is the wetting time and ω is the moisture content. In practice, the influence of the moisture in the thermal conductivity is given in the percentage of wetness level difference. In Hungary, tables taken from (Fekete, 1985) used in the design process provide information for determining the thermal conductivity at a certain moisture content. This above-mentioned book (Fekete, 1985) suggests a more simple approximate calculation, which is based on the following equation (Eq. 8):

$$\lambda_w=\lambda_0*(1+n/100) \quad (8)$$

where: n is a coefficient that depends on the moisture level and on the material. Moreover, n can be described as (Eq. 9):

$$n=\omega*Z \quad (9)$$

where: Z is a material constant (Z is set to a value of two for both plastic foams and for mineral wools (Fekete, 1985).

4. Results and discussion

Expanded polystyrene (EPS) materials are proven to be reasonable insulators; themes can achieve a relatively high efficiency of insulation (e.g., EPS 30 or graphite doped EPS), and they have a relatively low price. EPS materials are mainly used as frontage insulators because their sorption up-take capability does not allow their use at the plinth due to their open cells; moreover, these cells can be filled with water and can decrease the thermal efficiency, thereby leading to destruction of the building structure (except those with very high density). The fibrous (mineral-wool) insulation material can be used at the frontage and at roofs.

The filamentous structure of wool does not allow their use at the plinth because this property allows permeability for air. Extruded polystyrene (XPS), with its closed cells, can be used as a plinth insulation, i.e., these cells cannot be filled up easily with water. XPS materials are not only thermal but also water insulators (Lakatos, 2014). As a result, for all materials, two different curves will be presented: 1) the thermal conductivity change as a function of the moisture content, and the time-dependent ones, the so-called “kinetic curves”, which exhibit an increase in the moisture content as a function of the wetting time.

4.1. Measurements performed on the mineral wool samples

Mineral wool is made from a fibrous mineral that exhibits long pores in its structure. Such fibrous structure is capable of storing a large amount air, which makes this material an effective insulation. Consequently, the fibrous structure is consistent with the observation that pores in a material that are opened to the environment makes a material highly sensitive to sorption level changes. In Fig. 1, the value of thermal conductivity remains constant until the mineral wool reaches approximately 4% moisture content, above which an exponentially increasing thermal conductivity change is observed with increasing moisture content. This behavior is caused by the filamentous structure of the mineral wool.

Furthermore, after wetting for 20 hours at 90% relative humidity and at 293 K, an approximately 200% change was found for the thermal conductivity change.

For the prediction of the thermal conductivity of a wet mineral wool sample, an equation was determined by fitting the data with an exponential function. This equation is shown on the top of the figure, where A_1 is a constant, and ω and λ_w were defined before. In Fig. 2, one can observe an increasing amount of moisture content as a function of the wetting time; furthermore, the curve starts from the origin and follows a square root function shape.

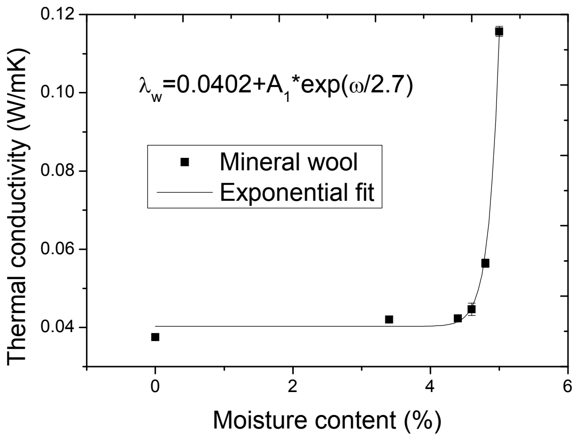

Fig. 1. The thermal conductivity of the mineral wool sample as a function of the moisture content

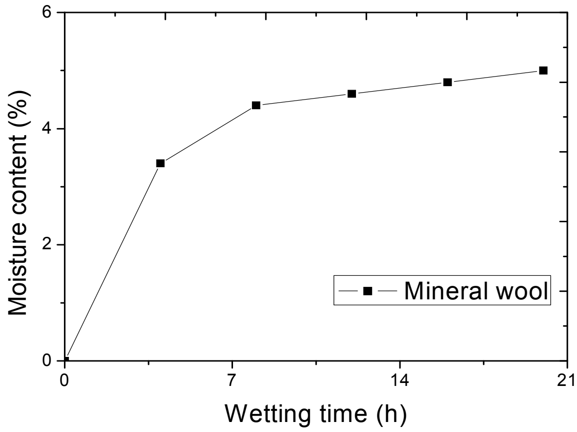

Fig. 2. The adsorbed amount of water as a function of the wetting time at 90% relative humidity for the mineral wool sample

Initially, a significant jump is found for wetting for eight hours; this jump is caused by the good adsorbate-adsorbent interaction, and then a simple linear increase is observed. This process can be explained by the slow impregnation of the pores.

4.2. Measurements performed on the EPS 30 samples

EPS 30 a blue signed expanded polystyrene, is a plastic foam material with open cells. EPS 30 has a mass density of approximately 15 kg/m^3 due to its fairly large pores. The sorption procedure should be different compared to that of the mineral wool because the structure of the pores is different.

While the mineral wool has lengthwise pores, the air pores of the EPS are rounded plastic bubbles. Initially, the water adsorbs to the external layer, and then it fills up the pores. In Fig. 3, a linear increase of the thermal conductivity as a function of the moisture content is observed from the measurements.

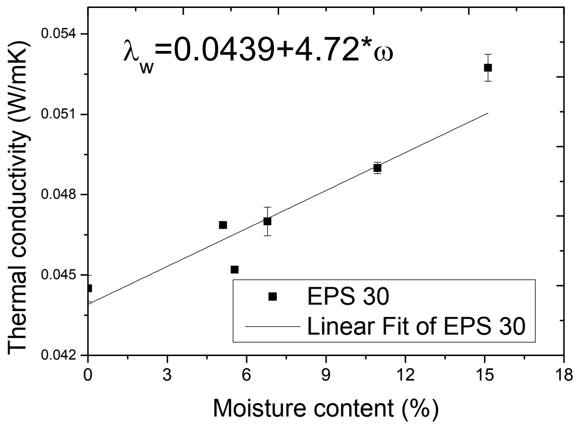

Fig. 3. The thermal conductivity of the EPS 30 as a function of the moisture content

On this graph, similar to Fig. 1, the estimated errors are also presented; for the data points without observable error bars, the error is too small and cannot be represented on the figure.

After 20 hours of wetting, 15% moisture content was measured. This result is interesting because, for the mineral wool, only 5% maximum moisture content caused a 200% increase in the thermal conductivity; moreover, for EPS 30, the maximum change in the thermal conductivity is approximately 20%. The great amount of the water content can affect the condensation of the water at the surface of the EPS samples. After long time wetting, the pores are filled up, and there is no place for the water to diffuse inside the sample.

The great amount of the water content can affect the condensation of the water at the surface of the EPS samples. After long time wetting, the pores are filled up, and there is no place for the water to diffuse inside the sample. As a result, the thermal conductivity of the sample will not significantly increase, but the moisture content will increase. From the measurement results, a linear equation for estimating the thermal conductivity of the damped sample was obtained. This equation is presented in Fig. 3. In Fig. 4, a sorption type curve is shown for the change of the moisture content as a function of time. This curve provides support for our above-mentioned model.

As we previously stated, initially, monolayer and multilayer sorption occurs followed by the slow filling up of the pores. After 12 hours of wetting, the rapid condensation of the water on the external surface of the samples occurs as a function of time.

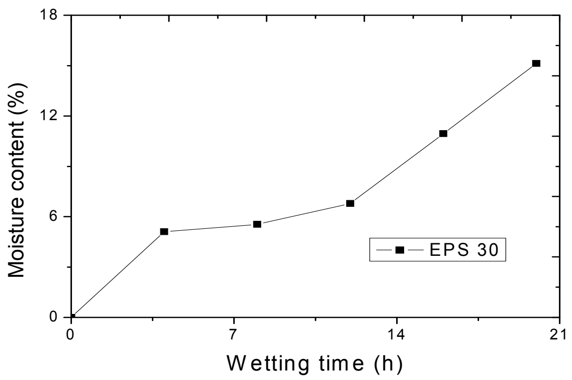

Fig. 4. The adsorbed amount of water as a function of the wetting time at 90% relative humidity for the EPS 30

4.3. Measurements performed on the graphite-doped EPS

The advantage of the graphite-doped EPS samples is its effective usage during the construction of passive houses. Nevertheless, the properties of polystyrene - graphite nanocomposites were analyzed as well in this study, and the research results indicate that due to the interfacial interaction between the graphite nanolayers and the polymer, the composites exhibit a higher glass transition temperature and higher thermal stability when compared to those of pure polystyrene.

One of the best insulation properties of the grey EPS materials is their outstanding resistance against the heat radiation inside the sample, due to its infrared reflection and absorption via the carbon particles (Fig. 5). The insulating properties of the grey EPS slabs are 15 to 20% better than that of conventional white Expanded Polystyrene, as clearly described in (Lakatos and Kalmár, 2013a, b). Fig. 6 shows a similar increase in the dampening as a function of time compared to the wetting process of EPS 30. Both of them have relatively large air-pore sizes. Moreover, the greatest amount of the water content is found to be approximately 16%, but the thermal conductivity does not go significantly above 0.044 W/mK. The shape of the curve on Fig. 6 supports that the same theory described above, i.e., after the complete filling of the pores, the condensation of water occurs.

4.4. Measurements performed on the yellow Extruded Polystyrene

Extruded polystyrene materials, in addition to their good thermal properties, are good water insulation materials because of their closed cells. These materials exhibit a denser structure than that of the open cell variants, which makes them more resistant to physical impacts. This composition also makes them slightly unaffected to sorption, i.e., diffusion inside the sample is not expected.

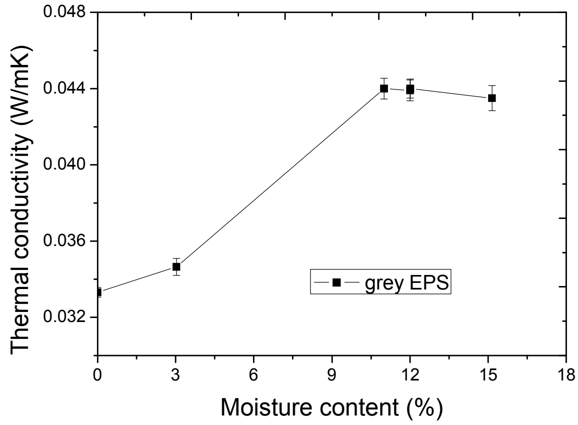

Fig. 5. The thermal conductivity of the grey EPS sample as a function of the moisture content

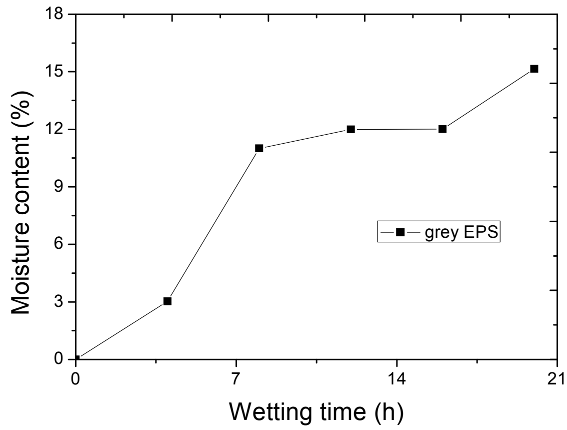

Fig. 6. The adsorbed amount of water as a function of wetting time at 90% relative humidity for the grey EPS

In Fig. 7 the measured thermal conductivities, with the estimated errors calculated from the difference from the average value, as a function of the wetness level is observed. Here, we could observe the expected behavior. By increasing the moisture content, no significant change was observed in the thermal conductivity. This phenomenon arises from the structure of the XPS materials. XPS materials have relatively high mass density (30 kg/m^3) compared to the EPS 30 and grey EPS, with small sized and closed cells. The water cannot diffuse inside the XPS materials and can only gather on the outer surface of the material as condensed water.

The curve on Fig. 8 is similar to the curves represented in Figs. 3 and 6; these data are a result of the type of material. All of these materials are polystyrene based materials, where the air is trapped into pores; depending on its type, the material exhibits open or closed cell.

5. Conclusions

Currently, the insulation of the walls of buildings has gained importance from the point of view of reducing the heating and cooling energy demand. The primary goal of this article was the investigation of the effect of the water on the thermal conductivity of a mineral wool and of extruded and expanded polystyrene insulating materials.

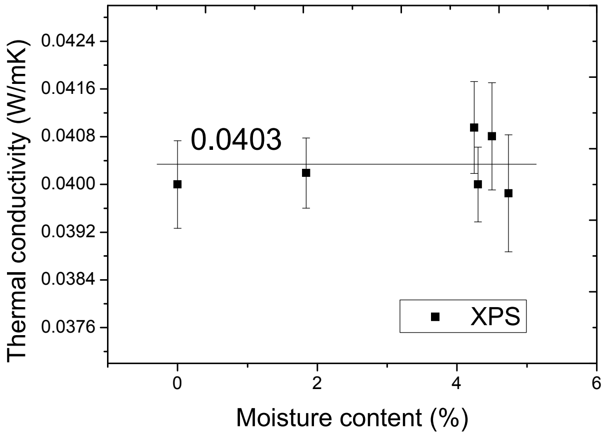

Fig. 7. The thermal conductivity of the XPS as a function of the moisture content

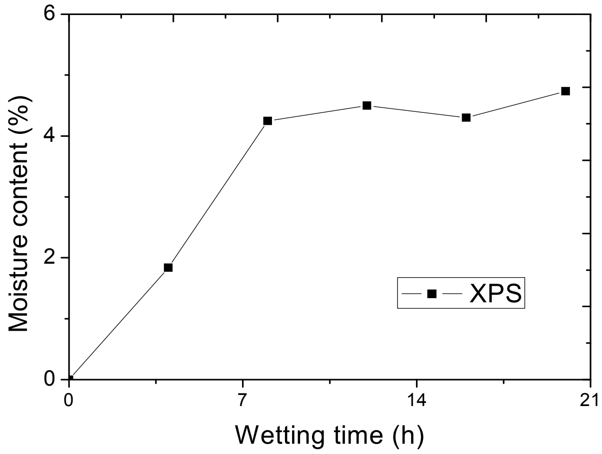

Fig. 8. The adsorbed amount of water as a function of the wetting time at 9% relative humidity for the XPS

The samples were exposed to wetting treatment at 293 K and 90% relative humidity for 0 to 20 hours in four-hour steps. The functions and relationships between the thermal conductivities and water contents measured were presented. Model theories were proposed for the moisture up-taking capability, both for the mineral wool and for the PS materials of different structures.

The literature equations were corrected, and the equations were determined to be valid at intervals; however, certain restrictions must be taken.

Acknowledgements

The work is supported by the TÁMOP-4.2.2.A-11/1/KONV-2012-0041 project. The project is co-financed by the European Union and the European Social Fund.

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