HYGROTHERMAL BEHAVIOR OF ULTRA-LIGHTWEIGHT POLYSTYRENE CONCRETE

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Abstract: The aim of the paper is to investigate the hygrothermal properties of a newly developed ultra-lightweight polystyrene concrete, based on laboratory measurements. It describes the measuring process of thermal conductivities, and determines the declared thermal conductivity. The temperature and moisture conversion coefficients are determined, and new approximate functions are introduced. The paper describes the sorption and desorption isotherms, and gives polynomial approximate functions. The paper also investigates the temperature dependency of sorption curves. It determines the water absorption coefficient and the free water saturation. Furthermore, it describes the measuring process of the water vapor permeability. The water vapor resistance factor and water vapor diffusion-equivalent air layer thickness are calculated.

Keywords: Hygrothermal properties, Lightweight concrete, Laboratory measurements

1. Introduction

The polystyrene-concrete is porous, lightweight building material produced by replacing the normal aggregate with expanded polystyrene beads. Expanded polystyrene is an artificial, non-absorbent aggregate [1]. Recently there is an increasing demand for this material due to its low density resulting in smaller cross-sections of load-bearing elements and possible reduction of foundation sizes [1]. There were also researches of using recycled expanded polystyrene aggregate to decrease the embodied energy and carbon emission [2]; therefore this material can contribute to a higher environmental performance as well [3].

Polystyrene-concrete can be applied for floors, roofs as well as wall structures, utilizing its good thermal and acoustical insulation capability, low weight and better fire resistance [4]. Its low density and higher strength/weight ratio [4] are advantageous especially in case of slab structures. It can also be applied in Cold-Formed Steel structures (CFS), since the polystyrene aggregate concrete can provide continuous bracing [5]. This material is also resistant to biological degradation [6]. However, polystyrene concrete has relatively low compressible strength, moreover, the increasing volume of Extruded PolyStyrene (EPS) results in lower density and lower compressive strength [4].

The thermal conductivity of polystyrene concrete depends on mainly the type of granules and the density [7]. Increasing the ratio of polystyrene, i.e. decreasing the density of material results in lower thermal conductivity [4], [7]-[9]. This phenomenon is similar to the behavior of cornstalk natural insulation [10]. Laukaitis et al. reached the thermal conductivity of 0.06 W/mK at the ratio of cement to fine polystyrene granules 1:3, i.e. 167.8 kg/m^3 density [7].

Hoefer in his study determined a slightly exponential connection between the density of polystyrene concrete and the thermal conductivity [11]. His measured and calculated values are about 0.06 W/mK at 150-200 kg/m^3 density.

As for hygric properties, Krus conducted a comprehensive study for porous materials. He distinguished three regions of moisture storage:

- the region of sorption;
- the capillary water region; and
- the region of super-saturation [12].

He demonstrated that the sorption-desorption isotherms often show hysteresis, because of different wetting characteristics for sorption and desorption, or pore space geometry; however, in most cases, applying the sorption isotherm during hygrothermal calculations is accurate enough. He also found that the lower part of the sorption isotherm (up to about 15% Relative Humidity (RH) is characterized by a monomolecular coating, and above this relative humidity level a multi-molecular coating is developed, and this region ends at about 50% RH. The sorption characteristic is also temperature dependent, and it is necessary to take into account for hygrothermal simulations [13].

In porous materials the moisture transport has three mechanisms: vapor diffusion, surface diffusion and capillary condensation [14]. In usual case vapor and surface diffusion transfer moisture in the opposite directions; however, they can be combined by employing the water vapor resistance factor (μ) [15]. The water vapor resistance factor can be measured by 'dry-cup'/'wet-cup' method [16], [17]. The difference between the results of the two tests is due to surface diffusion, and it can be used for calculating the liquid conduction coefficient [15]. During capillary condensation the driving force is the capillary tension that corresponds to relative humidity [18].

The thermal conductivity is moisture dependent. According to measurements, the thermal conductivity of concrete increases linearly with moisture content, however the thermal conductivity of polystyrene foam shows an exponential increase [18]. The

standard [19] describes an exponential approximation for moisture conversion in case of every building material.

The thermal conductivity is also temperature dependent; however, the hygric conditions usually do not depend sensitively on thermal conductivity values [20]. Therefore, in most cases, the linear approximation of temperature dependency is sufficient enough [21]; however, in standard [19] the temperature conversion is described by an exponential function [22].

The investigated material is newly developed ultra-lightweight polystyrene concrete. It is cement-based, containing 14% portlandite and 19% $CaCO_3$ (*Fig. 1*). The mixture includes 170 kg/m^3 cement, 170 kg/m^3 water and 1200 l/m^3 EPS pearls with diameter of 4 mm. The density of the material is 166 kg/m^3.
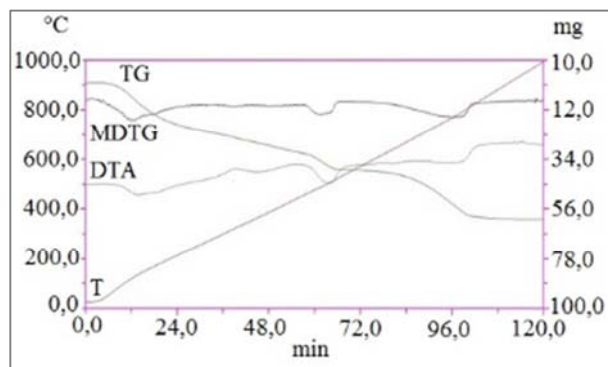

Fig. 1. EPS concrete samples and its derivatogram

2. Measurements

2.1. Thermal conductivity

16 dried-out samples were investigated at a temperature of 15, 25, and 35 °C. The measurements were carried out by a Taurus TLP 300 DTX thermal conductivity measuring instrument with guarded hot plate (*Fig. 2*). The Taurus instrument was placed under laboratory conditions (23 ± 2 °C, 50% ± 5% relative humidity). The size of samples were 15x15x10 cm, and they were edge protected by a 7.5 cm wide EPS

frame (*Fig. 2*) to avoid the influence of temperature and relative humidity of ambient environment. (It prevents humidity migration into/from the sample during measurement.) Based on results, the declared value was calculated at a temperature of 10 °C, furthermore the temperature and moisture conversion coefficients were also determined.
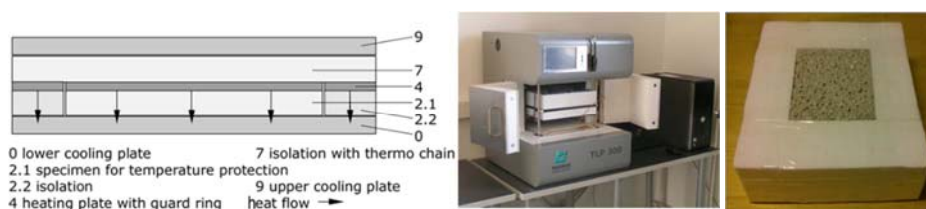

Fig. 2. TLP-300 DXT thermal conductivity measuring instrument with guarded hot plate
(left and middle), and the 15x15x10 cm sample in EPS frame (right)

The declared thermal conductivity was determined based on the standard [19], i.e. the test can be conducted under the following conditions: 10 °C or 23 °C on samples that are dried-out, or conditioned in climate chamber at a relative humidity of 50% until reaching constant weight. The measurements were conducted on dried-out samples at a 10 °C reference temperature. The results of measurements are summarized in *Table I*.

Table I

Measured thermal conductivities (dried-out samples, 10 °C) [W/mK]

SAMPLE	1.	2.	3.	4.	5.	6.	7.	8.
λ	0.0564	0.0538	0.0560	0.0555	0.0549	0.0559	0.0540	0.0552
SAMPLE	9.	10.	11.	12.	13.	14.	15.	16.
λ	0.0536	0.0540	0.0533	0.0538	0.0528	0.0528	0.0542	0.0547

Calculation of the declared value is summarized in *Table II*.

Table II

Calculation of declared thermal conductivity (10 °C)

Mean thermal conductivity (10°C, dry) [W/mK]	0.0544
Number of samples (n)	16
$k_{2,16}$ coefficient (p=90%)	1.84
$k_{2,16}$ coefficient (p=50%)	0.34
Estimators of the standard deviation (s)	0.0011265
Declared thermal conductivity (10°C), dry (p= 90%)	0.057
Declared thermal conductivity (10°C), dry (p= 50%)	0.055

2.2. Sorption and desorption isotherms

Sorption and desorption isotherms of test samples were determined with a Labmaster AW water activity measuring instrument and a precision scale with dryer [16] (*Fig. 3*). The laboratory measurements were carried out with different salt solutions according to the standard [23]. The dimensions of the cylinders shape samples were the following, diameter: 3 cm, thickness: 1 cm. The sorption and desorption isotherms generated from the measured data are shown in *Fig 4*.

Fig. 3. Labmaster AW water activity measuring instrument (left)
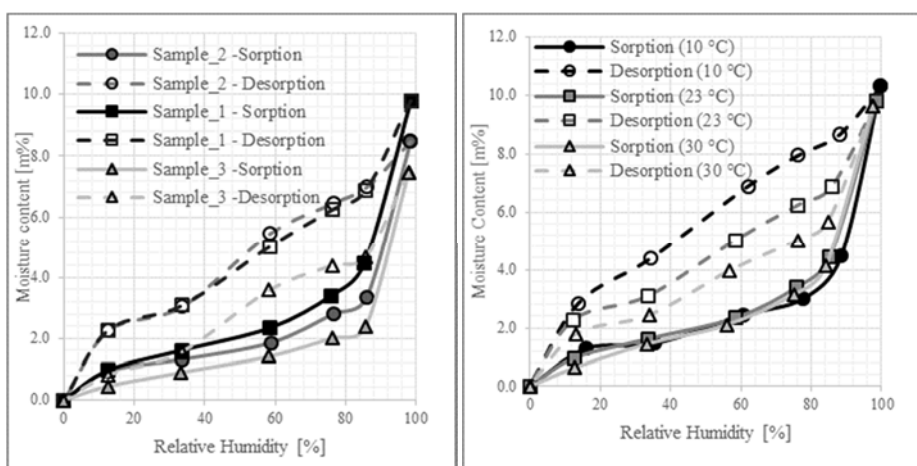and precision scale with dryer (right)

Fig. 4. Sorption-desorption isotherms (left)
and the temperature dependency of sorption curves (right)

The sorption/desorption curves depend on the temperature. However, the temperature has an impact mainly on desorption: the lower the temperature is, the lower the decrease of moisture content is, at decreasing relative humidity.

2.3. Water absorption

The water absorption was measured according to the standard [24], the water absorption coefficient was calculated by the following formula (1):

$$A_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{t_f}},$$
(1)

where, A_w [kg/m^{2}s$^{1/2}$] is the water absorption coefficient; $\Delta m'_{tf}$ [kg/m^2] is the amount of absorbed water at t_f time; $\Delta m'_0$ [kg/m^2] is the amount of absorbed water at t_0 time, $\sqrt{t_f}$ [$\sqrt{s}$] is the square root of the time period.

The results of measurement for the first 10 minutes (24.49 s$^{1/2}$) are plotted in *Fig. 5*. The water absorption coefficient is A_w=0.038 kg/m^{2}s$^{1/2}$, and the free water saturation is w_f=249.5 kg/m^3.
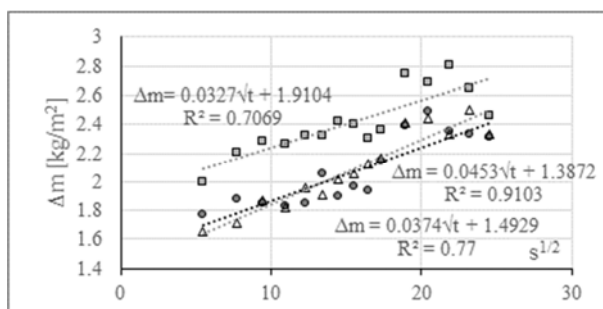

Fig. 5. Water absorption (above), the measured samples (below)

2.4. Water vapor permeability

The building physical parameters describing the vapor permeability of this special lightweight concrete i.e. water vapor permeability, water vapor resistance factor and water vapor diffusion-equivalent air layer thickness - were investigated according to the standard [25], [16].

During the measurement (*Fig. 6*), three aluminum bowls with a diameter of 145 mm, sealed by 30 mm thick specimens were taken onto high precision scales that were connected to a computer by a data logger. In the bowls, under specimens there was Magnesium nitrate salt solution providing constant relative humidity of 53% at the closed surface of specimens. The measurements were conducted under two different conditions: 'Dry cup' and 'Wet cup'.

Fig. 6. Vapor permeability measuring instrument

During the 'Dry cup' measurement 21% relative humidity and constant temperature were maintained in the climatic chamber. This constant relative humidity in the chamber was provided by Potassium acetate saturated salt solution. The salt solution in bowls lost weight, since it started drying out through the specimens. The decreasing weight of bowls was measured and recorded in every second, with a precision of 0.01 g.

During the 'Wet cup' measurement, the process was inverse, since the climatic chamber was set to 97% relative humidity by distilled water taken into the chamber. The salt solution in the bowls absorbed humidity through the special lightweight specimens; therefore the weight of bowls was increasing. The measurements were continued after reaching the steady-state vapor flow for at least 3 consecutive days.

The building physical parameters describing the vapor permeability were calculated from the measured data. The water vapor permeability (δ) can be calculated according to (2), based on the change of weight (m_2-m_1); the change of time (t_2-t_1); the difference in pressures; the *A* is the area and *d* is the thickness of the specimen,

$$\delta = \frac{\left|\dfrac{m_2 - m_1}{t_2 - t_1}\right|}{A \cdot \left|p_{chamber} - p_{bowl}\right|} \cdot d \; , \tag{2}$$

where m_1 is the mass of the test assembly at time t_1 [kg]; m_2 is the mass of the test assembly at time t_2 [kg]; t_2, t_1 are the successive times of measurements [s]; $p_{chamber}$ is the pressure in chamber [Pa]; $p_{bowl:}$ is the pressure in bowl [Pa]; A is the exposed area of the test specimen [m^2]; d is the thickness of specimen [m].

The water vapor resistance factor (μ) can be calculated by the following formula (3):

$$\mu = \frac{\dfrac{0.083 \cdot p_0}{R_v \cdot T \cdot p}\left(\dfrac{T}{273}\right)^{1.81}}{\delta} \; , \tag{3}$$

where, R_v is the gas constant for water vapor, 462 Nm/kgK; p_o is the standard barometric pressure, 1013.25 hPa; T is the thermodynamic temperature [K]; p is the water vapor pressure [Pa].

Due to the low value of the water vapor diffusion-equivalent air layer thickness ($s_d < 0.2$ m), the resistance of the air gap between the sample and the salt solution was taken into consideration according to the standard [25].

The building physical parameters describing the vapor permeability, based on laboratory measurements, are summarized in *Table III*.

Table III

Building physical parameters describing the vapor permeability ('Dry cup', 'Wet cup')

Water vapor permeability (δ) [kg/(m*s*Pa)]	3.37E-11	3.59E-11
Water vapor resistance factor (μ) [-]	5.72	5.53
Water vapor diffusion-equivalent air layer thickness (s_d) [m]	0.17	0.17

3. Results and discussion

3.1. Thermal conductivity conversion

Temperature conversion

The temperature dependency of thermal conductivity is shown in *Fig. 7*. The higher the temperature, the higher the thermal conductivity is.

According to standard the temperature dependency is determined by the following formula [19]:

$$F_T = e^{f_T(T_2 - T_1)} \; , \tag{4}$$

where F_T is the temperature conversion factor; f_T is the temperature conversion coefficient; and T_1, T_2 are the temperature values.
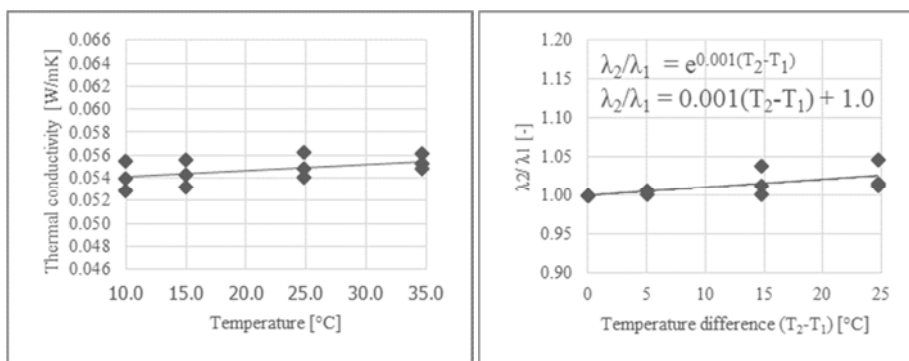

Fig. 7. Temperature dependency of thermal conductivity (left),
and approximation of temperature conversion (right)
according to standard [19] (dashed line)
and the linear approximate function (continuous line - overlapping)

The exponential approximation function factor is shown in *Fig. 7*. The temperature conversion coefficient is $f_T =0.0010$ K^{-1}. This value complies with the values of lightweight concretes declared in the standard [19] that is between 0.001-0.003 1/K depending on thermal conductivity. However, the 0.001 1/K value belongs to $\lambda=0.40$ W/mK thermal conductivity, which is much higher than the λ-value of the investigated material ($\lambda=0.057$ W/mK). Moreover, in case of $\lambda=0.10$ W/mK, the conversion coefficient is already 0.003 1/K (For $\lambda < 0.10$, the standard does not provide conversion coefficient.) The thermal conversion coefficients of expanded polystyrene are between 0.0030 and 0.0044. In case of the investigated ultra-lightweight concrete the thermal conductivity as well as the thermal conversion coefficient is low. This thermal conversion coefficient equals to the value of dense concrete.

Since in most cases a linear approximation of temperature dependency is sufficient enough [20], a new linear approximation function is introduced (applicable between 10-35 °C) (*Fig. 7*):

$$F_T = 0.001\left(T_2 - T_1\right) + 1.0 \tag{5}$$

where F_T is the temperature conversion factor and T_1, T_2 are temperature values.

Moisture conversion

The moisture dependency was investigated with 3 samples. Before measuring, the samples were taken into chambers with relative humidity of 33, 55, 74 as well as 97%. The conditions were made by different aqueous solutions and distilled water. (33% - $MgCl_2$; 55% - $Mg(NO_3)_2 \cdot 6H_2O$; 74% - NaCl; 97% - distilled water).

The measured thermal conductivity values at different moisture contents (mass by mass) are plotted in the *Fig. 8.*
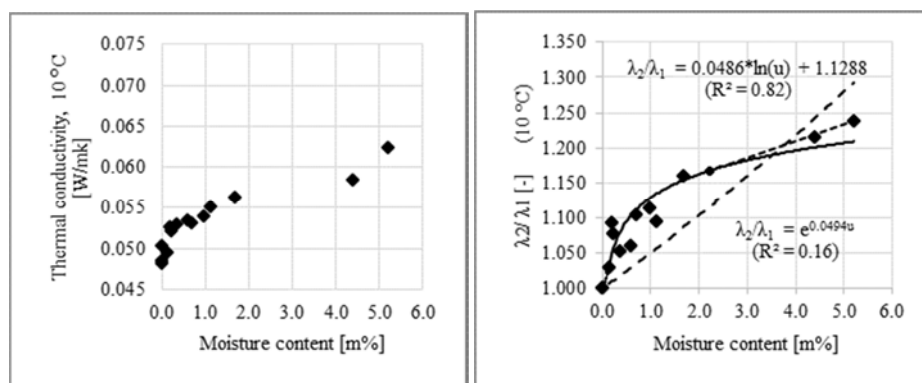

Fig. 8. Moisture dependency of thermal conductivity (left) and
the approximation of moisture conversation (right)
according to the standard [19] (dashed line)
and a new approximate function (continuous line and dense dashed line in the capillary
condensation phase)

According to the standard [19] the moisture dependency can be determined by the following formula:

$$F_m = e^{f_u(u_2 - u_1)}, \tag{6}$$

where F_m is the moisture conversion factor; f_u *is the* moisture conversion coefficient mass by mass; u_1, u_2 are the moisture content mass by mass.

The exponential approximation function factor is shown in *Fig. 8*. The moisture conversion factor is $f_u = 0.0494$ kg/kg. However, in case of this material exponential approximation does not estimate the thermal conductivity accurately ($R^2 = 0.16$), therefore, a natural logarithm function (7) is introduced that approximates the moisture dependency of thermal conductivity with higher precision before capillary condensation phase ($R^2 = 0.82$):

$$F_{m(0.12m\% < u < 2.20m\%)} = 0.0486 \cdot \ln(u) + 1.1288, \tag{7}$$

where F_m is the moisture conversion factor; u is the moisture content mass by mass.

At very low moisture content (<0.12m%), the moisture dependency can be approximated with a linear function:

$$F_{m(<0.12m\%)} = 0.250 \cdot u + 1.000. \tag{8}$$

During capillary condensation, the approximation function is also linear:

$$F_{m(>2.20m\%)} = 0.024 \cdot u + 1.115 \,. \tag{9}$$

Plotting the moisture conversion function along with the inverted sorption isotherm (*Fig. 9*), gives an opportunity to determine the moisture conversion factor for every relative humidity level. The inflexion points of the inverted sorption isotherm demonstrate the border of the three phases: monomolecular layer, multi-molecular layer (between 0.95 and 2.20 m% moisture content) and capillary condensation.
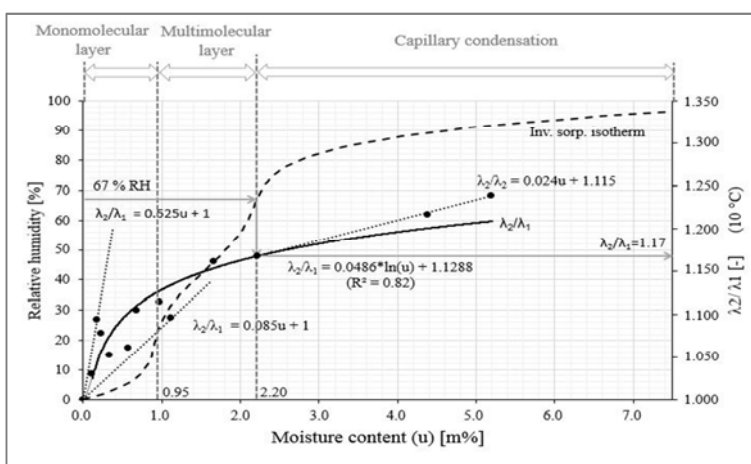

Fig. 9. Moisture conversion function (continuous line) along with the inverted sorption isotherm (dashed line)

The multi-molecular layer is developed at about 24% RH, and at this relative humidity level the F_m moisture conversion factor is 1.13 [-]. The capillary condensation begins at about 67% relative humidity. At the beginning of the capillary condensation the F_m moisture conversion factor is 1.17 [-].

3.2. Approximation of sorption and desorption isotherms

The sorption and desorption isotherms can be approximated by fifth-degree polynomial functions with high accuracy (*Fig. 10*):

$$m_{sorp}\% = 2 \cdot 10^{-8} \cdot \varphi^5 - 4 \cdot 10^{-6} \cdot \varphi^4 + 0.0003 \cdot \varphi^3 - 0.0098 \cdot \varphi^2 + 0.149 \cdot \varphi \,, \tag{10}$$

$$m_{desorp}\% = 2 \cdot 10^{-8} \cdot \varphi^5 - 5 \cdot 10^{-6} \cdot \varphi^4 + 0.0005 \cdot \varphi^3 - 0.0166 \cdot \varphi^2 + 0.2881 \cdot \varphi \,, \tag{11}$$

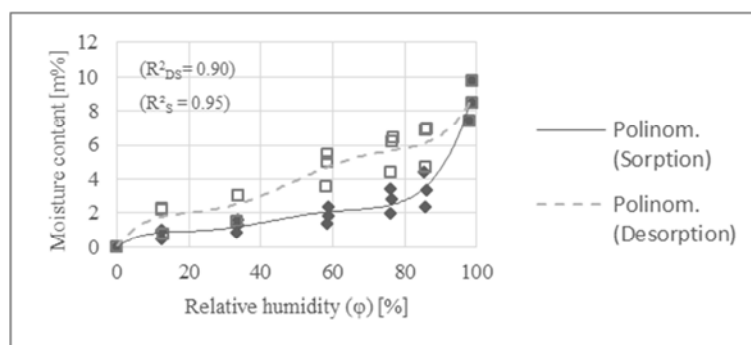where $m\%$ is the water content; $\varphi\%$ is the relative humidity.

Fig. 10. Approximation of the sorption and desorption isotherms

3.3. Water vapor permeability

The water vapor resistance factor (μ) [-] measured by the 'wet cup' test (μ_{wet}= 5.53) is smaller than the value measured by the 'dry cup' test (μ_{dry}=5.72); however, this difference is only 3.3%. The difference can be due to the surface diffusion, which is a liquid transport effect, and becomes noticeable at higher humidity level [15]. The small difference of water vapor resistance factors demonstrates that in case of this material, the effect of surface diffusion is significantly lower than the effect of vapor diffusion.

However, the difference also can be due to measurement uncertainty. The drying/saturation process of salt solutions changes slightly the relative humidity in the chamber as well as in the cups during measurements, and the scales are also exposed to the relative humidity in the chamber.

In summary, the results demonstrate, that within the investigated range of relative humidity in samples (37-75% RH), there is no significant difference in water vapor resistance factors, they can be considered identical, i.e. the vapor resistance factor (μ) is independent from the relative humidity.

4. Conclusions

The hygrothermal properties (including thermal conductivities, sorption and desorption isotherms, water absorption, water vapor permeability) of a newly developed expanded polystyrene concrete were measured in laboratory. Based on these measurements the declared thermal conductivity, water absorption coefficient, water vapor resistance factor and water vapor diffusion-equivalent air layer thickness were calculated.

The temperature and moisture conversion coefficients of the thermal conductivity were determined according to the exponential functions described in the standard then new approximation functions were introduced. For thermal conversion, a linear approximate function is recommended. For moisture conversion, a new ln(·) function is introduced for the phase before capillary condensation and two linear functions for the capillary condensation phase and for the case of very low moisture content. These

functions approximate the moisture dependency of thermal conductivity with higher precision, than the standard. Using the new moisture conversion function along with the inverted sorption isotherm, the moisture conversion factor can be determined at every relative humidity level.

The paper also investigates the sorption curves, and their temperature dependency. Fifth-degree polynomial approximate functions are introduced to approximate the sorption as well as the desorption isotherms with high precision. As for temperature dependency, the temperature has an impact mainly on desorption.

It is also concluded that, the vapor permeability of this material does not depend on the relative humidity, and the effect of surface diffusion is significantly lower than the effect of vapor diffusion.

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