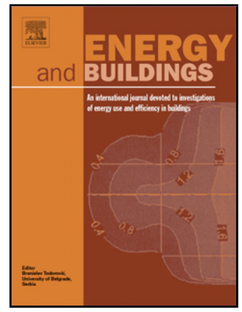

Title: Investigation of the moisture induced degradation of the thermal properties of Aerogel blankets: measurements, calculations, simulations

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Investigation of the moisture induced degradation of the thermal properties of Aerogel blankets: measurements, calculations, simulations

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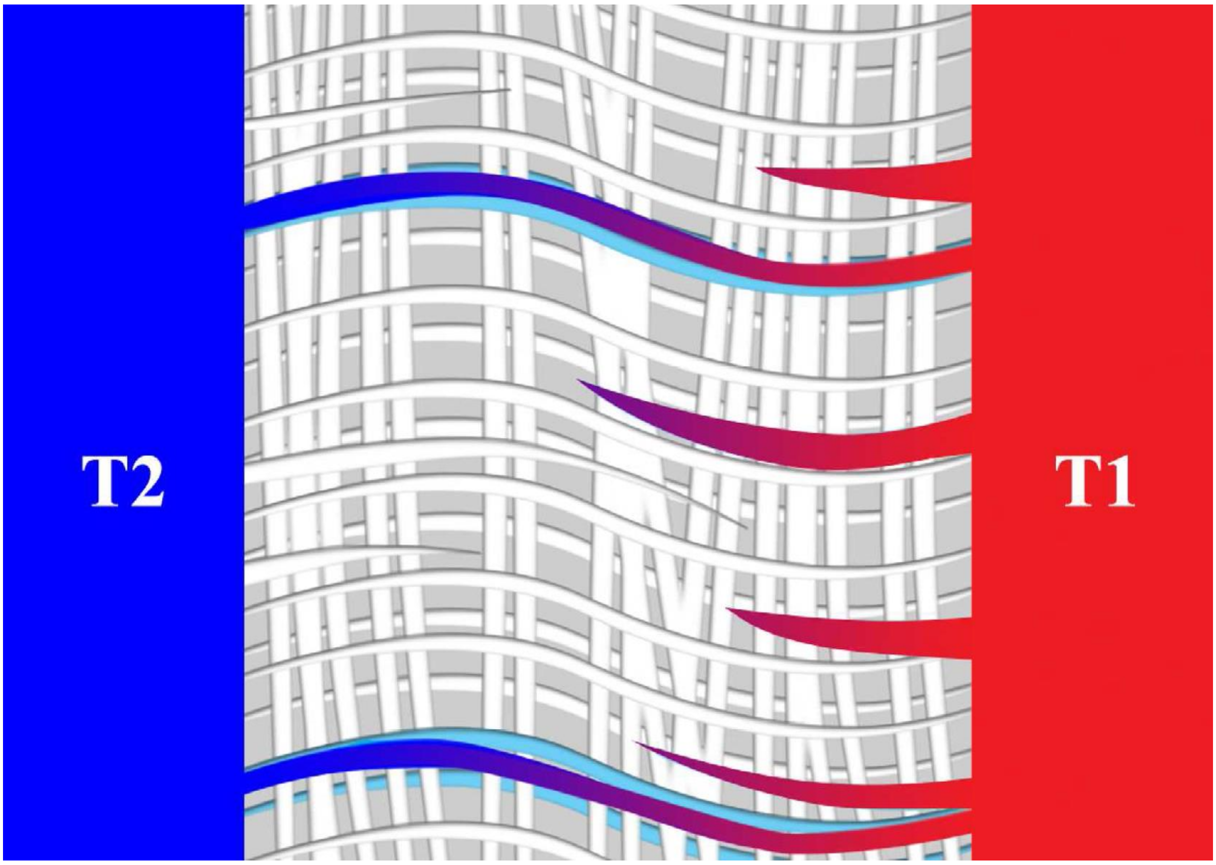
Graphical abstract



Highlights

- Three new sorption isotherms and water absorption coefficient for aerogel is given
- New moisture supplement for the thermal conductivity for aerogel is given
- Decreasing resistance of a wall covered with moist aerogel was tested
- 20 % moisture content increases the heat flux with 20% of an in-built system
- Heat and primary energy demands of a building are changing with moisture content

Abstract

Nowadays to reduce the energy loss as well as to minimize the emission of the green house gases of buildings can be solved by thermal insulating. Silica aerogels have a promising potential in the building and construction sector as thermal insulation due to their excellent thermal conductivity. At the present time the applications of silica aerogel blankets are truly widespread. This study focuses on the moisture induced degradation of the thermal conductivity of the above mentioned insulation slabs. Experimental studies show that the thermal conductivity of the aerogel blankets can be increased significantly (approximately 20-

40 %) after wetting them. For this case different types of investigations were carried out to investigate the changes in the thermal conductivity derived by the moisture content. Firstly, in order to see the temperature sensitivity of the moisture up-taking, sorption isotherm curves were registered at 283, 293 and 303 K after 24 hours after drying and wetting at 5 different relative humidities. Secondly, the decrease of the thermal conductivity was followed with a Holometrix type heat flow meter of individual aerogel slabs after wetting the dried samples for 0, 4, 8, 12, 16, 20 hours at 293 K and 90% relative humidity in a Climacell type climatic chamber. Finally, the change in the thermal resistance of a brick based wall covered with 0.013 cm thick aerogel insulation was registered by calibrated chamber method in function of the quantity of sprayed water. From the measurement results calculations were executed to see the changes of the thermo-physical properties of the aerogel samples due to the water absorption. The novelties of the article can be found in the comparison of the measurements of the same values and properties carried out by different methods. Moreover, the measurement results formed the basis of Building Energetic Simulations in order to show roughly the effect of the moisture.

Graphical abstract

In the graphical abstract one can see an aerogel blanket between a source (warm, T_1) and a sink (cold, T_2). The fast ways of the heat through the moist paths of the blanket are visible from wall to wall. These fast ways are representing the moisture increased conductive and convective part of the thermal conductivity of aerogel. The ways of the heat through the dry paths are also visible.

Keywords: Silica aerogel; moisture content; heat transfer, thermal conductivity

Nomenclature

Indexes:

cc: measured by Calibrated Chamber

is: internal surface

es: external surface

Properties:

T: temperature (K)

ΔT: Temperature difference (K)

t: time (h)

Φ: heat flux (W/m^2K)

λ=k: thermal conductivity (W/mK)

α: surface heat transfer coefficient (W/m^2K)

Δx=d: thickness (m)

R: Resistance (m^2K/W)

ρ: density (kg/m^3)

V: volume (m^3)

Z: moisture supplement for the thermal conductivity

A_w: water absorption coefficient (kg/m2s1/2)

U-value: Overall heat transfer coefficient (W/m2K)

1. Introduction

In the European Union, buildings account for about 20 - 40% of the total energy consumption [1-4]. This energy consumption contributes to producing around 25 – 30% of CO_2 emissions. The reduction both of the energy consumption and the emission of the green house gases can be achieved by thermal insulation. Several insulation materials are available, but the application of silica aerogel is very promising. The application of the aerogel is said to be a state-of-the-art thermal insulation solution, and looks to be the most reasonable one with the highest potential. Aerogel blankets/panels have already been used at all parts of the building envelopes except by the moisture loaded parts. Commercially available and affordable state-of-the-art aerogels have been reported to have excellent thermal conductivities between 0.014 and 0.022 W/(mK) at ambient pressure. However, its high production costs go against its applications. Aerogels have relatively high compression strength, but they are very fragile due to their very low tensile strength, moreover, the blanket/fibrous one is very dusty. A very interesting aspect with aerogels is that they can be produced as either opaque (in a blanket), translucent or transparent materials, thus enabling a wide range of possible building applications (window, external coating). [5-9] The heat transfer mechanisms for silica aerogel is clearly written and presented in a latest paper. [10] The laboratory measurements of the individual building materials as well as the building structures are very important if one would like to give the correct declared values of the thermal properties. In energy efficiency hygric performance is a key consideration in building envelope design. Moisture can cause undesirable changes both in the thermal properties of the materials and in the structure of the wall. These are clearly written in Ref. [11-17]. The novelty and the objective of this paper is to present a combined experimental and theoretical method to investigate the change in the thermal properties of the aerogel blankets derived by wetting both individual and in-built samples. Based on the measurement results calculations were carried out to show the change in the thermal transmittance, heat flux and in the surface heat transfer coefficients, moreover in the thermal inertia and heat absorption due the sorped amount of water. The temperature dependency of the moisture up-taking was also followed. As a result through estimations the change in the energy performance of a family house was also simulated and presented.

2. Theory

2.1. The sorption isotherms

Sorption isotherms are key characteristic of the materials. The sorption isotherm graphs can be easily reached by plotting the amount of the water taken up from the air in function of the certain relative humidity value at constant temperature. Different sorption isotherm graphs can be expected for different ambient temperatures. Because of the complexity of sorption processes isotherms cannot be determined by calculation, but should be recorded experimentally for each material, however different models for fitting and predicting the isotherm graphs are also available. The further effects of the moisture are clearly written in Ref. [12-17]

2.2. Thermal properties

In this article the most important thermal properties (thermal conductivity, resistance, heat absorption and thermal inertia) of the dry and moist aerogel samples are tested. Details about these building physics parameters can be found in Ref 16 and 17.

3. Materials and methods

3.1.The samples

Five opaque aerogel samples with 0.1 m x 0.1 m x 0.013 m for the sorption and five other samples with 0.3 m x 0.3 m x 0.013 m geometries for the thermal conductivity measurements were prepared from a fibrous blanket. For the thermal resistance measurements a continuous sample with 1.2 m x 1.2 m = 1.44 m^2 area was applied. The production of the materials was carried out in three steps by the manufacturer. The method for the production is clearly written in Ref [10]. At first, the fibrous batting was filled with a liquid-solid solution, then the solvents were extracted with supercritical carbon dioxide, finally the fiber-reinforced aerogel blanket forms were dried. For the thermal transmittance measurements the aerogel blanket was fixed on the wall with an acryl-styrene based insulation fixing glue. The thermal effect of this glue in the thermal conductivity of the aerogel can be neglected. Here should be noticed that on the wall no mechanical fixings were used. [10]

3.2.The sorption isotherm measurements

The sorption isotherm measurements were carried out by using the ISO 12571: 2013 standard (Hygrothermal performance of building materials and products -- Determination of hygroscopic sorption properties, Part B- climatic chamber method). The standard prescribes the measurement's order. The sorption measurements were carried out after drying the samples in a VentiCell drying laboratory oven to changeless weight regarding to the above mentioned standard for at least 24 h. In this equipment the samples can be dried up to 523 K ambient temperature. The homogeneity of the air temperature inside the chamber is can be reached by its inbuilt ventilator [12, 13, 17]. Before humidity treating the samples in the climatic chamber drying procedure was executed to changeless weight at 343 K under normal atmospheric pressure. This temperature was chosen because during the dehydrating process at this temperature the material does not suffer losses in its physical and chemical properties; moreover this temperature is fairly under the melting point of the aerogel sample (1473 K). To determine the sorption isotherm curves (moisture content of material in function of relative humidity (RH %) of air) fives samples were kept at 283, 293 and 303 K temperatures in the climatic chamber under 35, 50, 65, 80 and 90 % RH for 24 hours. The water/moisture content (ω %) of a solid material can be calculated from the next simple equation:

$$\omega=(m_w-m_d)/m_d \qquad \text{(Eq. 1)}$$

where m_d and m_w are the mass of the dried and the damped samples respectively. The results were obtained by averaging the five measurement results at a given temperature and relative humidity. The measurement method is clearly written in Ref. [12, 13, 17]

3.3.Steady State thermal conductivity measurement of wet samples

For measuring the thermal conductivity of individual materials Holometrix lambda 2000 Heat flow meter was used. The measurements were executed as the rules of the EN ISO 12664:2001 standard (Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Dry and moist products of medium and low thermal resistance). The thermal conductivity measurements were carried out after drying the samples in a laboratory oven as above mentioned to constant mass. The mechanisms, details and reproducibility of the heat flow meter are clearly written in our previous articles [10-13, 17]. To investigate the effect of moisture on thermal conductivity of the aerogel samples the above mentioned three equipments (Venticell, Clamicell and Holometrix) were combined. In order to attain the different wetness levels a Climacell (CLC) type laboratory incubator (climatic chamber) was used at 90% relative humidity and at 293 K temperature for 4, 8, 12, 16 and 20 hours. The 90 % relative humidity was chosen because it is the maximum humidity performance of the chamber. We wanted to load the samples with the moisture as much as we could. The temperature was fixed to 293 K because we did not observe any temperature dependency in the sorption properties. The reason to choose the 20 hours as the maximum wetting time comes from the directions of the ISO 12571 standard. The standard states that for reaching the sorption isotherm the materials should be wetted for at least 24 hours to reach the equilibrium. In this case we did not want the exchange of the water vapor between ambient air and material to reach the equilibrium point. In order to avoid any natural desorption from the surface of the wetted samples a foil layer was applied onto it.

3.4.Water absorption and moisture supplement

Thermal conductivity of wetted materials depends on their moisture content. Most of the time it will be conduction through the solid and the gas phase, however, if the pore size is “big” enough the convection of the filling gas can appear. In practice the influence of the moisture on thermal conductivity is given by the percentage of difference in wetness levels. In Ref. [12, 13, 16, 17] a simple approximate calculation is presented to find the thermal conductivity at certain moisture content:

$$\lambda_w=\lambda_0(1+(\omega Z/100)) \qquad \text{(Eq. 2)}$$

where: λ_w, λ_0 are the thermal conductivity of the wet sample and the dried sample respectively and Z is a material constant, presents the moisture supplement for the thermal conductivity.

The water absorption coefficient of the materials can be determined by using the following equation:

$$A_w=(m_w-m_d)/A(t)^{1/2} \qquad \text{(Eq. 3)}$$

where A_w is the water absorption coefficient in $kg/m^2s^{1/2}$. Following the definition, the water absorption coefficient A_w is given by the slope of the fitted curve divided by the contact area (A).

3.5.Steady State Thermal Transmittance measurements

These measurements are clearly written in our previous studies; however, this paper will introduce the method in brief. [18-20]. In order to measure the thermal resistance of in-built layer structures an adiabatic chamber, with zero heat loss is available (see Ref. 18-20 for details). The chamber is built from 0.5 m thick EPS 200 insulation sandwich system divided into two rooms (cold and warm) with about 7.5 m^2 areas each. In the temperatures between the rooms maximum 55 K difference can be reached. The cold room can be cooled down by three separated cryogenics. The warm room can be heated up by a portable electric radiator. In the middle of the dividing-wall a brick wall window with 0.25 m thickness and 1.44 m^2 surface area can be found, covered with 0.015 m conventional plaster at both sides. For the thermal transmittance measurements the base wall was covered with a 0.013 m thick aerogel insulation layer on the cold side, and as previously mentioned it was only fixed chemically. [18-20] The determination of steady-state thermal resistance and thermal insulation of wall structures by calibrated chamber (CC) should be executed according to the EN ISO:8990 standard. The details of the measurements can be found in Ref [18-20]. For these measurements a hot box is available at the warm side of the wall, made from a 0.1 m thick EPS 200 sandwich panel closed with 0.02 m thick OSB layers inside and out. The surface temperatures of the walls were given as the average of 16 measured temperatures values; moreover the air temperatures were measured with 4-4 pieces of Pt-100 type thermocouples. The temperatures values were taken in 5 minutes steps. Inside the box a small fan was used to circulate air and it was heated by two bulbs with 40 W electric powers each. The electric power of both the fan and the bulbs was measured outside the box with two calibrated electronic meters separately. The details both of the measurements with calibrated chamber and the calculation method is presented in Ref. [10, 18-20].

4. Results and discussion

4.1. The temperature dependency of the sorption

By the above mentioned methods the sorption isotherms of the aerogel blankets were taken up at 3 different temperatures (283 K, 293 K and 303 K) and for 24 hours wetting besides five (0, 35, 50, 65, 80 and 95 %) relative humidity values. In accordance to standard EN ISO 12571 at least 24 hours are needed and minimum five samples and at least five relative humidity values should be used to reach the sorption isotherm graphs. Galliano et al., Wakili et al., Ibrahim et al., Stahl et al and Ihara et al. in Ref. [6, 7, 9, 21, 22] were investigating the thermo-hygric properties of aerogel. It has to be mentioned that Galliano et al. compared measurement results with calculations, Stahl et al. and Ihara et al. reported their sorption measurements on aerogel granules and stated that the liquid water entered the nano-pores of the aerogel granulate due to the high pressure and damaged partially the aerogel structure. It remained trapped and it would take a very long time to dry. While the research group of Ihara tried to simulate the ageing of the granules by long-term wetting, Wakili et al. carried out in-situ measurements. Moreover, they stated that aerogel as a blanket would be better used as an internal insulation. Ibrahim et al. reported sorption isotherms and thermal conductivity dependency in function of relative humidity. They were using the same standards (EN ISO: 12571 and 12667) to reach the sorption values and the thermal conductivity change. The used temperature was not stated but concluding from the standard it should be 293 K. In Figure 1 one can see the sorption isotherm curves for the three temperatures.

In our case in order to see the temperature dependency of the sorption, besides the measurements at 293 K two further experiment series were also done. We took up the isotherms both at 283 and at 303 K. We reached to the conclusion that there is no strong dependency between the temperature and water content. For the sorped amount of water at different temperatures we did not observe any significant deviances so we took the average of the three series (and the estimated Error's as well) and presented in Fig. 1 as an average. Ibrahim et al. reported the sorption isotherms in kg/m^3, where they did not find any changes in the water up-taking before 75%. The shape of their curve presented at 20 ^{o}C (293 K) is similar to ours reached at the same temperature. However, they did not investigate it at the other two temperatures.

4.2.The change in the effective thermal conductivity in function of the wetting time

The research of Ihara et al. presented that the thermal conductivity of aerogel granules could increase up to ~10% after wetting. Nonetheless, those investigating aerogel applications in construction should seek to produce appropriate solutions to prevent moisture penetration into aerogel granules. Instalment specifications should avoid moisture sources (e.g., condensation and rain). When a specification considers moisture problems sufficiently, a long service life may be expected (e.g., decades). Otherwise an increased thermal conductivity should be considered in e.g., energy simulations. See Ref. [22]. Ibrahim et al. presented the dependence of thermal conductivity in function of the moisture content. We can see that the thermal conductivity is almost the same up to 60% relative humidity, and even when the rendering is very humid (φ> 90%) it still possesses a good thermal insulation level. Besides, we have found that the thermal conductivity of the aerogel is increasing in function of the moisture content. (See Figure 2a and Table 1). We have to mention that the moisture content is not increasing significantly after 8 h wetting, in accordance with the findings of Ihara et al. in Ref. [21], where they showed that the moisture content at 20 ◦C (293 K) and 98% RH did not increase monotonically with the number of moisture-aging cycles. We observed that the thermal conductivity of the dry materials is about 0.018 W/mK. Let me mention that after 12 h wetting the thermal conductivity changes with about 50%. However, after 20 h wetting it jumps up to almost 0.03 W/ mK.

According to Eq. 2 from the curve we found Z=10.7 for the moisture supplement of the thermal conductivity of the aerogel. The reason for this is that where moisture is absorbed into a material, it is uniformly distributed through the material and the moisture is able to conduct heat through the material. Stahl et al. in Ref [9] presented that a low water vapour transmission resistance helps to avoid moisture accumulation. Besides, when the water filling the nano-porous material of aerogel is heated on the hot side, the pressure will increase with the increasing temperature, while the pressure near the cold side of the material is still close to the initial pressure. Under this condition, the difference of the pressure between the hot and cold sides of the material will drive the moisture from the hot side to the cold side, and thus enhancing the heat transfer from the hot side to the cold side. The thermal insulation performance of the nano-porous material deteriorates correspondingly. To find the reason for the increase in the thermal conductivity we have to go deeper in the heat transfer inside the material. We suppose that with combining the material with itself the convective part of the air (gas diffusion) will take place in the heat transfer at the expense of the radiative and conductive parts. By replacing the air with water the conductive part of the water will be dominant. The aerogel material's thermal conductivity is perfect; however, the increasing amount of water inside the materials (absorption) demotes it. By Tang a similar effect was found belonging to the air content. [23] According to Eq. 3 on Figure 2b one can see the moisture absorption curve of the sample. Kumaran in Ref. [24] presents the following method: if we divide the water content with the contact area and plot in the function of the square roof of time, the water absorption coefficient can be reached. For the moisture absorption coefficient A_w=6E-2 was reached. [24]

4.3. The changes of the most important physical parameters in function of the wetting time and moisture content

In Table 1 and in Figure 3 the calculated values of the most important thermal parameters can be found. In the table one can find the change in the density, thermal conductivity, specific heat capacity and the change in the resistance of the samples with 0.013 m thickness, while in Figure 3 the changes in the heat absorption and in the thermal inertia are presented. The increase in the thermal conductivity and density was measured; however, the change in the specific heat capacity (increase), the resistance (decrease), the absorption (increase) and the inertia (decrease) were calculated. As a result, we can conclude here that the increasing moisture content helps to absorb and store more heat, which could be a positive effect; however, by decreasing the resistance has a negative effect.

4.4. Thermal resistance measurement with calibrated chamber method; measurement of the wet-iced walls

Most building materials have porous structure that can be filled with water easily, therefore at low temperature ice can form inside the material, causing undesirable changes in the thermal and physical properties of the materials. Koci et al. presented the effect of freeze/thaw induced damage in some materials. Ishizaki et al. showed that the outside of the buildings can be destroyed by frost, so to prevent this process moisture protection should be applied. However, integrated building materials in real constructions are exposed to dynamically changing conditions (temperature, relative humidity, rainfalls etc.) and appearance of full saturation is seldom. [10, 25, 26, 27] Furthermore, Cao et al., presents that the climate (both warm and cool) can significantly change the energy performance of the same ordered building, and ice (cold climate) can significantly increase the heat loss and the heating energy. [28] Liu showed the importance of the measurement and the simulation of the moisture induced heat transfer change. They reported that both the moisture transfer and the frost may severely influence the conduction loads through exterior walls. Since the water-ice and ice-water changes are accompanied with heat consumption or release, they can significantly affect the thermal or energy performance of building envelope, too.

In this section we will present the effect of the sprayed water on the wall at low temperature (approx. 256 K). Thermal resistance of the brick wall covered with aerogel insulation was measured at pure dry state; moreover, it was measured after wetting the surface with sprayed water. Water with five different quantities (0.035 kg, 0.15 kg, 0.19 kg and 0.28 kg) was evaporated on the surface of the wall and then the thermal transmittance of the walls was measured by CC method. However, it is hard to quantify exactly the amount of the moisture remaining on the wall by the spraying method, because the adsorption, evaporation, reflection and flow down of the water particles are also observable before freezing. Moreover, the surface can be dried by cooling as well. Therefore we could present only the quantity (difference) of the mass of the water in the spray container before and after spraying.

From Figures 4 to 6 and from Tables 2a and b one can find out the changes in the measured heat flux, resistance and surface heat transfer coefficients. In Figure 4 the change in one of the key parameters (heat flux) in function of the moisture content can be seen. The trend shows monotonic increase. A linear fit with about 98% regression was applied on the data. It shows a pure increase. After reaching 20% moisture content, the heat flux suffers an increase with about 25 %. It should be stated that it is a significant change.

In Figures 5a and b one can find the decrease in the resistances calculated from the measured wall and air temperatures calculated from the method presented in Ref 10. As Table 2a presents the air temperature difference was kept at about 38 K, while the wall temperature difference was kept to 32 K. In Figure 5a the pure decrease in the resistances can be seen. The curves are nearly parallel, confirming the accuracy of our measurements. By fixing the initial resistance (resistance of the dry wall) a correlated change in the moisture increased resistance can be evaluated. This is represented in Figure 5b. Nearly the same percentage change is observable in the resistances calculated regarding the wall and the air values. The change is about 5, 10, 15 and 22% respectively. By the above mentioned calculation method (see in Ref 10) effective surface heat transfer coefficient can be reached. It is very interesting that the doubled (effective) surface heat transfer coefficient ($\alpha_{is,es}$) is changing in the function of the moisture content. These values are found from taking the reciprocal value of the difference of the air and wall thermal resistances. After 20 % water content the doubled surface heat transfer coefficient increases with 1 W/m^2K (see Figure 6).

4.5. Computational modelling based the measurement results

Koci et al. in Ref 25 and 26 presents the importance of the combination of the measurements and simulations related to buildings. Most computational approaches to determine the thermal performance of building materials or building envelopes are conducted using the moisture dependent thermal conductivity of the involved materials [25, 26]. Papadopoulos et al., Warda et al., and Pourarian et al., Petersen, et al., Csáky and Kalmár, Moga et al., Koci et al, and Howard et al. showed the perfect utilities of Building Performance Simulation (BPS); it is an established method used in the design phase of buildings to predict energy consumption and guide design choices. It is well known that building energy consumption simulated at the design stage rarely agrees with observed data at post-design phase, and with the increasing deployment of energy monitoring systems this so-called ‘performance gap’ is becoming increasingly visible. [30 - 37] Moreover, in Ref [35] Moga et al. presents that the annual energy demand of the building is directly influenced by the external climatic phenomenon. Building Energy Simulation (BES) was evaluated by the CASAnova building simulation software (only estimation) to investigate the moisture increased change in the heat energy demand and in the primary energy demand of a family house as the following. By using the following equation, the overall heat transfer coefficient (U-value) of an external wall can be calculated:

$$U=1/(1/\alpha_{is}+R_{wall}+1/\alpha_e) \qquad \text{(Eq. 4)}$$

where α_{is}=8 and α_e=24 W/m^{2}K regarding to the energy performance calculation of buildings in Hungary. Two types of BES’s were carried out. Firstly, the U-value of the above mentioned plaster_0.02 m/brick_0.25 m/aerogel_0.013m/plaster_0.02 m system was calculated. The thermal conductivities of the brick and plaster were given by the manufacturers as 0.5 and 0.81 W/mK respectively; while for the thermal conductivity of the aerogel the measured values reached with Holometrix apparatus (dry and wet values) were used. Secondly the R_{wall} values obtained by the CC method were completed with α_{is}=8 and α_e=24 W/m^{2}K and the U-values for the water sprayed walls were calculated. The calculated U-values in function of the moisture contents can be seen in Table 3.

By using the changing U-values as input parameters for a simple family house, heat energy and primary energy demand were calculated using the Budapest (Hungary) climate database. The main parameters and properties of the test house can be found in Table 4.

Let me mention that the test house was simplified as much as it was possible, because our aims were only to show and emphasize the changes in the energy performance of the building caused by the wetness. From the simulations carried out on the energy performance of the family house column diagrams were created for the values reached by the two methods. Figures 7a and 7b present the values of the heat and primary energy demands in function of the moisture content. One can see the increasing values of all demands in both cases. The highest increase in the slopes (about 20 %) belongs to the primary energy demand reached by the results used from the Holometrix measurements. The smallest increase (10 %) belongs to the heat energy demand reached by the calculations based on the CC method. Here it has to be mentioned that the slopes from the CC method are much smaller than the results reached from the measurements made by the Holometrix apparatus.

5. Conclusions

In this extensive article the comparison of moisture induced changes in the heat transfer phenomena of an aerogel insulation slab as well as of a brick based wall covered with aerogel layer are presented. By combining research methods the article would show an accurate picture of the causes and the results of sorption behaviour. After the sorption investigations, thermal conductivity and heat transfer investigations were carried out also, both on individual samples and on in-built wall structures. Based on the measurement results Building Energy Simulations were carried out. The combination of measurement and simulation-based optimization is undoubtedly a promising approach to achieve many building design targets, opening a new era of design to architects and engineers.

To bring the paper to a close we would summarize the main goals and novelties of this paper point by point:

- Sorption isotherms of aerogel blankets at 283 K, 293 K and 303 K were given. It was found that there is no temperature dependency of the amount of the water taken up after 24 h wetting.
- Moisture supplement for the thermal conductivity of the aerogel was given at 293 K: Z=10.7

- Water absorption coefficient for the aerogel was calculated from the amount of the water taken up: A_w=0.06 kg/m^{2}s$^{1/2}$.
- The change in the heat absorption and thermal inertia of the aerogel was calculated. It was presented that the heat absorption is increasing in function of the wetting time (moisture content), while the thermal inertia is almost constant.
- Heat transfer investigations were carried out and were presented on 0.25 m thick brick based wall covered with 0.013 m thick aerogel insulation in function of moisture content.
- It is presented that the both the heat flux (increasing) and the thermal resistance (decreasing) are changing with at least 20% if they contain at least 20 % moisture.
- The article stated that the surface heat transfer coefficient changes with 1 W/m^{2}K after spraying 0.28 kg water on the wall.
- Based on the measurement results simple Building Energy Simulations were executed on a family house by changing the U-value of the external wall in function of moisture content. It is presented that both the heat energy demand and the primary energy demand are increasing significantly in function of the moisture content.

And last but not least we have to underline that this article aims to give some help to decision makers, designers and practitioners as well. Furthermore, we would like to emphasize that these results can be useful for every real-life applicant by helping building designers, stakeholders or policy makers to reduce energy losses of buildings and environmental impacts.

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Figure captions:

Figure 1: The sorption isotherm curves at 283, 293 and 303 K

Figure 2a: The change in the thermal conductivity in function of moisture content

Figure 2b: The change in the thermal conductivity in function of the wetting time.

Figure 3: The calculated heat absorption and inertia in function of the wetting time.

Figure 4: The change in the heat flux in function of the water content

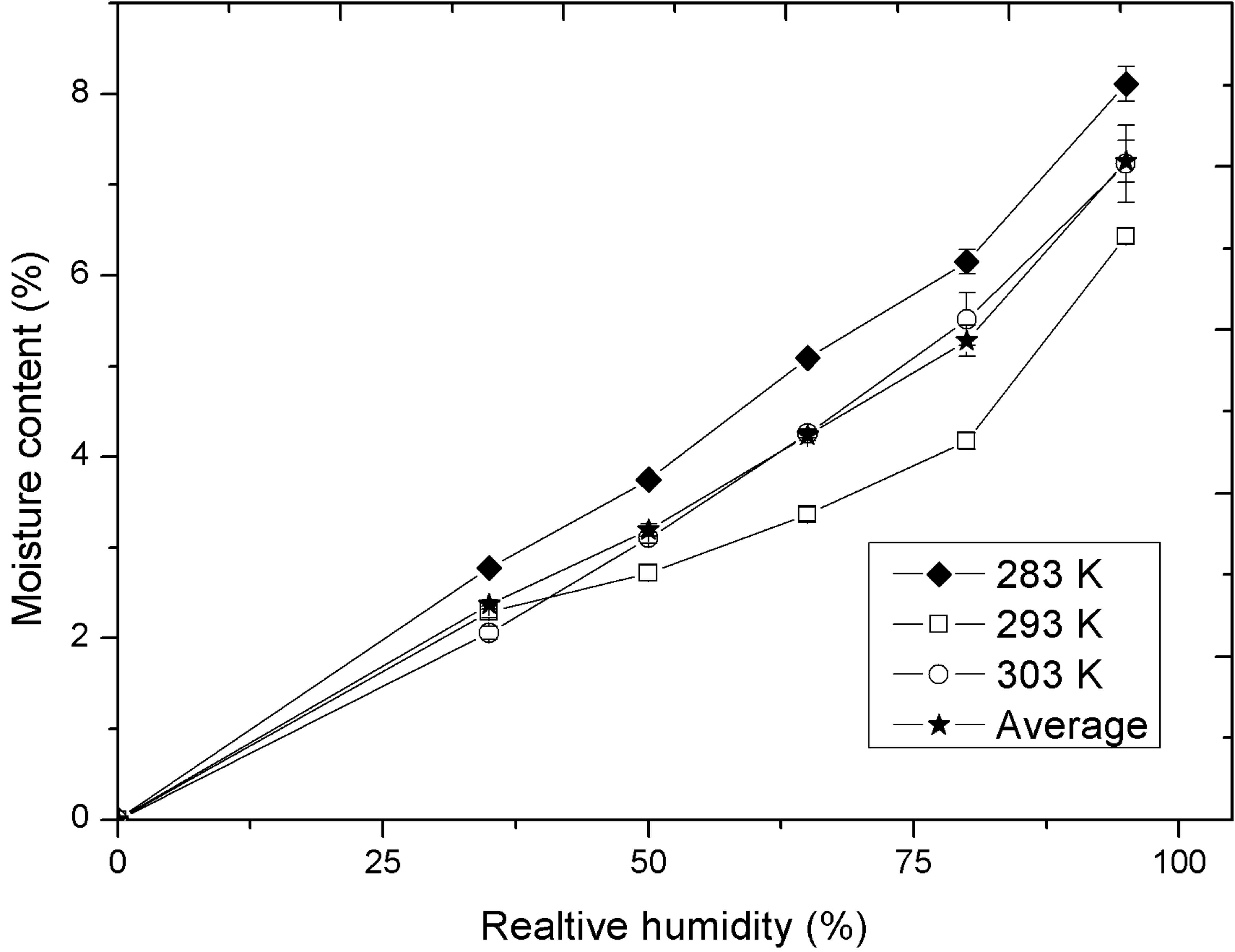
Figure 5a: The decrease in the resistance in function of the water content

Figure 5b: The percentile decrease in the resistance in function of the water content

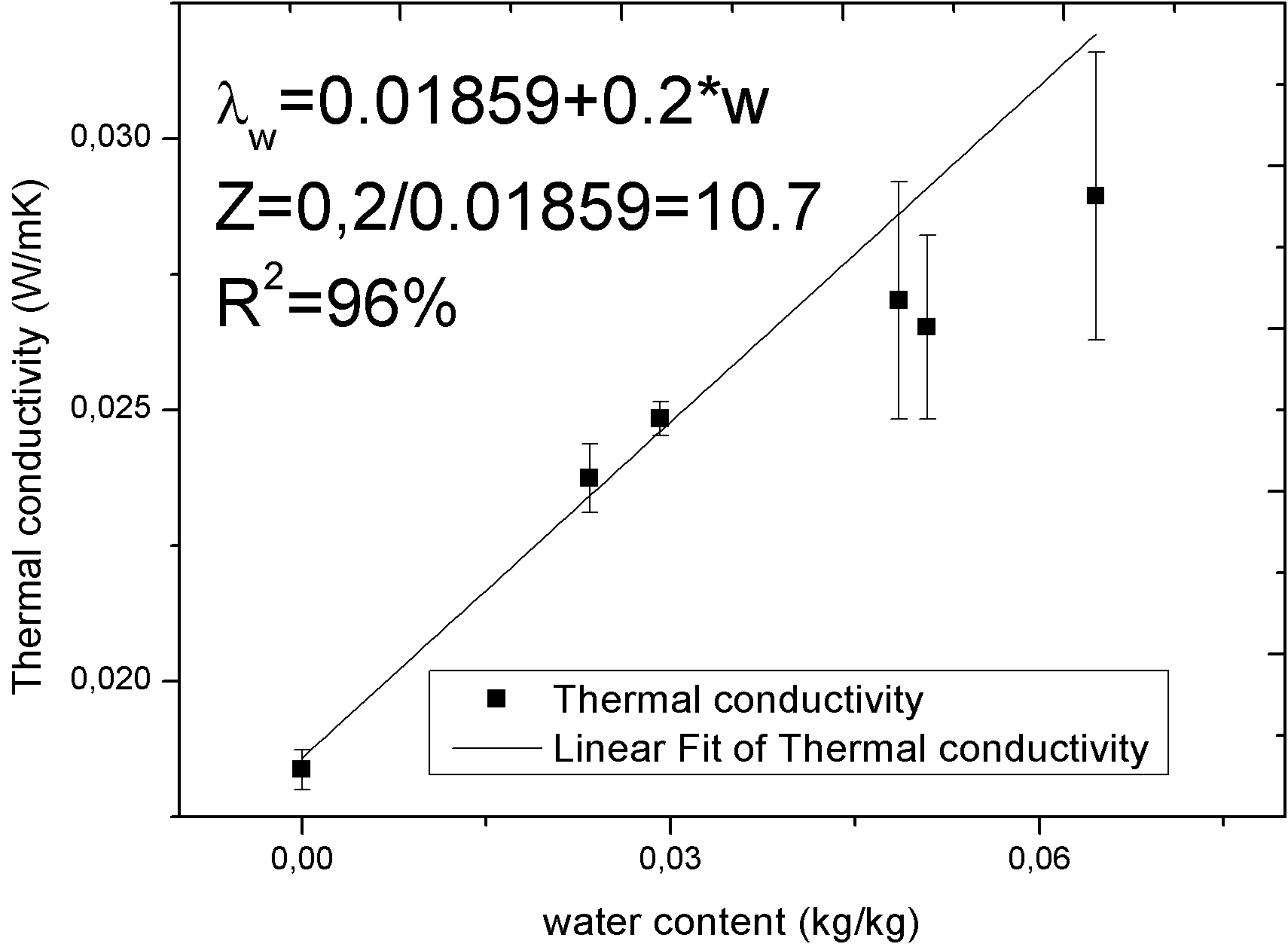
Figure 6: The change in the surface heat transfer coefficient in function of the water content

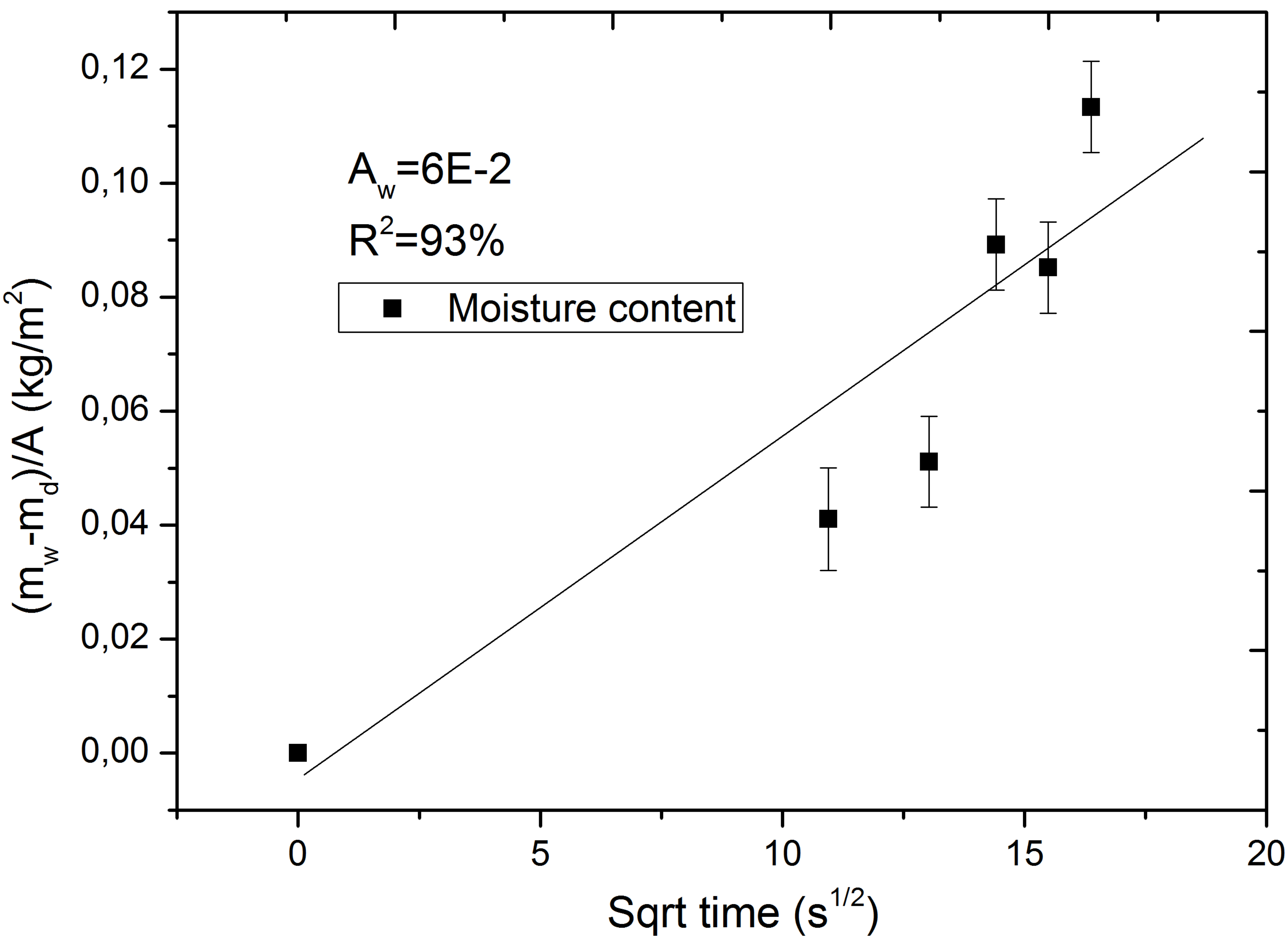
Figure 7a: The change in the primary and heat energy demand from cc method

Figure 7b: The change in the primary and heat energy demand from the results reached from the measurements with Holometrix apparatus

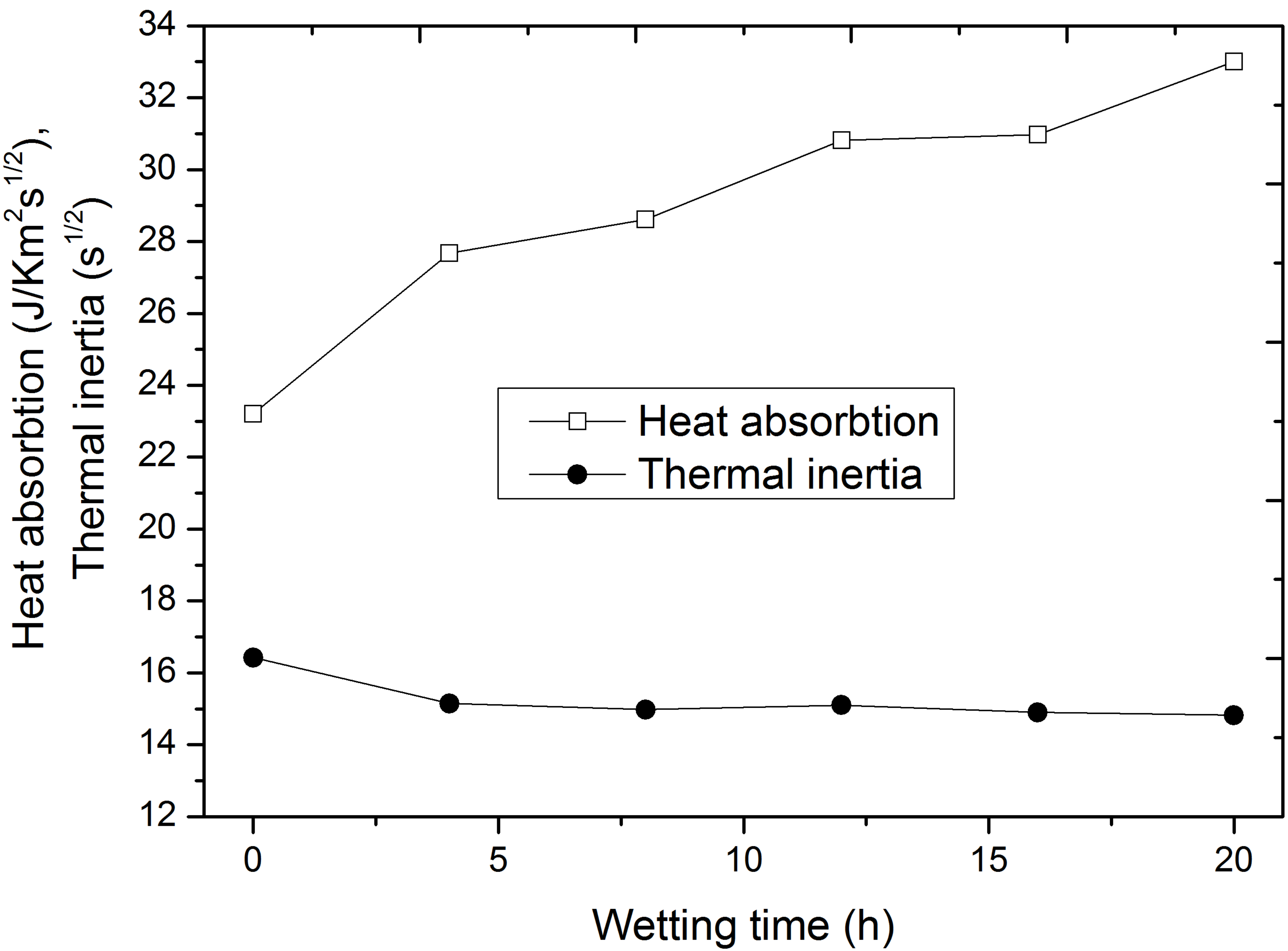


Moisture content (%)
0
2
4
6
8
0
25
50
75
100
Realtive humidity (%)
283 K
293 K
303 K
Average

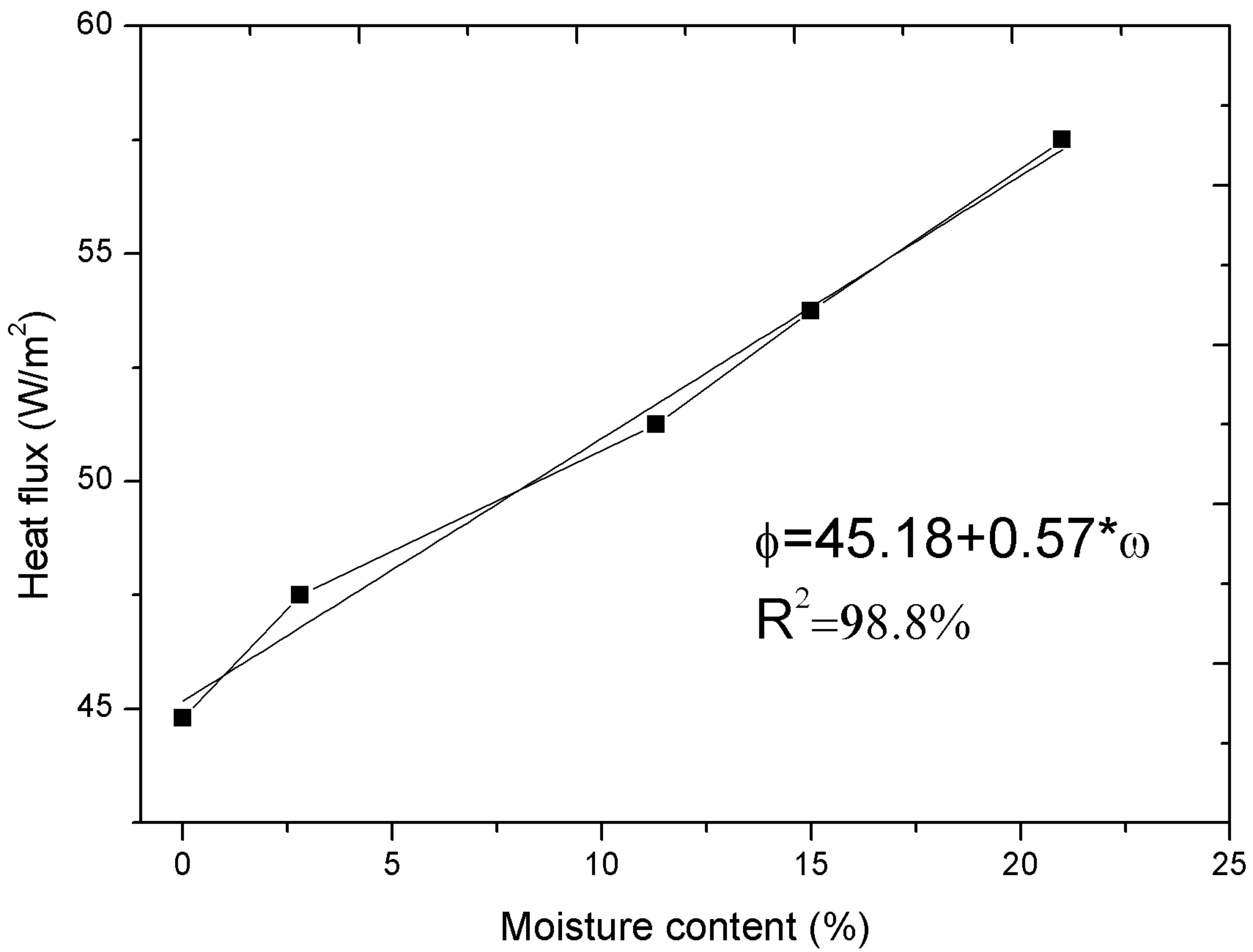

λw=0.01859+0.2*w
Z=0,2/0.01859=10.7
R2=96%
0,030
0,025
0,020
Thermal conductivity (W/mK)
0,00
0,03
0,06
water content (kg/kg)
Thermal conductivity
Linear Fit of Thermal conductivity



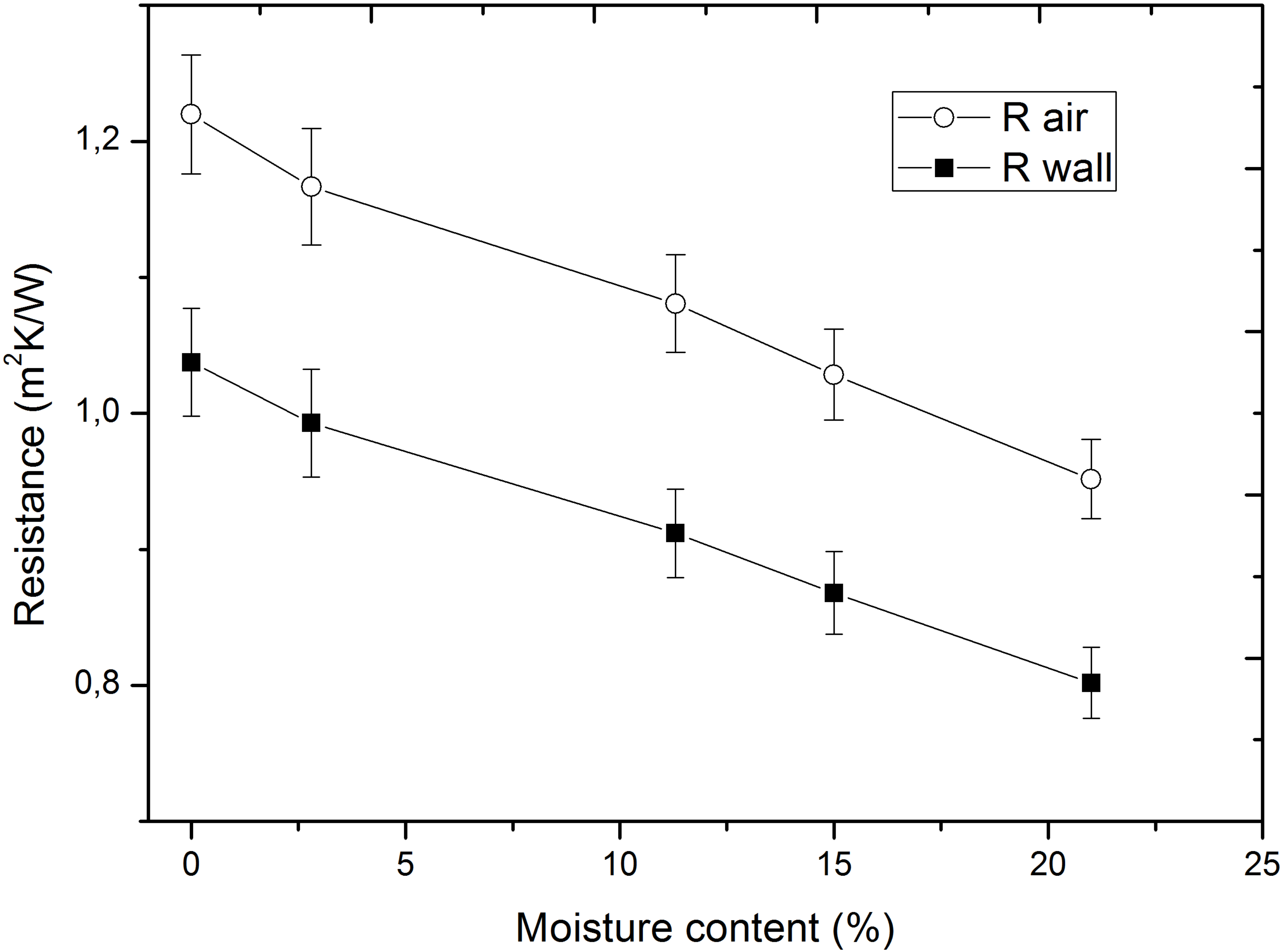
A_w=6E-2
R^2=93%
Moisture content
$(m_w-m_d)/A$ (kg/m^2)
0,12
0,10
0,08
0,06
0,04
0,02
0,00
0
5
10
15
20
Sqrt time (s$^{1/2}$)

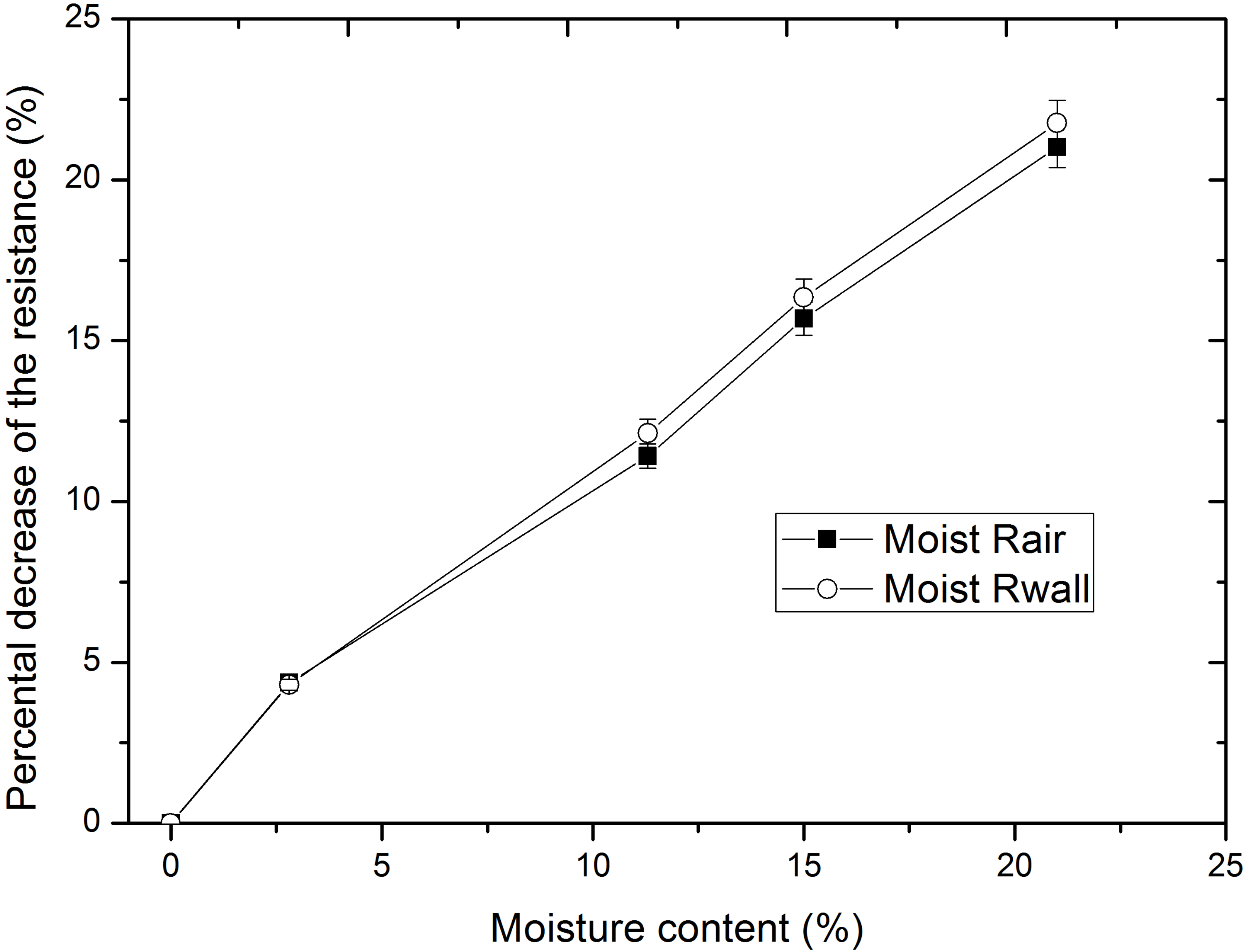


Heat absorbtion (J/Km²s^1/2),
Thermal inertia (s^1/2)
Wetting time (h)
Heat absorbtion
Thermal inertia
34
32
30
28
26
24
22
20
18
16
14
12
0
5
10
15
20

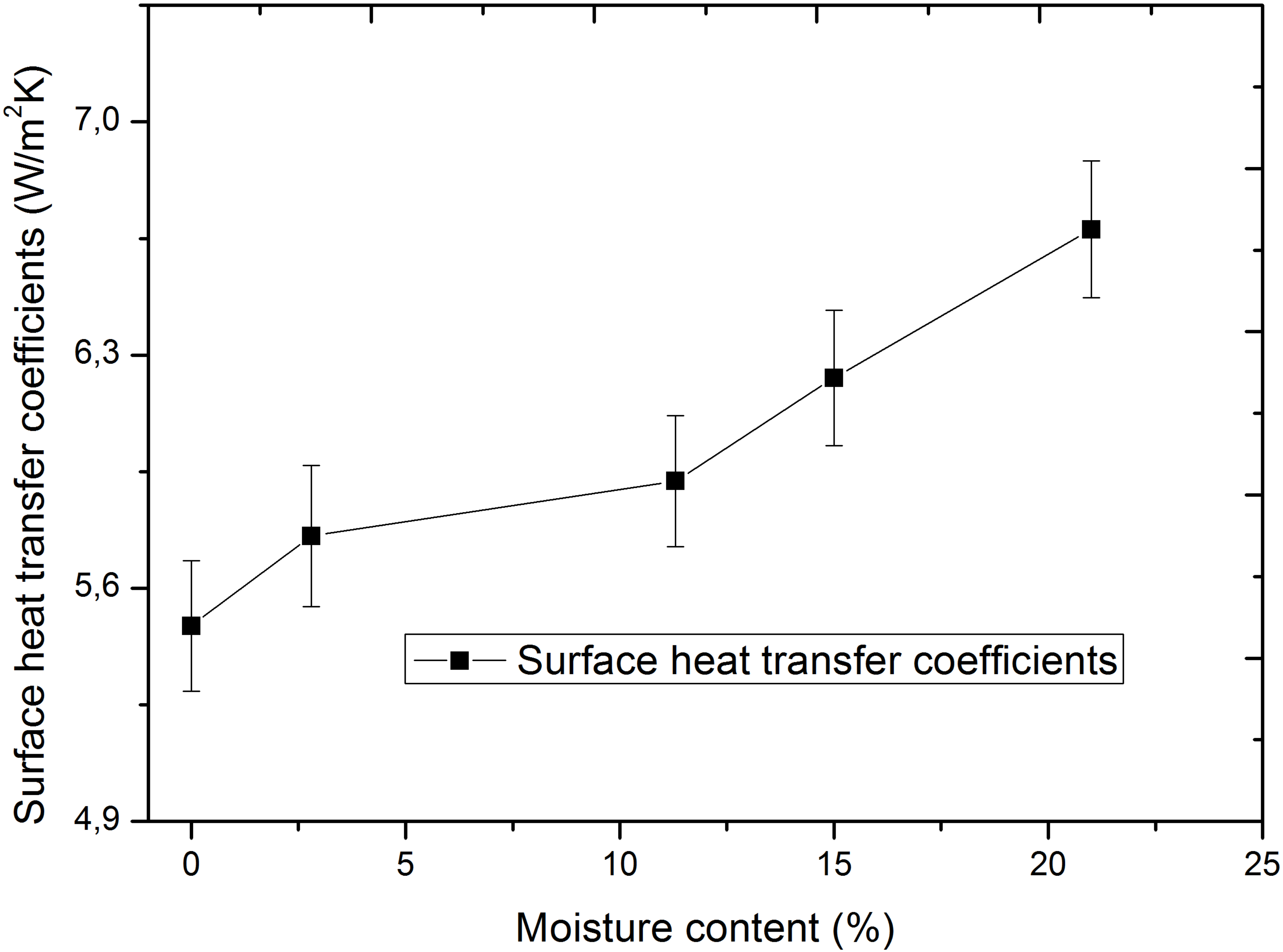


60
55
50
45
Heat flux (W/m2)
0
5
10
15
20
25
Moisture content (%)
ϕ=45.18+0.57*ω
R2=98.8%

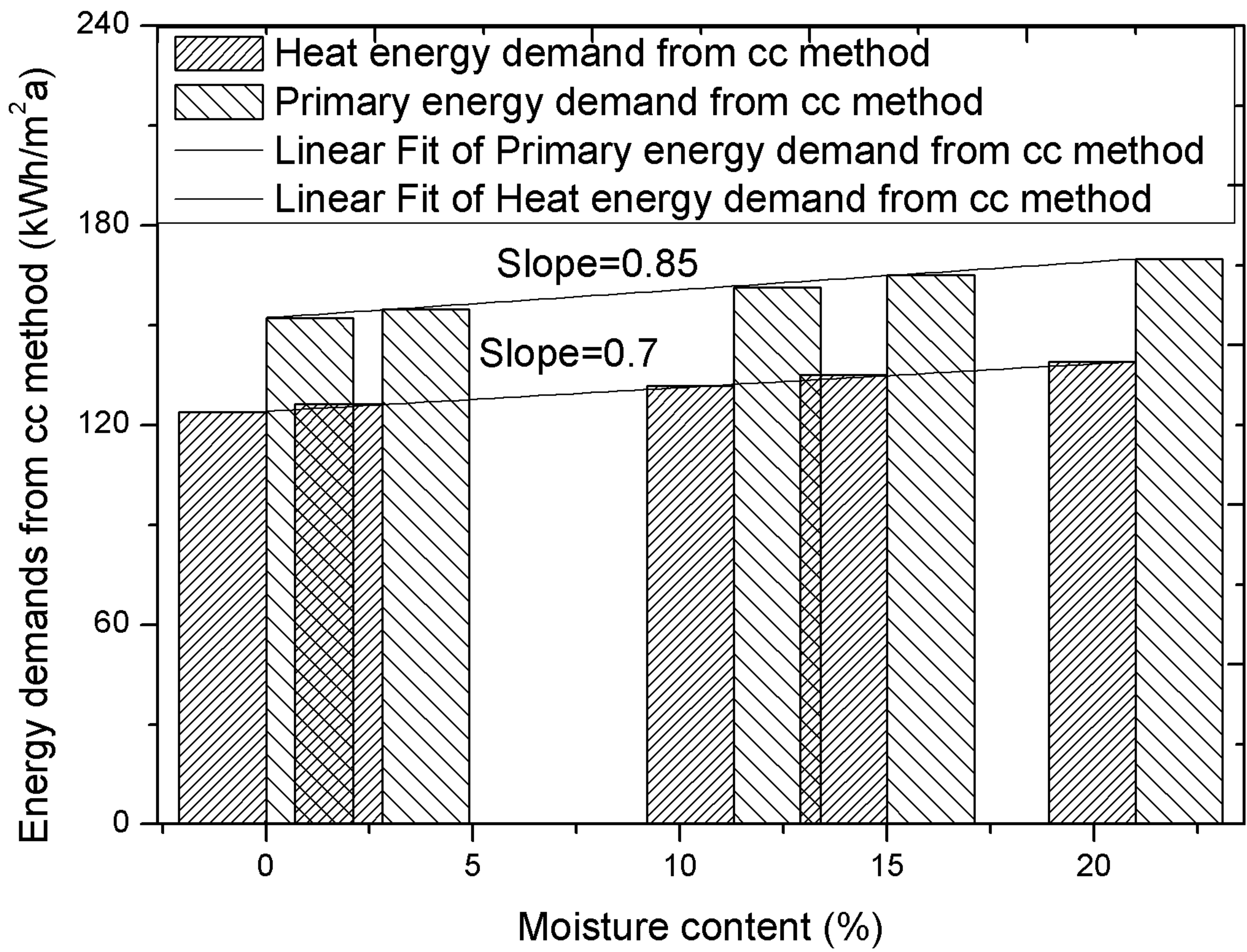

R air
R wall
Resistance (m²K/W)
1,2
1,0
0,8
0
5
10
15
20
25
Moisture content (%)

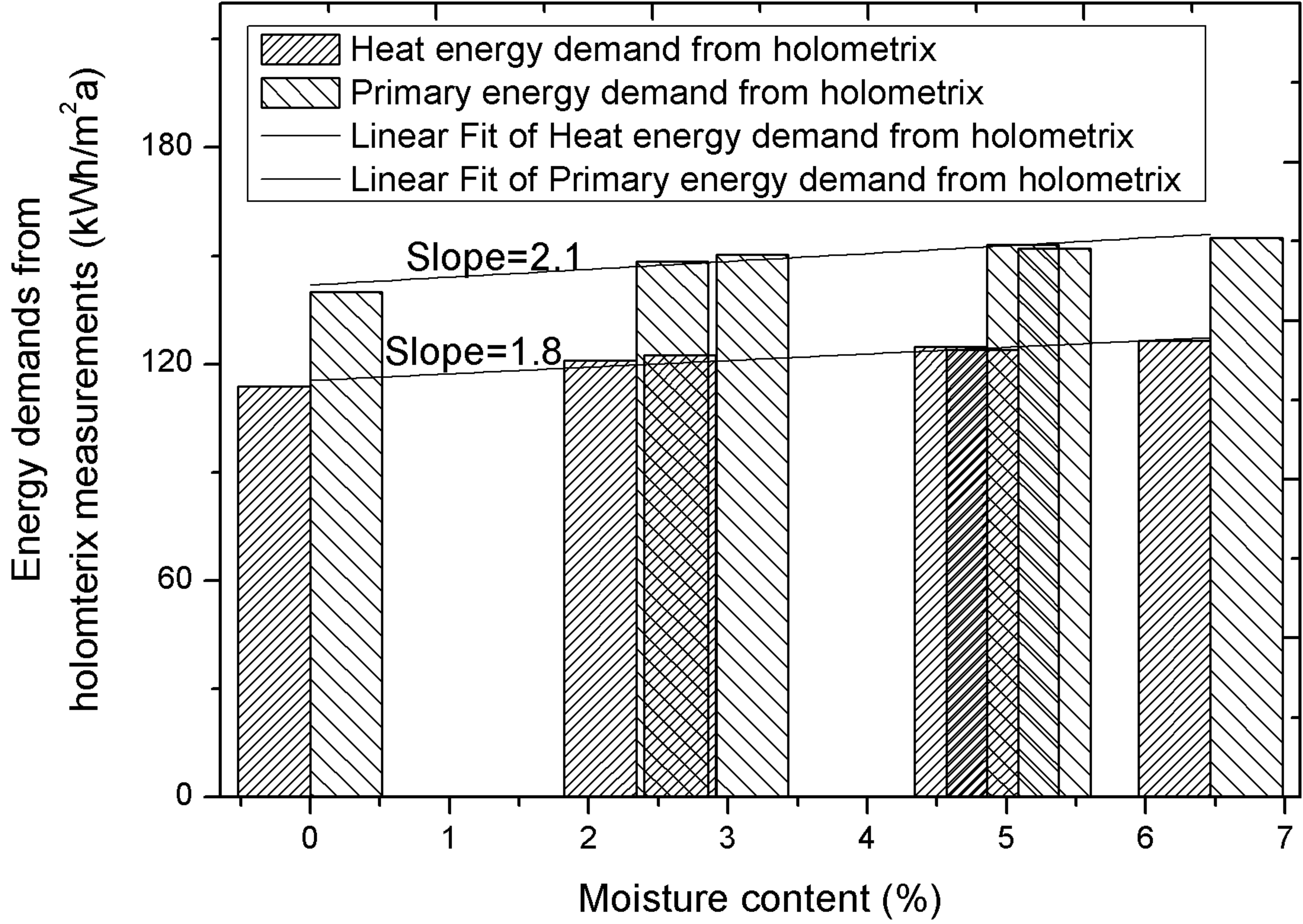


Percental decrease of the resistance (%)
0
5
10
15
20
25
Moisture content (%)
Moist Rair
Moist Rwall



Surface heat transfer coefficients (W/m2K)
7,0
6,3
5,6
4,9
0
5
10
15
20
25
Moisture content (%)
Surface heat transfer coefficients


Heat energy demand from cc method
Primary energy demand from cc method
Linear Fit of Primary energy demand from cc method
Linear Fit of Heat energy demand from cc method
Slope=0.85
Slope=0.7
Energy demands from cc method (kWh/m2a)
240
180
120
60
0
0
5
10
15
20
Moisture content (%)



Heat energy demand from holometrix
Primary energy demand from holometrix
Linear Fit of Heat energy demand from holometrix
Linear Fit of Primary energy demand from holometrix
Slope=2.1
Slope=1.8
Energy demands from holomterix measurements (kWh/m2a)
0
60
120
180
0
1
2
3
4
5
6
7
Moisture content (%)

Table 1. The Changes of the main thermal parameters of the materials in function of the mositure content and wetting time

Wetting time at 293 K 90% (h)	Moisture content (%)	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	Thermal resistance (m^2K/W)
0	0.0000	29.3213	0.0184	1000.0000	0.7077
4	2.3403	30.0075	0.0238	1074.4209	0.5474
8	2.9152	30.1760	0.0248	1092.7030	0.5233
12	5.0870	30.8128	0.0265	1161.7663	0.4900
16	4.8581	30.7457	0.0270	1154.4869	0.4811
20	6.4629	31.2163	0.0289	1205.5198	0.4492

Table 2a. The change in the measured wall and air temperatures and in the heat flux

Water content (kg)	Water content (%)	DT air (K)	Er. (K)	DT wall (K)	Er.(K)	Heat Flux (W/m^2)
0	0	37.950	1.359	32.280	1.233	44.800
0.035	2.8	38.480	1.535	32.750	1.307	47.500
0.15	11.3	38.460	1.377	32.450	1.162	51.250
0.19	15	38.390	1.340	32.400	1.131	53.750
0.28	21	38.000	1.239	32.020	1.044	56.800

Table 2b. The change in the effective surface heat transfer coefficients and in the resistances

Water content (kg)	Water content (%)	eff. Alfa (W/m^{2}K)	Er. (W/m^{2}K)	Decrease in Rair (%)	Er.	Decrease in Rwall (%)	Er.
0	0	5.487	0.196	0.000	0.000	0.000	0.000
0.035	2.8	5.757	0.211	4.367	0.160	4.311	0.172
0.15	11.3	5.922	0.197	11.411	0.379	12.125	0.434
0.19	15	6.231	0.203	15.685	0.511	16.341	0.570
0.28	21	6.596	0.202	21.023	0.645	21.762	0.709

Table 3. The overall heat transfer coefficients of the walls

Moisture content of aerogel (%)	U-value from Holometrix (W/m^2K)	Moisture content of the sprayed water (%)	U-value from CC method (W/m^2K)
0.00	0.70	0.00	0.83
2.34	0.79	2.80	0.86
2.92	0.81	11.30	0.93
5.09	0.83	15.00	0.97
4.86	0.84	21.00	1.02
6.46	0.86		

Table 4. The main parameters of the test house

Orientation	East
Ground area	10 m x 10 m=100 m^2
Floor	1
Height	2.3 m
V	230 m^3
window area	
North	5%
South	40%
East	5%
West	5%
Sum	12.8 m^2
Same window at all sides	U=1 w/m^2K, heat protected double glazing
Heat bridges	construction with nearly no heat bridges
Door on north facade	1.5 m^2, U=1.5 W/m^2K
U value, upper and lower floor	0.2 W/m^2K
Indoor set tempertaure	20 ^{o}C
Internal gains	25 kWh/m^2a
Natural ventilation	0.6 1/h
Construction	Medium
Mechanical ventilation	0
Heating system	Low tempereature burner, boiler
Heat transfer	radiators on outside walls, thermostatic valves, 70/55 ^{o}C, operation