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Computer aided design of interior thermal insulation system suitable for autoclaved aerated concrete structures

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HIGHLIGHTS

- Interior thermal insulation systems for autoclaved aerated concrete structures are investigated.
- Computational simulations of hygrothermal performance are presented.
- Freeze/thaw resistance of the envelope is considered.
- Suitable hygric properties of thermal insulation layer and connecting layer are proposed.
- Types of materials suitable for application in the interior thermal insulation system are discussed.

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ABSTRACT

The idea of using interior thermal insulation systems for autoclaved aerated concrete (AAC) structures is introduced. In the computer aided design, the hygric properties of the thermal insulation layer and the connecting layer between the AAC block and the thermal insulation board are investigated. The computational analysis shows that the moisture diffusivity, κ, of the thermal insulation layer should be very high ($\approx 1 \times 10^{-6}$ m^2/s), its water vapor diffusion resistance factor, μ, very low ($\approx$3–5), and hygroscopic moisture content, w_{hyg}, moderate ($\approx$0.01 m^3/m^3). This combination of properties can potentially be met by modifications of some not commonly used thermal insulation materials, such as are hydrophilic mineral wool or calcium silicate. On the other hand, the hygric properties of the connecting layer are not found very restrictive. Common lime–cement or lime–pozzolan mortars can meet the required criteria of $\kappa \approx 1 \times 10^{-9}$ m^2/s–1×10^{-8} m^2/s, $\mu \approx$ 10–20, and $w_{hyg} \approx$ 0.05 m^3/m^3. The application of an interior thermal insulation system with the properties given above for an AAC envelope can reduce the hygrothermal straining of exterior plaster, which is typical for the exterior thermal insulation systems, in a very significant way, thus increase the service life of the whole envelope.

1. Introduction

Energy efficiency of buildings is currently one of the most important topics in civil engineering. In European Union, 24.6% of total energy is consumed by households [1] and almost 70% of that amount is represented by heating energy [2], but this number differs according to the region. It is obvious that all over Europe significant energy savings can be achieved by the improvement of thermal insulation properties of building envelopes. Such improvement can be accomplished basically in two ways, either using load bearing materials with better thermal insulation properties or applying thermal insulation systems of various kinds.

Autoclaved aerated concrete (AAC) is an example of building material which can serve two purposes at the same time, as it has both load bearing- and thermal insulation capability. However, the contradictory requirements for high strength and low thermal conductivity can be matched to a limited extent only. Despite the extensive research being conducted during the last decade in that respect, it does not seem that a breakthrough solution is any closer than before.

The current research on AAC involves primarily the investigation of pore structure [3] which is unique in comparison with traditional building materials and imparts specific hygric and thermal properties. This was confirmed for instance by Jerman et al. [4] where hygric parameters of AAC were found to depend

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remarkably on moisture content. The high moisture content typical for AAC can, however, be reduced using hydrophobic agents, as it was reported by Beben and Manko [5]. Improvement of mechanical properties which is another important task in the research related to AAC was achieved by Laukaitis et al. [6] by adding carbon fiber additives. Substantial part of research activities aims also at the economical aspects of AAC production and tries to use waste products in order to reduce costs, while studying their influence on final properties. The most frequently used waste, bottom ash, is produced mainly by power industry and can partially replace cement. According to Wongkeo et al. [7], it can lead to improvement of mechanical parameters such as compressive or flexural strength, but the bottom ash ratio has to be balanced [8]. Moreover, presence of bottom ash does not affect thermal insulating properties of AAC [9]. There are also other waste products used in AAC production such as clayey waste [10], silica fume [11] or slag [12]. They have very similar impact on the properties of AAC but their application is limited because of lower production volume.

Thermal insulation systems are, nowadays, mostly applied for such building envelopes where the materials of load bearing structure such as concrete do not have a substantial thermal insulation capability [13]. Thus, thermal insulation systems lead to improvement of economical aspects of buildings (e.g., [14]), but sometimes this may lead to excessive thickness of thermal insulation layers and/or problems in hygric performance of the envelope.

A combination of load bearing materials with good thermal insulation properties and specific thermal insulation systems appears as a third viable alternative for the achievement of energy savings in buildings. This solution was not the preferred one hitherto. Nevertheless, the increasing demands for reducing thermal loss of buildings which are in Europe currently manifested by the adoption of the Energy Performance of Building Directive II [15] in national thermal standards of EU member countries may lead to reconsideration of this option in the near future.

In the case of AAC, the application of thermal insulation systems may help avoiding unrealistic masonry thickness while the positive properties of the envelope such as the good permeability for water vapor and air can be maintained. However, such solution is not straightforward. The computational analysis presented in Ref. [16] showed that the common exterior thermal insulation systems when applied for AAC masonry remarkably enhance hygrothermal straining of external surface layers of the envelope, thus reduce their service life in a very significant way. Therefore, such thermal insulation systems must be tailored, taking into account the specific thermal and hygric properties of AAC [17].

In this paper, we introduce an idea of using interior thermal insulation systems for AAC-based building envelopes. Nowadays, this kind of insulation system is applied mostly for historical buildings where the original appearance of facades is to be maintained. For instance, Grunewald et al. [18] applied such a system for the Rijksmuseum in Amsterdam, Toman et al. [19] for a brick-built house in Prague constructed in the end of the 19th century. The design of interior thermal insulation systems is relatively complex from a hygric point of view [20], because a lot of risks, such as moisture accumulation and subsequent condensation, must be avoided [21]. For this reason, materials involved in the composition of these types of building envelopes must have optimal moisture transport properties [22], or the results must be obtained or at least verified under realistic conditions [23]. In addition, for load-bearing structures without thermal insulation capability a frost damage risk is to be dealt with [24]. For AAC the application of interior thermal insulation systems may be easier than for the historical masonry. AAC has relatively good thermal insulation properties which can reduce a possible danger of frost damage. It also has very convenient moisture transport and storage properties [25] which can decrease a risk of water vapor condensation. Therefore, the hygrothermal straining of exterior plaster is certainly lower as compared with the exterior thermal insulation systems. It can even be anticipated that the currently used plasters which were developed for AAC without any insulation might be applicable for the AAC-based envelopes with interior thermal insulation systems without any modification. However, the interior thermal insulation system itself is certainly to be tailored. A computer aided design is to be adopted for the achievement of both satisfactory hygrothermal performance and acceptable service life of the envelope.

2. Description of the analyzed building envelope and methods of computational analysis

The AAC block P2-350 (Xella) was assumed as the material of load bearing structure. From exterior side it was provided with MVR Uni plaster (Baumit). This plaster is recommended by the producer as specific for AAC masonry without thermal insulation and for that particular case its good hygrothermal performance was confirmed by previous computational analysis [16]. The thermal insulation system positioned on the interior side of the AAC block consisted of a connecting layer and a thermal insulation layer. Finally, MVR Uni plaster was used on the interior surface. A detailed scheme of the analyzed building envelope which was assumed to be oriented to the south is shown in Fig. 1a.

The material parameters applied in the computer aided design are summarized in Table 1, where the following symbols are used: ρ – bulk density [kg/m^3], ψ – porosity [%], c – specific heat capacity [J/kg K], μ – water vapor diffusion resistance factor [–], λ_{dry} – thermal conductivity in dry state [W/mK], λ_{sat} – thermal conductivity in water saturated state [W/mK], κ_{av} – average value of moisture diffusivity [m^2/s], w_{hyg} – maximum hygroscopic moisture content by volume [m^3/m^3]. The properties of AAC were taken from Ref. [25], for MVR Uni plaster the data presented in Ref. [26] were used. In the case of thermal insulation layer and connecting layer, the data for basic physical parameters and thermal parameters were fixed in the computational simulations. They were chosen in such a way that they conformed with the supposed generic properties of the respective types of materials. For example, the thermal conductivity of thermal insulation materials corresponded to the data given by Kayfeci et al. [27]. The hygric parameters of both layers, which are known to be the key factors for the hygrothermal performance and service life of the whole envelope [21], were subject of computer aided design.

The computer simulation tool HEMOT (HEat and MOisture Transport) [28], which is based on the general finite element package SIFEL (SImple FInite Elements) [29], was used for the assessment of hygrothermal performance of the analyzed building envelope. Künzel's mathematical model of coupled heat and moisture transport [30] was implemented in HEMOT for the calculations throughout this paper. The balance equations of moisture (1) and heat (2) were formulated as follows:

$$\frac{d\rho_v}{d\varphi}\frac{\partial\varphi}{\partial t} = \mathrm{div}\left[D_\varphi \mathrm{grad}\varphi + \delta_p \mathrm{grad}(\varphi p_s)\right] \tag{1}$$

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \mathrm{div}(\lambda \mathrm{grad}T) + L_v \mathrm{div}\left[\delta_p \mathrm{grad}(\varphi p_s)\right] \tag{2}$$

where ρ_v is the partial density of moisture (mass of moisture per unit volume of the porous body), φ relative humidity, δ_p permeability of the material to water vapor, p_s partial pressure of saturated water vapor, H enthalpy per unit volume, L_v heat of evaporation, λ thermal conductivity and T temperature,

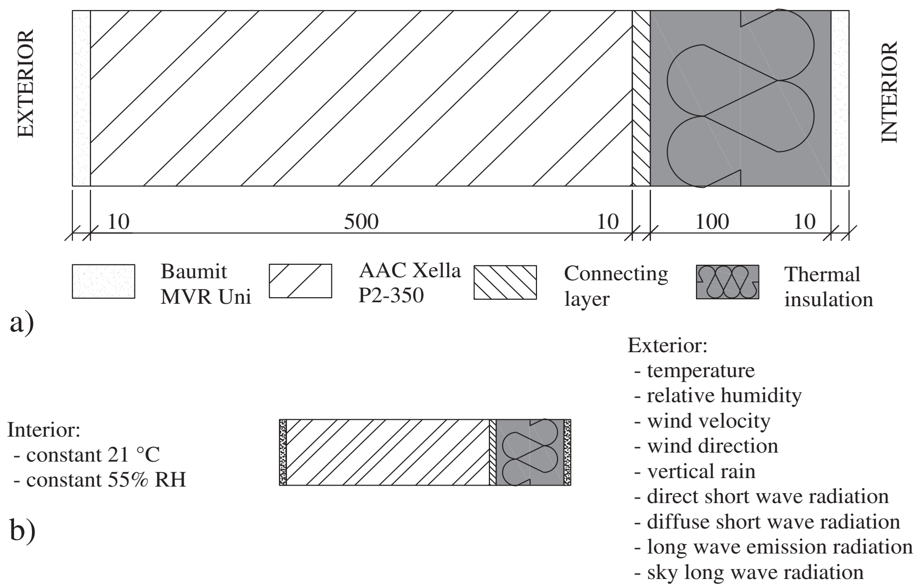

Fig. 1. Scheme of investigated building envelope (a) with boundary conditions (b).

$$D_\varphi = D_W \frac{d\rho_v}{d\varphi} \quad (3)$$

is liquid moisture diffusivity coefficient, D_W is capillary transport coefficient. This model has been verified [31] and successfully applied in many hygrothermal simulations before, dealing with hygrothermal performance of building envelopes [16], optimization of building envelope composition [17] or service life estimates [32].

The exterior boundary conditions were applied in a form of reference-year climatic data for Prague, Czech Republic. This data contained long-time-average (30 years) hourly values of temperature, relative humidity, wind direction and velocity, rainfall, and sun radiation (Fig. 1b). On the interior side, constant values of temperature and relative humidity prescribed in the relevant Czech versions of the EU thermal standards were used. Constant initial conditions corresponding to the interior temperature and relative humidity were applied in the studied envelope. The calculations were performed for the time period of five years.

In the process of computer aided design only such building envelopes were considered as suitable, which did not contain any liquid moisture in both the exterior plaster and load bearing structure during the winter period. In this way, the frost damage of the envelope could be avoided. A possible presence of liquid water in the thermal insulation layer was tolerated, but for very short time periods only, so its thermal insulation function could not be impaired.

Table 1
Basic material characteristics.

	AAC P2-350	Baumit MVR Uni plaster	Thermal insulation layer	Connecting layer
ρ [kg/m^3]	367	1402	200	1500
ψ [%]	81.6	44.4	90.0	40.0
c [J/kg K]	1160–1450	1020–1780	1200	1000
μ [–]	3.3–12	4.5–12.4	Sensitivity analysis 3–10	Sensitivity analysis 5–20
λ_{dry} [W/mK]	0.083	0.443	0.05	0.10
λ_{sat} [W/mK]	0.746	1.380	0.50	1.00
κ_{av} [m^2/s]	2.48×10^{-9}	1.59×10^{-9}	Sensitivity analysis 1×10^{-6}–1×10^{-10}	Sensitivity analysis 1×10^{-7}–1×10^{-10}
w_{hyg} [m^3/m^3]	0.021	0.0588	Sensitivity analysis 0.001–0.1	Sensitivity analysis 0.001–0.2

3. Computational results and discussion

A sensitivity analysis of hygric parameters of the thermal insulation layer and connecting layer was done at first to determine their appropriate values which could avoid or at least minimize the presence of water in liquid phase during a reference year in the building envelope. The characteristic results are presented in a form of the distribution of relative humidity across the building envelope for November 22 of the reference year. This day appeared statistically as one of the most critical from the point of view of hygric performance. According to the reference climatic data for Prague, a 3-day period with highly increased relative humidity of the air (>97%) due to the effect of rainfalls ends in this day (see Fig. 2). Such high value of the relative humidity (in Fig. 2 it is marked with gray color) corresponds to the overhygroscopic

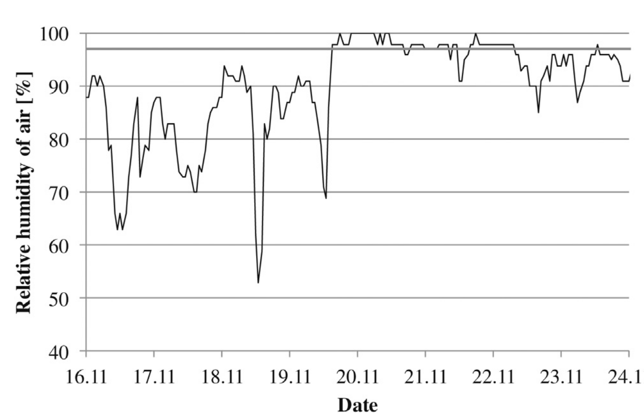

Fig. 2. Climatic data – relative humidity of air in November of reference year for Prague.

(liquid) moisture content, thus the presence of liquid moisture in the pore space of exposed building materials is to be expected. Although in the subsequent days the relative humidity of the air is still very high, it remains in the hygroscopic range and the liquid moisture in the materials of surface layers can already begin to evaporate. Therefore, the moisture content in the external layer of the studied envelope at the end of the mentioned 3-day period can be considered to belong to the highest; this was confirmed in the test calculations. Taking into account the subsequent weather development, this moisture could get frozen within the next weeks.

The most suitable value of moisture diffusivity κ of the thermal insulation layer was 1×10^{-6} m^2/s (Fig. 3a). Apparently, moisture could be transported relatively quickly from the interior to the exterior so that moisture content in the surface layer was acceptable. On the other hand, a low value of moisture diffusivity (1×10^{-10} m^2/s) caused moisture accumulation in the AAC block and subsequently in the surface layer. Water vapor diffusion resistance factor μ of the thermal insulation layer played a less significant role in the hygric performance of the envelope (Fig. 4a), as well as its maximum hygroscopic moisture content w_{hyg} (Fig. 5a). For all studied variations of these two parameters the presence of liquid moisture was avoided. Therefore, in the subsequent phases of computer aided design the values $\mu = 3$ and $\mu = 5$, $w_{hyg} = 0.005$ m^3/m^3 and $w_{hyg} = 0.01$ m^3/m^3 were selected for the thermal insulation layer.

Hygric properties of the connecting layer between the AAC block and the thermal insulation layer affected the overall hygric performance of the analyzed building envelope only slightly within their investigated range (Figs. 3b, 4b and 5b). The following values were selected for the further studies: $\kappa = 1 \times 10^{-9}$ m^2/s and $\kappa = 1 \times 10^{-8}$ m^2/s, $\mu = 10$ and $\mu = 20$, $w_{hyg} = 0.05$ m^3/m^3.

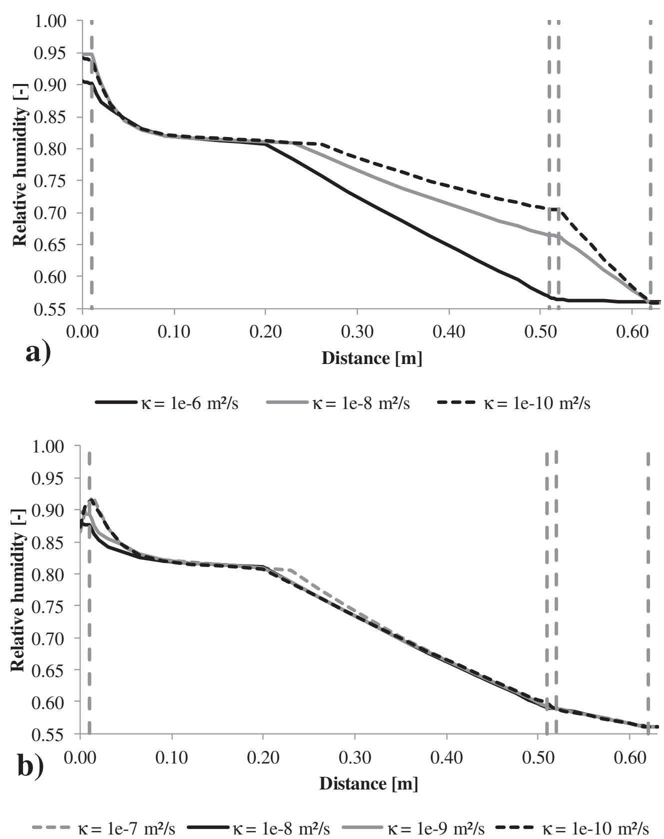

Fig. 3. Sensitivity analysis of moisture diffusivity of the thermal insulation layer (a) and connecting layer (b).

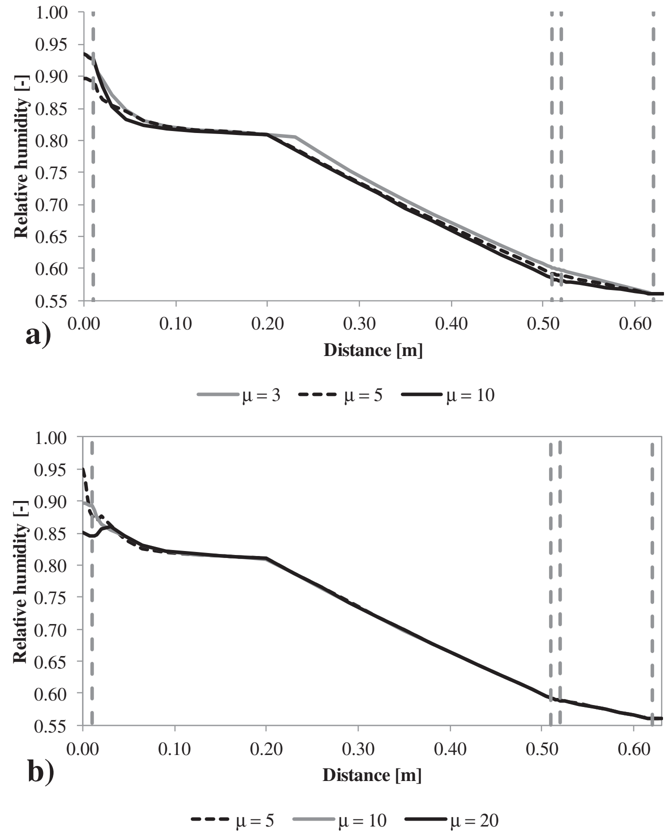

Fig. 4. Sensitivity analysis of water vapor diffusion resistance factor of the thermal insulation layer (a) and connecting layer (b).

In the second phase of the computer aided design the combinations of hygric properties of the thermal insulation layer and connecting layer which are summarized and marked in Tables 2 and 3 were investigated. Similarly as in the first phase, the distribution of relative humidity across the building envelope for November 22 of the reference year was adopted as characteristic for a risk of frost damage. The main criterion of acceptability of a particular combination was again the avoidance or at least minimization of the presence of water in liquid phase in the whole envelope during a reference year. The best results (Figs. 6–9) were achieved for the combinations $I_{21}L_{11}$, $I_{21}L_{22}$, and $I_{22}L_{21}$.

In the third phase, hygrothermal performance and freeze/thaw resistance of building envelopes including thermal insulation layer and connecting layer with the prospective combinations of hygric parameters, which were identified in the second phase, was assessed during a whole reference year. The moisture and temperature profiles were recorded every hour for five years. We focused on the point in the exterior plaster 2 mm under the surface. This position was assumed critical for the appearance of freeze/thaw cycles, because water freezing just on the surface does not lead to mechanical damage. One freeze/thaw cycle was counted only when two conditions were met at the same time: moisture content was in the overhygroscopic (liquid) range and temperature was below zero for at least 2 h. The main objective of this part of computational analysis was to find such combinations of properties of thermal insulation layer and connecting layer which excluded the appearance of freeze/thaw cycles. The obtained results were for all the prospective combinations $I_{21}L_{11}$, $I_{21}L_{22}$, and $I_{22}L_{21}$ very similar. Therefore, only the hygrothermal performance of $I_{21}L_{22}$ is presented in Fig. 10. Apparently, not any freeze/thaw cycle

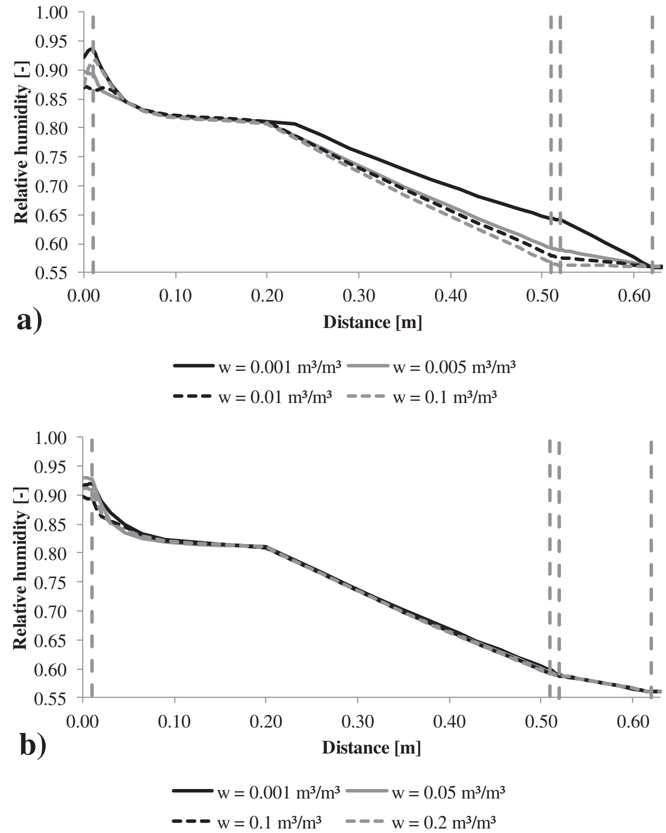

Fig. 5. Sensitivity analysis of hygroscopic moisture content of the thermal insulation layer (a) and connecting layer.

appeared during a reference year because of low moisture content (gray line), which did not reach overhygroscopic range at all, so all three combinations met the required conditions.

In the computational analysis performed up to this point the average values of moisture diffusivity of connecting layer and thermal insulation layer were assumed, for the sake of simplicity. These values are known to correspond roughly to the moisture diffusivity determined for the moisture content of about 2/3 of its saturation value, in many cases [33]. However, for more accurate calculations it is useful to apply the moisture diffusivity κ as a function of moisture content w [28]. This assumption was adopted in the further course of computer aided design.

The moisture diffusivity function $\kappa(w)$ has often a shape similar to the exponential function [34], so it can be described as follows

$$\kappa(w) = k \cdot e^{bw}, \tag{4}$$

where k, b are constants determining the shape of the exponential curve. The constant b determines the range of functional values and has been set to $b = 2.5$ according to the usual shape of $\kappa(w)$ curves [34]. The value of constant k was subsequently calculated using the equation

Table 2
Properties of the thermal insulation layer.

$\kappa = 1 \times 10^{-6}$ m²/s		μ [−]	
		3	5
w_{hyg} [m³/m³]	0.005	I_{11}	I_{12}
	0.010	I_{21}	I_{22}

Table 3
Properties of the connecting layer.

$w_{hyg} = 0.05$ m³/m³		κ [m²/s]	
		1×10^{-8}	1×10^{-9}
μ [−]	10	L_{11}	L_{12}
	20	L_{21}	L_{22}

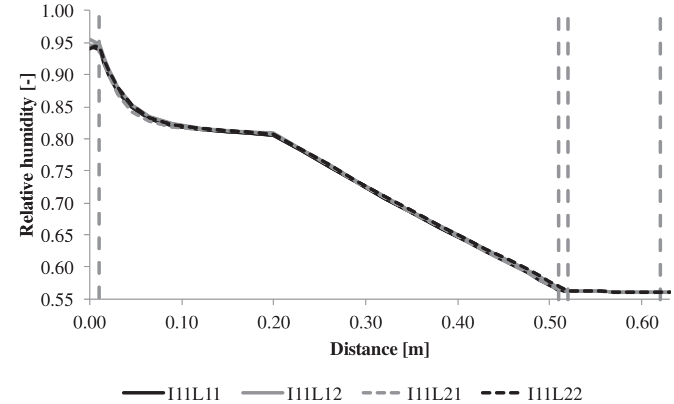

Fig. 6. Hygric performance of selected types of building envelopes ($I_{11}L_{11}$, $I_{11}L_{12}$, $I_{11}L_{21}$, $I_{11}L_{22}$).

$$\kappa_{av} = k \cdot e^{b \cdot \frac{2}{3} w_{sat}} \tag{5}$$

where κ_{av} is the average value of moisture diffusivity, w_{sat} is the saturation moisture content.

The $\kappa(w)$ functions of thermal insulation layer and connecting layer obtained using the appropriate values of κ_{av} are shown in Fig. 11.

Fig. 12 shows the results of computational simulation of the hygrothermal performance of AAC-based building envelope with the thermal insulation layer and connecting layer having the prospective combinations of hygric properties identified above, using the moisture diffusivity as a function of moisture content given in Fig. 11. Only the calculations performed for $I_{22}L_{21}$ are presented as the other two combinations, $I_{21}L_{11}$ and $I_{21}L_{22}$, gave very similar courses of temperature and moisture. Also in this case, not a single freeze/thaw cycle was counted during the fifth reference year because moisture content (gray line) did not reach overhygroscopic range at all during the reference year. Therefore, the combinations

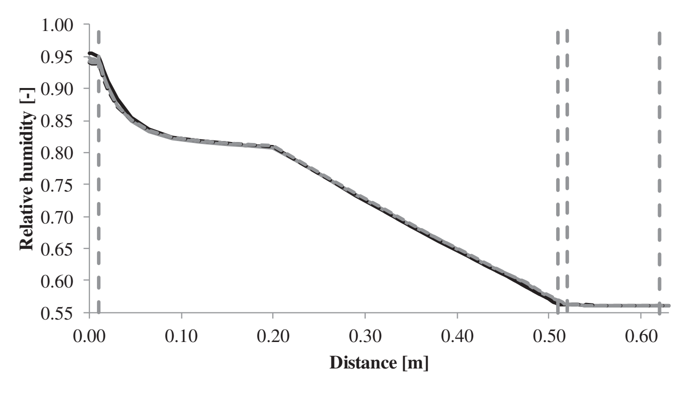

Fig. 7. Hygric performance of selected types of building envelopes ($I_{12}L_{11}$, $I_{12}L_{12}$, $I_{12}L_{21}$, $I_{12}L_{22}$).

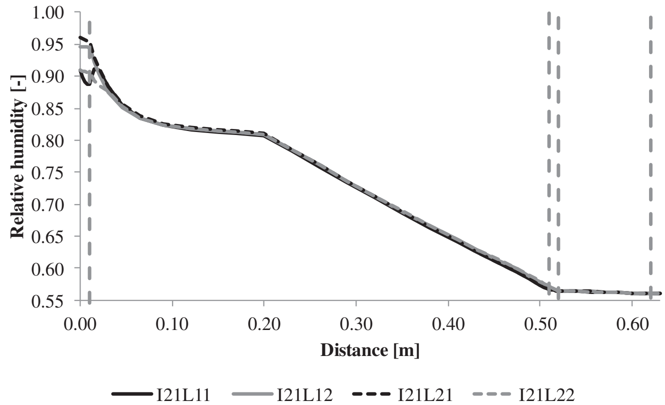

Fig. 8. Hygric performance of selected types of building envelopes ($I_{21}L_{11}$, $I_{21}L_{12}$, $I_{21}L_{21}$, $I_{21}L_{22}$).

$I_{22}L_{21}$, $I_{21}L_{11}$, and $I_{21}L_{22}$ of the hygric properties of thermal insulation layer and connecting layer with the moisture diffusivities given in Fig. 11 could be considered as a successful result of the computer aided design. Distribution of temperature across this building envelope in selected winter and summer day is shown in Fig. 13.

Analyzing the obtained results from a point of view of materials available on the current market, the requirement of a high moisture diffusivity, κ, of the thermal insulation layer ($\approx 10^{-6}$ m^2/s) is certainly the most critical. Common thermal insulation materials such as expanded polystyrene or hydrophobic mineral wool are supposed to prevent a construction from moisture ingress so that their κ values are very low [35]. However, some not very common solutions with tailored hydrophilic [21] or capillary active [20] materials applied as thermal insulation layers appeared in the past for brick and stone masonry. Similar types of materials can potentially be used also for AAC-based envelopes. Hydrophilic mineral wool [36] or calcium silicate plates [34] can achieve moisture diffusivity in an order of 10^{-6} m^2/s, thus they appear as prospective solutions. The required low values of water vapor diffusion resistance factor, μ, of the thermal insulation layer present, on the other hand, not a serious problem. Both hydrophilic mineral wool [36] and calcium silicate [37], which were identified as suitable from the point of view of liquid water transport parameters, conform to the condition of fast water vapor transport as well. The required hygroscopic moisture content, w_{hyg}, of the thermal insulation layer of 0.01 m^3/m^3 seems to be too high for hydrophilic mineral wool which has almost no capability of water vapor storage [36] and too low for calcium silicate which is highly hygroscopic [37]. However, this may not be a critical problem as the properties of both materials can be tailored during the production process.

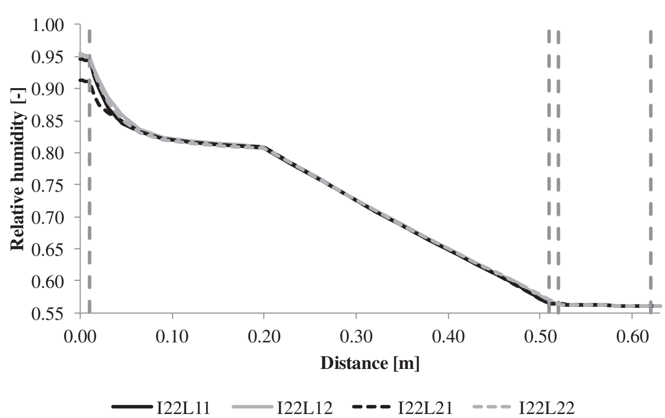

Fig. 9. Hygric performance of selected types of building envelopes ($I_{22}L_{11}$, $I_{22}L_{12}$, $I_{22}L_{21}$, $I_{22}L_{22}$).

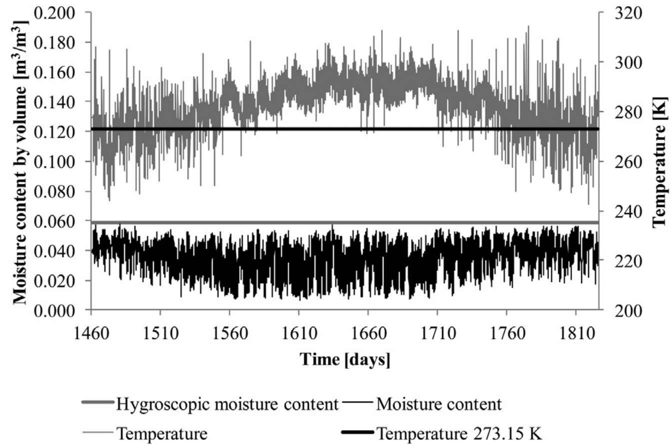

Fig. 10. Hygrothermal performance of $I_{21}L_{22}$ building envelope.

On the other hand, the hygric properties of the connecting layer were not found very restricting. The combination of moisture diffusivity κ of 1×10^{-9} m^2/s–1×10^{-8} m^2/s, water vapor diffusion resistance factor μ of 10–20 and hygroscopic moisture content, w_{hyg}, of about 0.05 m^3/m^3 is common for instance for lime–cement [38] or lime–pozzolan [39] mortars.

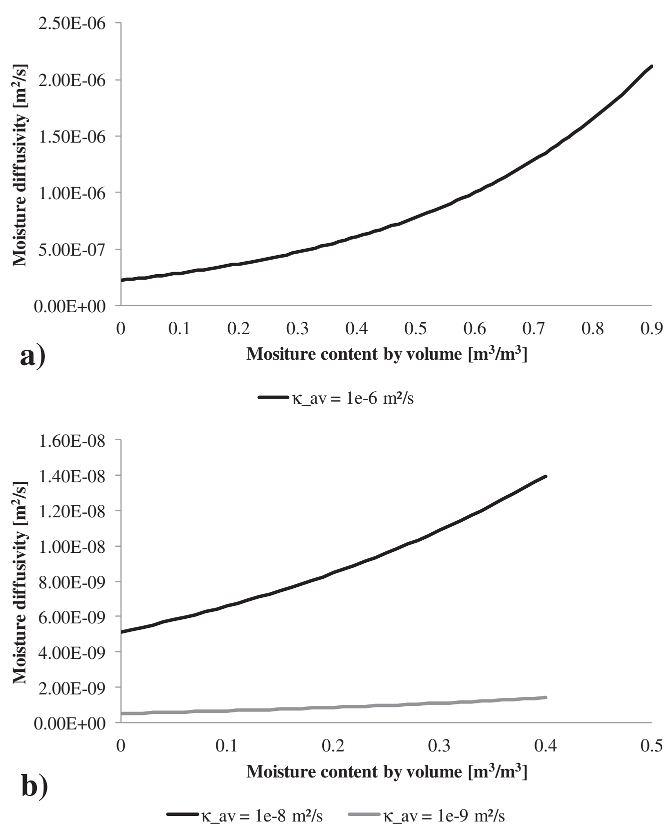

Fig. 11. Moisture diffusivity of the thermal insulation layer (a) and connecting layer (b) as a function of moisture content.

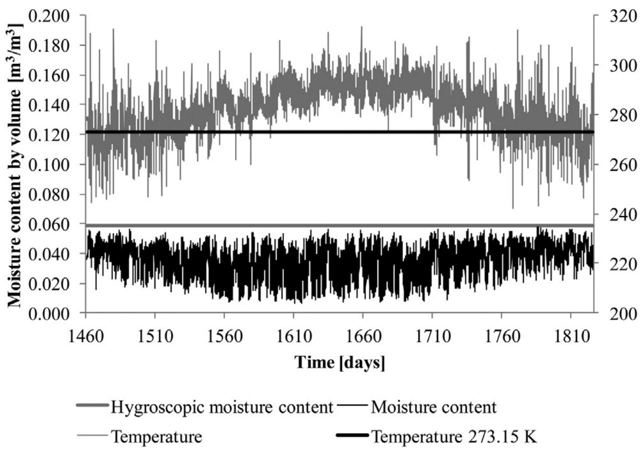

Fig. 12. Hygrothermal performance of $I_{22}L_{21}$ using moisture diffusivity as a function of moisture content.

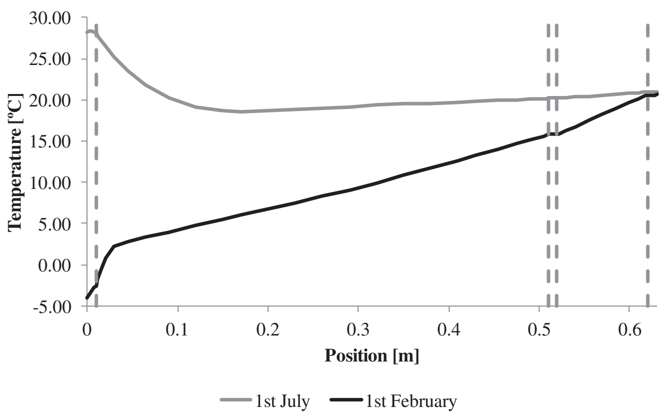

Fig. 13. Distribution of temperature across the building envelope ($I_{21}L_{22}$).

In this paper, besides the heat transport also moisture transport was included in the investigations, which can be considered as its main contribution to the methodology of service life analyses. Thermal performance of building envelopes or their parts was studied very frequently within the last few years. However, in most cases building energy performance codes (e.g., ANSYS, Design Builder) or mathematical models assuming only simple heat transfer were used. For example, Barrios et al. [40] neglected any presence of moisture in building materials while they calculated thermal performance of several types of external walls or roofs using one dimensional heat transfer model. Ozel [41] in his estimate of the optimal thickness of thermal insulation adopted basically the same simplifications as Barrios et al. [40] but he at least used a more sophisticated implicit finite difference method and dynamic thermal conditions. On one hand, such a choice significantly reduces requirements on the input parameters, which have to be experimentally measured, as well as it simplifies the calculation methods. On the other, the results of simplified calculations may not always express the physical reality with a sufficiently high accuracy and the service life assessments may be impaired.

4. Conclusions

The computational analysis presented in this paper revealed that interior thermal insulation systems can be considered a viable solution for the AAC-based building envelopes in the future. The main results of the computer aided design aimed at this kind of systems can be summarized as follows:

- The moisture diffusivity, κ, of the thermal insulation layer should be very high ($\approx 1 \times 10^{-6}$ m^2/s), its water vapor diffusion resistance factor, μ, very low ($\approx$3–5), and hygroscopic moisture content, w_{hyg}, moderate ($\approx$0.01 m^3/m^3). Such combination of properties is very rare for the currently used thermal insulation boards. The closest materials which can possibly meet such requirements are hydrophilic mineral wool or calcium silicate.
- The hygric properties of the connecting layer between the thermal insulation board and the AAC block are, on the other hand, not very restrictive. Common lime–cement or lime–pozzolan mortars can meet the required criteria of $\kappa \approx 1 \times 10^{-9}$ m^2/s–1×10^{-8} m^2/s, $\mu \approx$ 10–20, and $w_{hyg} \approx 0.05$ m^3/m^3.

The next step in the construction design of an interior thermal insulation system suitable for AAC envelopes should be the development of appropriate materials conforming with the specifications obtained in the computer aided design. Considering the properties of current hydrophilic mineral wool and calcium silicate which appear as the most prospective thermal insulation materials for that purpose, the necessary adjustments seem to be feasible.

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