SAFETY ENGINEERING OF ANTHROPOGENIC OBJECTS

ANALYTICAL MODEL OF WETTING THE POROUS MEDIUM

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Streszczenie

Celem tego artykułu jest opracowanie modelu analitycznego do określania osłabienia zdolności izolacji termicznej materiałów porowatych - wełny mineralnej i polistyrenu z powodu zwiększonej zawartości wody. W stanie suchym przyjęto, że próbka składa się ze szkieletu i wypełnionych powietrzem porów bez zawartości wilgoci procesowej. W stanie wilgotnym wzięto pod uwagę szkielet i pory suchego materiału z zawartością suchego powietrza i wilgoci. Ponadto przedstawiono wyniki badań procesu absorpcji wilgoci w różnych środowiskach nawilżających dla obu rodzajów materiałów. Na podstawie przyjętego modelu obliczeniowego wartość współczynnika przewodzenia ciepła w stanie suchym została ustalona na podstawie sumy iloczynów udziałów objętościowych poszczególnych składników próbki materiału, tj. szkieletu i porów. Uzyskane w ten sposób wyniki współczynnika przewodzenia ciepła λ są zgodne z wynikami uzyskanymi z pomiarów podczas eksperymentu. Umożliwiło to weryfikację poprawności przyjętego modelu obliczeniowego.
Słowa kluczowe: wilgotność w materiałach porowatych, współczynnik przewodzenia ciepła, nawilżanie

Abstract

The purpose of this article is to develop an analytical model for determining the weakening of the thermal insulation capacity of porous materials - mineral wool and polystyrene because of increased water content. In the dry state, it was assumed that the sample consists of a skeleton and air-filled pores without process moisture content. In the second shot, however, dry material skeleton and pores with dry air and moisture content were taken into account. In addition, the results of tests involving the process of absorbing moisture in different moisturizing environments for both types of materials were presented. Based on the adopted calculation model, the value of the heat conduction coefficient in the dry state was determined based on the sum of the products of the volume shares of individual components of the material sample, i.e. the apparent volume of the sample material skeleton and the volume of air pores contained. The results of the thermal conductivity coefficient λ obtained in this way are consistent with those obtained from measurements during the experiment. This allowed to determine the validation of the adopted calculation model.
Key words: humidity in porous materials, heat transfer coefficient, moisturizing

INTRODUCTION

The subject of this article is the presentation of the results of studies on the dependence of the moisture content of a material on its heat conduction characteristics, the development of a calculation model that allows determining the weakening of the thermal insulation capacity of porous materials commonly used for performing thermal insulation works in construction.

MODEL OF POROUS MATERIAL

In the dry state, it was assumed that the sample consists of a skeleton and pores filled with air without technological moisture.
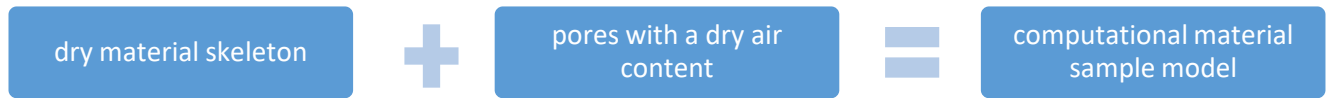
| dry material skeleton | ➕ | pores with a dry air content | ＝ | computational material sample model |

Fig. 2.1 The assumed calculation model in the dry state

As part of the dry state analysis, considerations began with determining the actual sample volume V_r. This volume was determined on the basis of dimensions. The apparent density of the material in the dry state was determined according to the definition:

$$\rho_{poz} = \frac{m_{ss}}{V_r} \tag{2.1}$$

The skeleton mass was obtained by subtracting from the sample mass two grams of process moisture. The next step is to determine the porosity of the material, which will ultimately allow the calculation of the pore volume in the material sample. So:

$$P = 1 - \frac{\rho_{poz}}{\rho_{rz}} \tag{2.2}$$

where ρ_{rz} is true density of solid material

The pore volume in the sample volume is the product of the porosity and the volume of the entire sample, because the porosity is the proportion of air-filled pores:

$$V_{por} = P \cdot V_r \tag{2.3}$$

After determining the volume of air pores contained in the sample, we can easily calculate the volume of the skeleton in the entire sample volume, as a difference of the total volume and volume of dry air pores in the sample:

$$V_{sz} = V_r - V_{por} \tag{2.4}$$

The coefficient of heat conduction λ of the porous medium was calculated as the sum of the products of volume shares and heat conduction coefficients of the components, i.e. the skeleton and pores of dry air. By ingredients we mean respectively air for pores and basalt for mineral wool and polystyrene for polystyrene. Volume shares:
- dry skeleton:

$$r_{sz} = \frac{V_{sz}}{V_r} \tag{2.5}$$

- dry air pores:

$$r_{por} = \frac{V_{por}}{V_r} \qquad (2.6)$$

As a consequence, the thermal conductivity coefficient λd of a dry porous medium was determined based on the following equation:

$$\lambda_d = r_{por} \cdot \lambda_{por} + r_{sz} \cdot \lambda_{sz} \qquad (2.7)$$

λ_{por} – dry air heat transfer coefficient 0.025 [W / mK],

λ_{sz} – heat transfer coefficient of dry skeleton: basalt - for mineral wool and polystyrene - for polystyrene, [W / mK].

In the case of taking into account the moisture content of the sample material, the following sample content scheme was assumed:
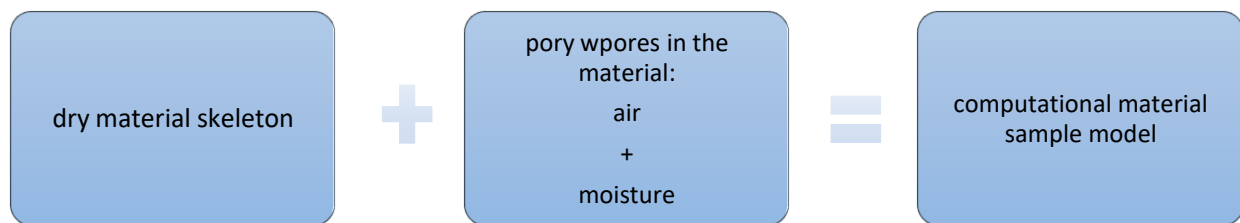
| dry material skeleton | **+** | pory wpores in the material:
air
+
moisture | **=** | computational material sample model |

Fig. 2.2 The assumed calculation model in the wet state

EVENT OF THE FIRST TYPE - MOISTENING OF THE MATERIAL WITH AMBIENT MOISTURE

In the event of the first kind we are dealing with a sample of material (polystyrene or mineral wool) subjected to the process of moistening with moisture from the air. The way the measurements were carried out allowed measurements of moisture content in individual events. First, we determine the value of apparent moisture density contained in the material:

$$\rho_l = \frac{m_l}{V_r} \qquad (2.8)$$

ρ_l – apparent density of moisture contained in the material, [g / cm3]

m_l – moisture mass contained in the material, [g].

According to Fig. 2.2, the pore volume in the material sample corresponds to the volume of air contained in the sample pores and the moisture that has entered the free spaces of the material from the humid environment. Therefore, we can save:

$$V_{por} = V_{pow} + V_l \qquad (2.9)$$

$V_l = \frac{m_l}{\rho_l}$ – volume of moisture contained, [cm^3]

ρ_l – water density = 0.997 g / cm^3.

The volume of air contained in the sample of material will be determined, therefore, from the difference between the total volume of pores and the volume of moisture contained in the pores:

$$V_{pow} = V_{por} - V_l \qquad (2.10)$$

The next step is to determine the saturation of the material with water, S. Saturation of the material with water is equal to the quotient of the volume of moisture contained in the material and the volume of pores.

$$S = \frac{V_l}{V_{por}} \qquad (2.11)$$

Similarly to the dry state, in the next step the volume shares r and of individual components constituting the sample in the wet state should be determined.

$$r_{sz} = \frac{V_{sz}}{V_{por}}, \quad r_l = \frac{V_l}{V_{por}}, \quad r_{pow} = \frac{V_{pow}}{V_{por}} \qquad (2.12)$$

Ultimately, the heat transfer coefficient is the sum of the products of the volumetric shares of individual components and their heat transfer coefficients.

$$\lambda_d = r_{pow} \cdot \lambda_{pow} + r_{sz} \cdot \lambda_{sz} + r_l \cdot \lambda_l \qquad (2.13)$$

EVENT OF THE 2$^{\text{ND}}$ TYPE - MOISTENING OF THE MATERIAL WITH MOISTURE FROM CAPILLARY ACTION AND THE ENVIRONMENT

This case consists of many factors describing the process of water absorption by a sample of material. The first is Pascal's law saying that liquid pressure has the same value in its entire volume, equal to the sum of the external and hydrostatic pressure exerted on the liquid. This pressure is always directed perpendicular to the vessel walls and surfaces of bodies immersed in the liquid, regardless of their shape. Analytically, hydrostatic pressure can be described as follows:

$$p = \rho \cdot g \cdot h \qquad (2.14)$$

ρ – liquid density, [kg / m^3],
g – gravitational acceleration, [N / kg],

h – liquid height relative to reference level, [m].

Knowing the value of hydrostatic pressure, we can determine the liquid stream that enters the material sample as a result of this pressure as:

$$q_m = grad\, p \cdot C \qquad (2.15)$$

q_m – stream of liquid caused by hydrostatic pressure,

$grad\, p$ – hydrostatic pressure gradient,

C – coefficient characterizing the porosity of the material and the resistance it generates during flow.

Capillary flow is another mechanism that directly affects the absorption of moisture or liquid water. The mechanism of capillary movement can be considered in the body diagram in the form of a parallel bundle of "tubes" - capillaries with the same radius. In the case of circular-shaped capillaries and the wetting liquid, the capillary walls of the meniscus take the form of a concave hemisphere. On both sides of the meniscus there is a pressure difference Δp conditioning the rise of liquid in the capillary. In the case of a capillary as shown in the radius r and cross-sectional area πr ^ 2, inclined to the vertical at an angle ϑ liquid movement will occur under the influence of capillary pull-up force:

$$F = \frac{2\sigma cos\theta}{r}\pi r^2 \tag{2.16}$$

It is a force balanced by three forces:
- inertia negligible due to the low flow rate:

$$\frac{d^2 l}{dr^2}\rho l\pi r^2 \tag{2.17}$$

- friction resulting from Poiseuille's law:

$$-\frac{8\eta l}{r^2}\frac{dl}{d\tau}\pi r^2 \tag{2.18}$$

- vertical gravitational force component:

$$g\rho l cos\vartheta\pi r^2 \tag{2.19}$$

So the force balance equation takes the following form:

$$\frac{2\sigma cos\theta}{r} + g\rho l cos\vartheta - \frac{8\eta l}{r^2}\frac{dl}{d\tau} = 0 \tag{2.20}$$
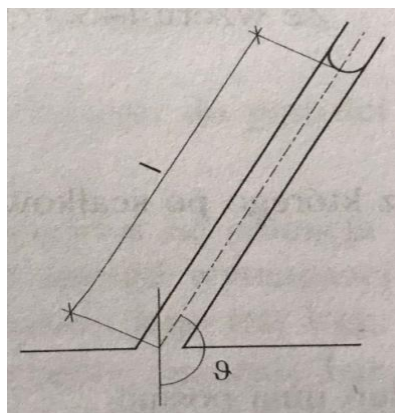

Fig. 2.3 Example of a capillary [5]

The total stream density of capillary moisture can be expressed by the formula:

$$q_m = -\frac{\rho^2 r^2}{8\eta} grad\left(-\frac{2\sigma cos\theta}{r\rho}\right) \qquad (2.21)$$

And hence present in the form:

$$q_m = -\lambda_m grad E \qquad (2.22)$$

$\lambda_m = \frac{\rho^2 r^2}{8\eta}$ - capillary moisture conduction coefficient,

$E = -\frac{2\sigma cos\theta}{r\rho} = \frac{\Delta p}{\rho}$ - ratio of capillary vacuum to water density.

The E value occurring here in terms of potential is called the capillary bonded moisture potential. The potential itself corresponds to the energy required to introduce a mass unit of water into the capillary, and its dimension is J / kg. Thermal diffusivity is an important parameter characterizing the heat exchange in solids. In the case of building walls, its knowledge allows to determine the dynamic thermal properties of the walls by solving the Fourier equation. Dynamic characteristics affect the indoor climate of the building, the selection of heating and air conditioning equipment and the length of the heating season. There are many works on the phase shift of the diurnal temperature variability, the surface thermal capacity and the attenuation coefficient where it is necessary to know the thermal diffusivity of the partition. [3] The value of diffusivity, and therefore also the error are variable in time, with the help of data it is possible to draw conclusions as to the conditions that must be met to determine the value of diffusivity in real measurements with the required accuracy. In the phenomenon of water vapor diffusion in the air treated as inert gas, which is right at the partial pressure of water vapor, which is about 3% of the total value of the humid air pressure, the vapor diffusion density is described by Fick's law [4]:

$$q_m = -\beta' grad\, c \qquad (2.23)$$

β' - mass transfer factor
c - concentration of water vapor in the air.

The concentration of water vapor in the air can be described as follows:

$$c = \frac{p}{RT} \qquad (2.24)$$

p - partial pressure of water vapor,
R - gas constant,
T - absolute temperature.

For small temperature differences in the considered system, it can be written that:

$$q_m = -\frac{\beta'}{RT} grad\, p = -\beta grad\, p \qquad (2.25)$$

This is also where the Krischer formula for coarse-porous materials comes from:

$$q_m = -\frac{\beta'}{\mu} grad\, p \qquad (2.26)$$

μ - diffusion resistance coefficient, defined as the ratio of the water vapor diffusion intensity through a layer of air thickness d to the diffusion intensity through a layer of material of the same thickness.

The β / μ ratio is called the vapor conductivity coefficient δ and is determined on the basis of water vapor flow through a material sample. Such tests are conducted in an isothermal environment by placing the material between two environments with different relative humidity. One of them is the air in the desiccator above the salt solution providing a certain relative humidity, the other is the air above water or a hygroscopic substance inside the sealed perimeter. Depending on the content of the vessel, the relative humidity in it can be around 100% above water or close to 0% above silica gel. Tests of thermal insulation materials indicate that their vapor conductivity factor does not depend on the test method. Lowering the sample temperature below zero has a greater impact. Then the ice crystals close the pores and the vapor conductivity of the materials decreases. The mass stream density by water vapor diffusion is described by the formula:

$$g = -\frac{\delta_0}{\mu} \cdot \frac{\Delta p}{\Delta x} = -\delta_0 \frac{\Delta p}{s_d} \qquad (2.27)$$

g - mass flow density
p – partial pressure of water vapor,
x - spatial coordinate,
μ - diffusion resistance coefficient,
s_d - diffusively equivalent air layer thickness,
δ_0 - water vapor diffusion coefficient in the air equal to $2 \cdot (10)^{(-10)}$ kg / m $\cdot$ s $\cdot$ Pa

To check the possibility of condensation in the partition, determine the temperature profile in the partition. Then, for subsequent values of determined temperatures, the value of saturated steam pressure is assigned. Where the actual steam pressure exceeds the saturated steam pressure for a given temperature value, steam condensation occurs.
Finally, the moisture model describes the density of the total moisture stream q:

$$q = -\delta_0 \frac{\Delta p}{s_d} - \frac{\rho^2 r^2}{8\eta} \, grad \left(-\frac{2\sigma cos\theta}{r\rho} \right) + C \cdot grad \, p \qquad (2.28)$$

Which gives simplified form:

$$q = -\beta' \cdot grad \, c + \lambda_m \cdot gradE + C \cdot grad \, p \qquad (2.29)$$

EXPERIMENTAL RESEARCH ON THE MOISTURE ABSORPTION RATE OF SELECTED MATERIALS

A parallel measurement of moisture content increases and changes in the value of the thermal conductivity coefficient for samples of mineral wool and polystyrene subjected to moisturizing processes by absorbing moisture from air, air and water were made. Samples of mineral wool and polystyrene with a volume of 2200 cm^3 were suspended freely in the air in a sealed container along with a 24-hour measurement of temperature and humidity in the air, and the same samples in terms of material and geometry were immersed in water to a height of h = 5 cm in the same sealed containers

with constant humidity and temperature measurement. Below is how the parameters regarding humidity [%] and temperature [^{o}C] have changed:
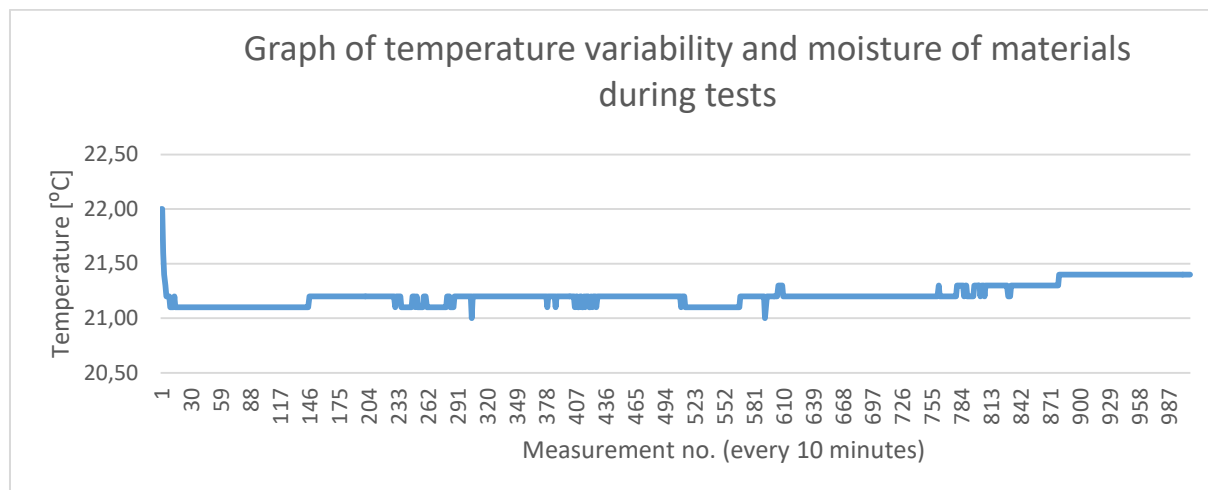
Fig. 3.1 Graph of temperature variability and moisture of materials during tests.

The test results are presented in the form of events. Each event covers a 24h research period. The following results were obtained as part of daily measurements:

Tab. 3.1 Measurement results for mineral wool suspended in the air.

Mineral wool in the air					

Description	Mineral wool. Air humidification 24 h 12-13.07.2018				
Dry mass of skeleton [g]	100.098000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	100.896	0.798000	0.007972	0.041200	5.167967
After	100.899000	0.801000	0.007999	0.041265	5.158881

Description	Mineral wool. Air humidification 24 h 13-14.07.2018				
Dry mass of skeleton [g]	100.098000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	100.899	0.801	0.007998828	0.0399	4.988230776
After	100.95	0.852	0.008512	0.040018	4.701362782

Description	Mineral wool. Air humidification 24 h 14-15.07.2018				
Dry mass of skeleton [g]	100.098000				

	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	100.950000	0.852000	0.008512	0.039900	4.687500
After	100.960000	0.862000	0.008612	0.039936	4.637300

Description	Mineral wool. Air humidification 24 h 15-16.07.2018				
Dry mass of skeleton [g]	100.098000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	100,960000	0,862000	0,008612	0,039936	4,637300
After	100,970000	0,872000	0,008711	0,039936	4,584500

Description	Mineral wool. Air humidification 24 h 16-17.07.2018				
Dry mass of skeleton [g]	100.098000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	100,970000	0,872000	0,008711	0,041200	4,729652
After	101,172000	1,074000	0,010726	0,041320	3,852321

Description	Mineral wool. Air humidification 24 h 17-18.07.2018				
Dry mass of skeleton [g]	100.098000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	101,172000	1,074000	0,010726	0,041320	3,852321
After	101,373000	1,275000	0,012741	0,041442	3,252649

Tab. 3.2 Measurement results for mineral wool immersed in water to a depth of h = 5 cm.

Mineral wool in the water

Description	Mineral wool. Humidification in the water 24 h 12-13.07.2018				
Dry mass of skeleton [g]	86,630000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	87,240000	0,610000	0,007000	0,040600	5,800000
After	218,133330	130,890000	1,500000	0,048200	0,032000

Description	Mineral wool. Humidification in the water 24 h 13-14.07.2018				
Dry mass of skeleton [g]	86,630000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w

Before	218,133333	130,890000	1,500000	0,048200	0,032000
After	268,980000	182,350000	2,100000	0,043400	0,020000

Description	Mineral wool. Humidification in the water 24 h 14-15.07.2018				
Dry mass of skeleton [g]	86.630000				
	Masa [g]	Masa wody [g]	Wilgotność masowa [w]	λ_w	λ_w/w
Before	268,980000	182,350000	2,100000	0,043400	0,020000
After	342,826700	256,200000	2,960000	0,046600	0,016000

Description	Mineral wool. Humidification in the water 24 h 15-16.07.2018				
Dry mass of skeleton [g]	86.630000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	342,826700	256,200000	2,960000	0,046600	0,016000
After	407,543300	320,910000	3,700000	0,052400	0,014000

Description	Mineral wool. Humidification in the water 24 h 16-17.07.2018				
Dry mass of skeleton [g]	86.630000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	407,543300	320,910000	3,700000	0,052400	0,014000
After	412,016700	329,390000	3,800000	0,054100	0,014000

Description	Mineral wool. Humidification in the water 24 h 17-18.07.2018				
Dry mass of skeleton [g]	86.630000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	412,016700	329,390000	3,800000	0,054100	0,014000
After	487,300000	404,673300	4,670000	0,049900	0,011000

Tab. 3.3 Measurement results for expanded polystyrene.

Styrofoam in the air

Description	Styrofoam. Air humidification 24 h 12-13.07.2018				
Dry mass of skeleton [g]	30,890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,040000	0,150000	0,004860	0,038300	7,880658
After	31,050000	0,160000	0,005180	0,038100	7,355212

Description	Styrofoam. Air humidification 24 h 13-14.07.2018				
Dry mass of skeleton [g]	30.890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,050000	0,160000	0,005180	0,038100	7,355212
After	31,050000	0,160000	0,005180	0,038100	7,355212

Description	Styrofoam. Air humidification 24 h 14-15.07.2018				
Dry mass of skeleton [g]	30.890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,050000	0,160000	0,005180	0,038100	7,355212
After	31,063300	0,173300	0,005610	0,039000	6,951872

Description	Styrofoam. Air humidification 24 h 15-16.07.2018				
Dry mass of skeleton [g]	30.890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,063300	0,173300	0,005610	0,039000	6,951872
After	31,183300	0,293300	0,009490	0,037800	3,983140

Description	Styrofoam. Air humidification 24 h 16-17.07.2018				
Dry mass of skeleton [g]	30.890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,183300	0,293300	0,009490	0,037800	3,983140
After	31,056700	0,166700	0,005400	0,038300	7,092593

Description	Styrofoam. Air humidification 24 h 17-18.07.2018				
Dry mass of skeleton [g]	30.890000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	31,056700	0,166700	0,005400	0,038300	7,092593
After	31,183300	0,293300	0,009490	0,038800	4,088514

Tab. 3.4 Measurement results for mineral wool immersed in water to a depth of h = 5 cm.

Styrofoam in the water

Description	Styrofoam. Humidification in the water 24 h 12-13.07.2018				
Dry mass of skeleton [g]	29,370000				

	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	29,520000	0,150000	0,005110	0,038800	7,592955
After	34,026700	4,656700	0,158550	0,037600	0,237149

Description	Styrofoam. Humidification in the water 24 h 13-14.07.2018				
Dry mass of skeleton [g]	29,370000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	34,020000	4,656700	0,158550	0,037600	0,237149
After	37,280000	7,910000	0,269320	0,041600	0,154463

Description	Styrofoam. Humidification in the water 24 h 14-15.07.2018				
Dry mass of skeleton [g]	29,370000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	37,280000	7,910000	0,269320	0,041600	0,154463
After	39,766700	10,396700	0,035399	0,039100	1,104551

Description	Styrofoam. Humidification in the water 24 h 15-16.07.2018				
Dry mass of skeleton [g]	29,370000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	39,766700	10,396700	0,035399	0,039100	1,104551
After	36,953300	7,583300	0,258200	0,041900	0,162277

Description	Styrofoam. Humidification in the water 24 h 16-17.07.2018				
Dry mass of skeleton [g]	29,370000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	36,953300	7,583300	0,258200	0,041900	0,162277
After	40,436700	11,066700	0,376800	0,042000	0,111465

Description	Styrofoam. Humidification in the water 24 h 17-18.07.2018				
Dry mass of skeleton [g]	29.370000				
	Mass [g]	Water mass [g]	Mass humidity [w]	λ_w	λ_w/w
Before	40,436700	11,066700	0,376800	0,042000	0,111465
After	37,960000	8,590000	0,292480	0,042700	0,145993

The measurement results obtained are comparable to the results obtained in the work of M. Jerman and R. Cerny [1]. In this article, in addition to construction materials, expanded polystyrene and lamella mineral wool were also tested.

According to the theoretical model of a porous medium, an analytical method was determined based on measurement results, distinguishing dry state and wet state, the value of heat conduction coefficient λ of a dry material sample and moist material sample, apparent moisture density contained in moist materials and saturation with water S. Obtaining the last two in as a result of calculations, diagrams of their mutual dependence were drawn up. And so, the distribution of these parameters is presented in the following charts (Fig. 3.2 - Fig. 3.5):
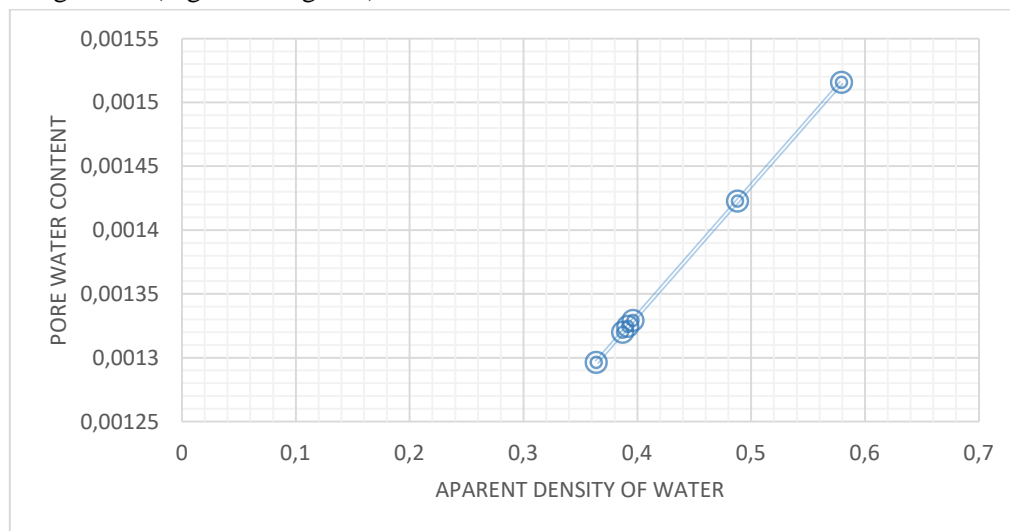

Fig. 3.2. Relationship between the apparent density of water contained and the saturation of pores with water for mineral wool suspended freely in the air.
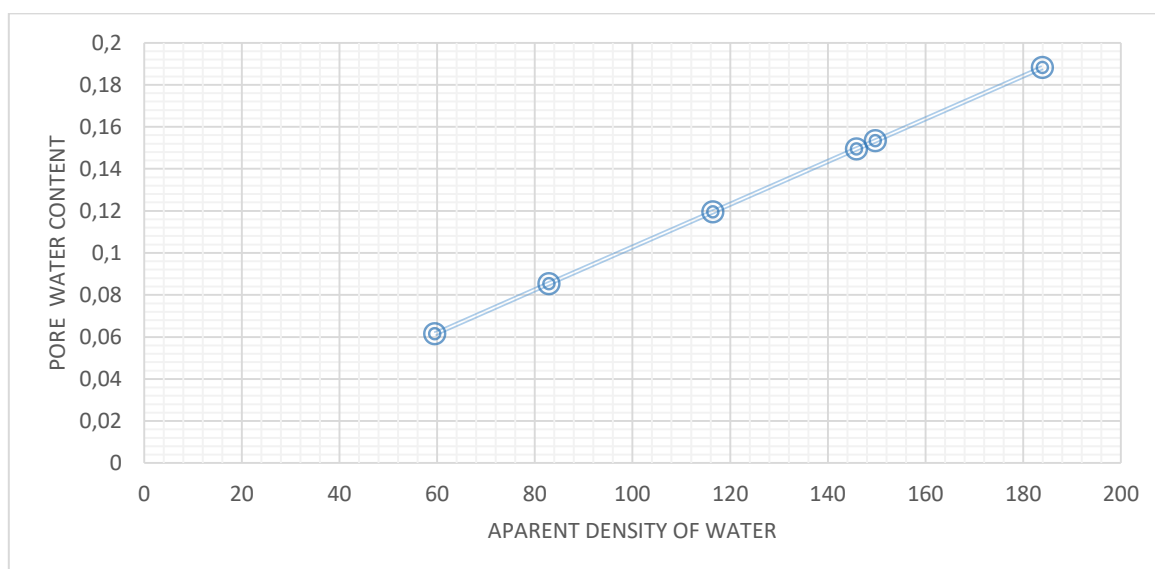

Fig. 3.3. Relationship between the apparent density of water contained and the saturation of pores with water for mineral wool immersed to a height of h = 5 cm in water.
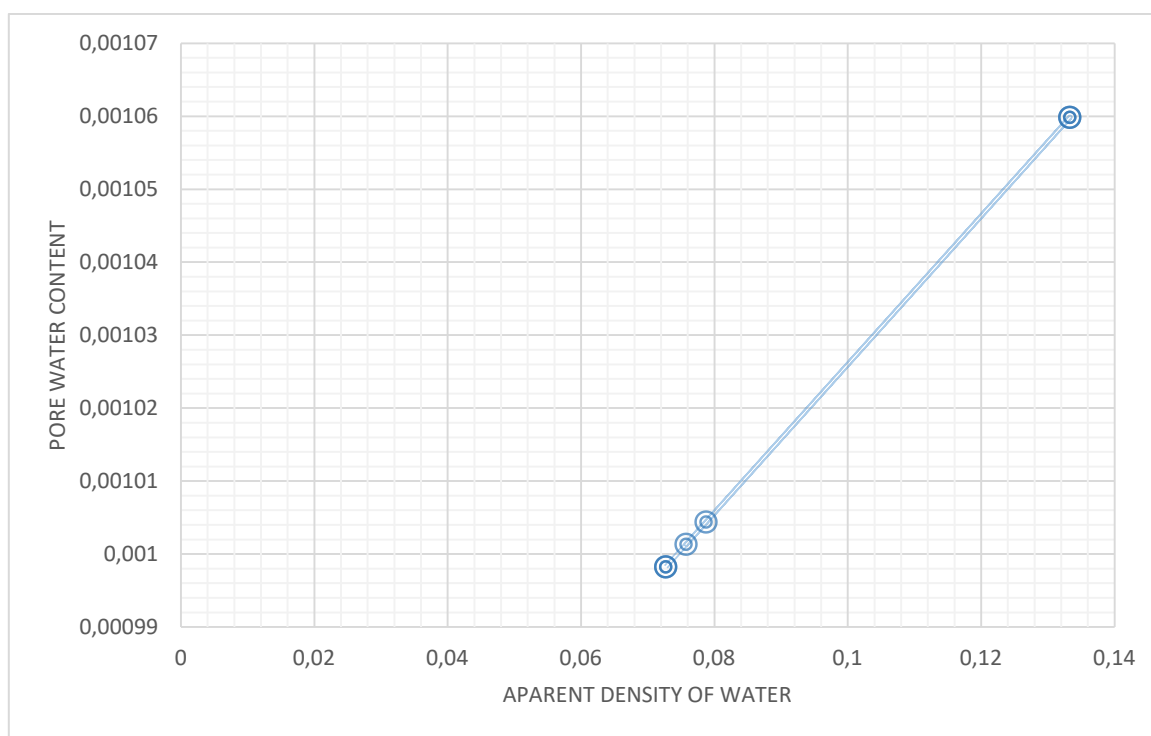
Fig. 3.4. Relationship between the apparent density of water contained and the saturation of pores with water for polystyrene hanging freely in the air.
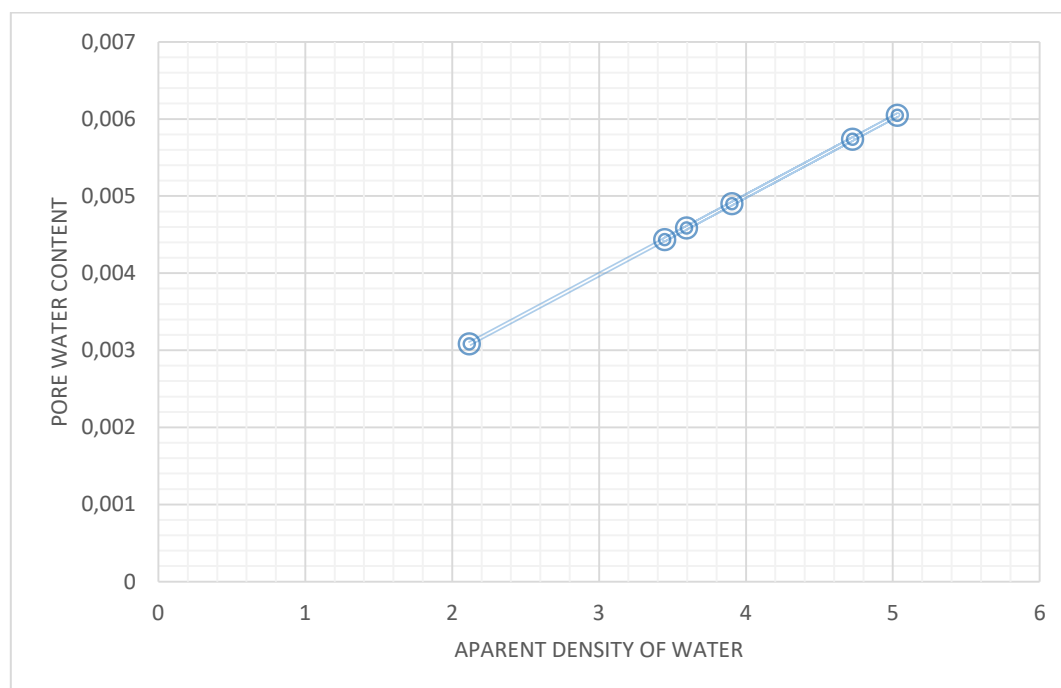

Fig. 3.5. Relationship between the apparent density of water contained and the saturation of pores with water for foamed polystyrene immersed up to a height of h = 5 cm in water.

Below is a summary of the measurement results and corresponding values of the apparent density of water and the saturation of the pores with water.

Tab. 3.5 Summary of apparent water density and water saturation of the pores

	Mineral wool in air		Mineral wool in water		Foamed polistrene in air		Foamed polistrene in water	
Lp.	Density [g/cm^3]	Saturation	Density [g/cm^3]	Saturation	Density [g/cm^3]	Saturation	Density [g/cm^3]	Saturation
1	0,364090909	0,001296460	59,495454545	0,061508938	0,072727273	0,000998250	2,116681818	0,003083774
2	0,387272727	0,001320065	82,886363636	0,085327510	0,072727273	0,000998250	3,595454545	0,004586903
3	0,391818182	0,001324694	116,454545455	0,119509428	0,078772727	0,001004396	4,725772727	0,005737887
4	0,396363636	0,001329323	145,868181818	0,149460842	0,133318182	0,001059855	3,446954545	0,004435688
5	0,488181818	0,001422819	149,722727273	0,153385861	0,075772727	0,001001346	5,030318182	0,006048001
6	0,579545455	0,001515854	183,942409091	0,188231191	0,133318182	0,001059855	3,904545455	0,004901645

For individual cases, the charts were approximated by connecting points of obtained results. In each of them the graph is a linear function. According to the porous material model, the co-tangent of the angle of inclination α of the approximated linear function to the X axis, i.e. to the apparent density of water, was determined.

$$ctg\,\alpha = \frac{\Delta\rho}{\Delta S} = \frac{\dfrac{\Delta m_l}{V_c}}{\dfrac{\Delta V_l}{V_{por}}} = \frac{\Delta m_l}{V_c}\frac{V_{por}}{\Delta V_l} = \frac{\Delta m_l V_c P}{V_c \Delta V_l} = \frac{\rho_{rzl}\Delta V_l P}{\Delta V_l} = \rho_{rzl}P \tag{3.1}$$

As a result of calculations, the following results were obtained in accordance with Table 3.6:

Tab. 3.6 Summary of the co-angle value of the angle of inclination α of the approximated linear function to the X axis

Mineral wool in air		Mineral wool in water		Foamed polistrene in air		Foamed polistrene in water	
ctg α =	982.045	ctg α =	982.045	ctg α =	983.540	ctg α =	983.540

The obtained value is almost comparable for each moisture event - both for the case of mineral wool in both moisture tests and for foamed polystyrene also in both moisture tests.

In order to compare the values of the thermal conductivity coefficient obtained from the model presented in this article and measurements, charts were prepared in the coordinates of both coefficients. If they are completely compatible, the charts should be straight lines. Deviations from a

straight line can therefore be taken as a sure match between model and measurement. The squares of the distance from the vertical axis from the line y = x were calculated for individual points and added up.

Tab. 3.7 Theoretical and measured lambda coefficients for wool in the air

Moisture mass [g]	Lambda measurement λ_p [W/(mK)]	Lambda calculated λ_t [W/(mK)]	$(\lambda_p - \lambda_t)^2$
0,801	0,041265	0,04301	3,04502E-06
0,872	0,039936	0,043926	1,59201E-05
0,852	0,0399	0,04391	1,60801E-05
1,074	0,041320	0,043988	7,11822E-06
0,862	0,039936	0,043904	1,5745E-05
1,275	0,041442	0,044046	6,78082E-06
Sum:			6,46893E-05

Tab. 3.8 Theoretical and measured lambda coefficients for wool in water

Moisture mass [g]	Lambda measurement λ_p [W/(mK)]	Lambda calculated λ_t [W/(mK)]	$(\lambda_p - \lambda_t)^2$
130,89	0,0482	0,087242	0,001524278
320,91	0,0524	0,15438	0,01039992
182,35	0,0434	0,104439	0,00372576
329,39	0,0541	0,154228	0,010025616
256,2	0,0466	0,12845	0,006699423
404,6733	0,0499	0,177073	0,016172972
Sum:			0,048547968

Tab. 3.9 Theoretical and measured lambda lambda coefficients in the air

Moisture mass [g]	Lambda measurement λ_p [W/(mK)]	Lambda calculated λ_t [W/(mK)]	$(\lambda_p - \lambda_t)^2$
0,16	0,0381	0,026697	0,000130028
0,2933	0,0378	0,026744	0,000122235
0,1667	0,0383	0,026696	0,000134653
0,1733	0,039	0,026698	0,000151339
0,2933	0,0378	0,026739	0,000122346
Sum:			0,000660601

Tab. 3.10 Theoretical and measured lambda coefficients for foamed polystyrene in water

Moisture mass [g]	Lambda measurement λ_p [W/(mK)]	Lambda calculated λ_t [W/(mK)]	$(\lambda_p - \lambda_t)^2$
4,6567	0,0376	0,0281211	8,98495E-05

7,5833	0,0419	0,0291764	0,00016189
7,91	0,0416	0,029217	0,000153339
11,0667	0,042	0,0303208	0,000136404
10,3967	0,0391	0,03	8,281E-05
8,59	0,0427	0,0293195	0,000179038
Sum:			0,00080333

The smallest sum of deviations occurs for wool moistened in air, the values calculated from the model correspond to measurements. The proposed measure only indicates that the distribution of points is the least different from the straight line, but it cannot be interpreted strictly as the accuracy of the model, because the coefficients were calculated at different water contents. In second place is a sample of expanded polystyrene moistened in air. For such a process, the moisture gradients in the sample are smaller than for moisturizing in water, which probably contributes to the fact that the measured values show a slight deviation from the average value obtained from theoretical calculations.

CONCLUSIONS

Based on the adopted calculation model, the value of the heat conduction coefficient in the dry state was determined based on the sum of the products of the volume shares of individual components of the material sample, i.e. the apparent volume of the sample material skeleton and the volume of air pores contained. The results of the thermal conductivity coefficient λ obtained in this way are consistent with those obtained from measurements during the experiment. This allowed to determine the correctness of the adopted calculation model. A similar approach was taken when determining the value of the thermal conductivity coefficient λ in a wet state. In this case, in addition to the volume fraction of the sample skeleton and air, the volume of moisture contained in the material was taken into account. In addition, the value of pore water saturation S was determined for each event and graphs of the dependence of apparent water density on the pore moisture saturation were made. For each event, a graph was identified of the relationship between the apparent density of water and the saturation of pores with water. In each of them the graph is a straight line. The inclination of the approximated graph to the X axis (angle α) was then investigated by calculating the co-angle value of that angle. For mineral wool suspended in a humid environment and immersed in water, the ctgα-wool values are equal to 982,045. For expanded polystyrene suspended freely in the air and immersed in water, these values also overlap, and what is more, they are very similar to the results obtained for mineral wool ctgα styrofoam = 983,540.

Therefore, a method of determining the value of the thermal conductivity coefficient λ of a porous medium was obtained in both dry and wet condition. For such an analysis, the characteristics of the dry material and the mass content and consequently the volume moisture contained in the material must be known. The model used refers to porous media, no less proved its validity limited to the most commonly used thermal insulation materials in construction. It can be used when estimating the necessary value in performing thermal insulation of building elements, knowing in advance or assuming the threat that results from moisture in the thermal insulation material. Moisture in construction is a particularly dangerous aspect when it comes to durability, performance and climatic comfort of a building, because if it gets inside the building structure it is extremely difficult to remove.

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