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Exterior thermal insulation systems for AAC building envelopes: Computational analysis aimed at increasing service life

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ABSTRACT

A computational analysis aimed at increasing service life of exterior thermal insulation systems suitable for building envelopes based on autoclaved aerated concrete (AAC) in the climatic conditions of Central Europe is presented. In the first step, a sensitivity analysis of the effect of hygric parameters of materials involved in thermal insulation systems on the hygrothermal performance of AAC envelopes is accomplished, in order to identify appropriate ranges of their values. Computational simulations of temperature and moisture fields in AAC building envelopes are then performed, using proper combinations of properties of exterior layers. The results are evaluated from the point of view of frost resistance of the whole building envelope, and the appropriate values of hygric properties of thermal insulation layer and exterior plaster are identified. Finally, prospective types of materials suitable for the investigated thermal insulation system are proposed.

1. Introduction

Besides the load bearing capability which, obviously, will always remain the most important factor in construction design, the thermal insulation solutions present nowadays one of the key factors for assessment of material composition of building envelopes [1,2]. One of the main design objectives is thus to reach thermal insulation properties as good as possible. This can easily be accomplished using thermal insulation layer whereas the most important decision is to choose a proper insulation material. Thickness of thermal insulation layer is then calculated according to appropriate standards.

However, taking into account also other points of view such as hygric properties or hygrothermal performance, one can notice that a designed envelope may not be as perfect as it seemed before. Inappropriate material combination can lead to accumulation of moisture inside the material and water condensation consequently. If the moisture-related problems are combined with the effects of temperature, such as water freezing/thawing in the pore system, the end result can be early destruction of some materials or at least significant decrease of durability of building envelope.

One of the current trends in building industry is to use new materials with better thermal insulating properties which make possible to avoid thermal insulation layers in building envelope and reach financial savings in that way. A typical material of this kind is autoclaved aerated concrete (AAC) [3,4]. Despite the current availability of many advanced AAC products on the European market [5], an extensive research is still in progress, aimed at the improvement of thermal, hygric and mechanical parameters of AAC. The innovations in AAC composition are being sought for instance by using hydrophobic agents [6], natural zeolites [7], or various waste materials such as bottom ash [8,9], silica fume [10], gasification residues [11], clayey waste [12], and fly ash from cellulose industry [13].

The valid Czech standard ČSN EN 73 0540-2 [14] requires for vertical walls the overall heat transfer coefficient (U-value) of 0.38 W/m^2 K but recommends 0.25 W/m^2 K. Nowadays, many current AAC materials available on the European market in the dry state safely meet this requirement, so that they are allowed to be used in single-layer masonry without thermal insulation. Some AAC products meet in the dry state even the recommended U value. However, the requirements of European standards on thermal protection of buildings are steadily increasing during the last years. For instance, last updating of British Approved document L1A [15] requires the U-value of 0.25 W/m^2 K. The proposal of updated ČSN EN 73 0540-2 which is to be issued before the end of 2011 decreases the required U value for vertical walls to 0.30 W/m^2 K and specifies the target U values for passive houses within 0.18–0.12 W/m^2 K. While the more stringent requirements on vertical walls of common buildings can still be met using the current assortment of AAC products, perhaps with some slight adjustments, the very low U values recommended for passive houses make the application of single-layer AAC masonry in this particular segment of building market rather difficult.

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Thermal insulation systems are currently not applied for AAC-based building envelopes, mainly because their use is not supported by major AAC producers. However, taking into account the increasing demand for reducing thermal loss of buildings, which persists in Europe at least since the energy crisis in 1970s, a situation may arise in a not very distant future when for AAC walls the recommended *U*-values might be achievable only with unrealistic masonry thickness. Therefore, a study of the applicability of thermal insulation systems in AAC-based building envelopes seems to be timely at present. An additional argument for such an analysis is the still unresolved problem of the hygric behavior of AAC walls, which the current standards do not take into account, and the related problem of their real service life.

2. Previous work on the service life assessment of AAC-based building envelopes

Precise analyses of hygrothermal performance of AAC-based building envelopes based on sound scientific knowledge were not performed very frequently to date. The experimental work presented in [3,16] and computational analyses reported in [17–20] belong to the few exceptions. As showed by the results reported in [17], the service life of simple AAC wall without any finishes was relatively short because of exposition to high moisture straining and freezing of condensed water which in the conditions of Central Europe could be realized as much as 19 times per a reference year. The first signs of material damage could then occur already after 2 years. So, it was confirmed necessary to provide AAC block with a suitable external finish in order to eliminate the amount of incoming moisture. However, with respect to very specific hygric behavior of AAC the common plasters could not be used, because service life of that building envelope would be very limited. For instance, hygrothermal simulation of AAC masonry provided with common lime plaster showed even higher accumulation of moisture inside the wall and the higher number of freezing cycles in AAC than in unplastered wall. The first sign of damage would occur before the second year. Apparently, it was this fact that led in the past years to the development of specific plasters designed especially for AAC. For example, hygrothermal performance of AAC masonry provided with MVR Uni, which is specific plaster developed for AAC by Baumit Ltd., was entirely sufficient and there were not any freezing cycles in whole envelope during a reference year in Central Europe. Common thermal insulation systems improved thermal properties of envelope and protected well AAC against the effect of climatic conditions [17] but the exterior plaster was found to be exposed to abnormal straining. Its service life was then limited to 6 or 7 years.

In this paper we present a computational analysis aimed at the identification of appropriate properties of thermal insulation material and exterior plaster which are supposed to be used in AAC-based building envelopes. Based on the results of this analysis, a new AAC-specific thermal insulation system can be developed. Thanks to that, reliable protection of AAC against the effect of climatic straining can be accomplished and simultaneously the service life of exterior plaster can be extended.

3. Methods of computational analysis

Building envelopes always behave as systems. Therefore, the properties of the parts of the system, of the particular materials, have to be compatible. It is not sufficient to develop and employ one excellent material, but it is necessary to develop a working multi-layered systems consisting of different materials. This is the most important feature of any computational design of a building envelope from the point of view of building physics. In the particular case solved in this paper, we considered a system consisting of internal plaster, load-bearing structure, connecting layer, thermal insulation layer, and external plaster. The studied system is composed of a fundamental part, which is supposed to be fixed in the computational analysis, and a free part, whose properties are subject of variations within chosen limits. In our case, the fundamental part consisted of an AAC layer (P2-400 produced by H+H was chosen as a typical representative of AAC blocks currently used in Europe), internal plaster (Baumit MVR Uni as a material known to perform reasonably in the previous studies) and connecting layer (Mamut M2 mortar, also known from previous analyses); thermal insulation layer and external plaster formed the free part (Fig. 1). The envelope is oriented to the south.

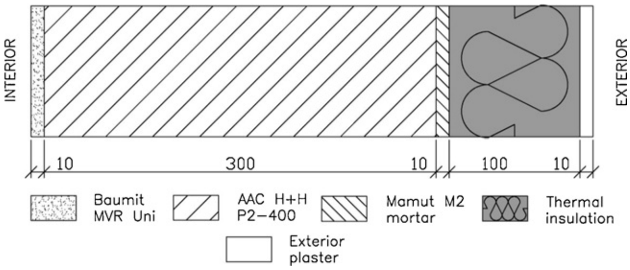

Fig. 1. Scheme of investigated building envelope.

The hygric, thermal and basic physical properties of materials presented in Fig. 1 are shown 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/m K), λ_{sat} – thermal conductivity in water saturated state (W/m K), κ_{av} – average value of moisture diffusivity (m^2/s), w_{hyg} – maximum hygroscopic moisture content by volume (m^3/m^3). For AAC, interior plaster and connecting layer, the data of hygric, thermal and basic physical properties were taken from [5]. The properties of thermal insulation layer and external plaster were subject of computational analysis. Some of these properties were prescribed in advance. For the bulk density, open porosity, and specific heat capacity the values characteristic for thermal insulation materials and plasters were chosen. The thermal conductivity was supposed to conform to the common requirements for the analyzed types of materials. The main hygric parameters of the thermal insulation layer and external plaster, namely the water vapor diffusion resistance factor, moisture diffusivity and maximum hygroscopic moisture content were considered free parameters in the computational analysis. The reason for this choice was the principal role of hygric parameters of both thermal insulation material and exterior plaster in the service life of exterior plasters which was revealed in the previous analysis reported in [17].

The computer simulation tool HEMOT [21] was used in the calculations, which was developed at the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague and can be used to solve 1D or 2D transport problems. In this paper, the investigated building envelope was solved as 1D model. The construction of the code is based on the application of the general finite element computer simulation tool SIFEL (SImple Finite ELements) [22]. The moisture and heat balance equations were formulated in the simplified form proposed by Kuenzel [23]. This model has already been verified and successfully applied in many hygrothermal simulations before [5,24,25].

In service-life aimed analyses, the calculations should be done for the conditions as close as possible to the real conditions on building site. Therefore, hourly values of meteorological data in the form of a reference year for Prague, Czech Republic, were used as

Table 1
Basic material characteristics.

	AAC H+H P2-400	Mamut M2 mortar	Baumit MVR Uni plaster	Thermal insulation	Exterior plaster
ρ (kg/m^3)	367	1430	1402	200	1500
ψ (%)	81.6	42.6	44.4	90.0	40.0
c (J/kg K)	1160–1450	1020	1020–1780	1200	1000
μ (–)	3.3–12	12.4	4.5–12.4	Sensitivity analysis	Sensitivity analysis
λ_{dry} (W/m K)	0.083	0.481	0.443	0.05	0.10
λ_{sat} (W/m K)	0.746	2.022	1.380	0.50	1.00
κ_{av} (m^2/s)	2.48×10^{-9}	1.07×10^{-9}	1.59×10^{-9}	Sensitivity analysis	Sensitivity analysis
w_{hyg} (m^3/m^3)	0.021	0.201	0.042	Sensitivity analysis	Sensitivity analysis

exterior boundary conditions (Fig. 2). The temperature and relative humidity typical for residential buildings in Czech Republic were chosen as interior boundary conditions.

The hygrothermal calculations have to be performed in a sufficiently long time period. Under certain circumstances hygrothermal properties of a system can worsen gradually, so that damage can appear only after a longer time period. Therefore, not only the actual values of main hygrothermal quantities are important but also their development in the subsequent years. The time period of 5 years was chosen in this paper which was supposed to be long enough for deciding if the system performed without substantial damage.

In the computational analysis, such solutions were sought that excluded the presence of water in liquid state in the thermal insulation material during the whole reference year. High moisture content in any thermal insulation material leads to substantial increase of its thermal conductivity, thus damages its thermal insulation capability. In the exterior render the liquid water appearance was permitted only in short term and preferably not in the winter period. Presence of liquid water in surface layers may lead in winter to its freezing and subsequent mechanical damage.

4. Computational results and discussion

Sensitivity analysis of hygric properties of thermal insulation material and exterior plaster was performed at first. Its main objective was to set limits to the values of investigated properties. The moisture diffusivity and maximum hygroscopic moisture content were assumed in a wide range, $\kappa_{av} = 10^{-6}$, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10} m^2/s; $w_{hyg} = 0.0001, 0.001, 0.005, 0.01, 0.02, 0.05$ m^3/m^3. The water vapor diffusion resistance factor, on the other hand, was presumed to have relatively low upper limit, corresponding to the μ value of AAC, $\mu = 3, 5, 10$.

Characteristic results are presented in Figs. 3–8. They show the relative humidity across the envelope in the 691st day of simulation. This day appeared statistically as one of the most critical during reference year (22nd of November) because of high content of liquid moisture in external layers of the envelope which can get frozen subsequently. There are dash lines in each figure which show the material interfaces according to Fig. 1 and dash-and-dot line which shows the relative humidity of 97.6% which corresponds to maximum hygroscopic moisture content. Taking into account the basic criteria given in last paragraph of Section 3, the optimal values of moisture diffusivity of thermal insulation were within the range of 10^{-7}–10^{-6} m^2/s, moisture diffusivity of exterior plaster

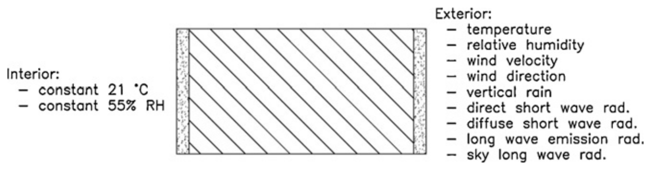

Fig. 2. Scheme of boundary conditions.

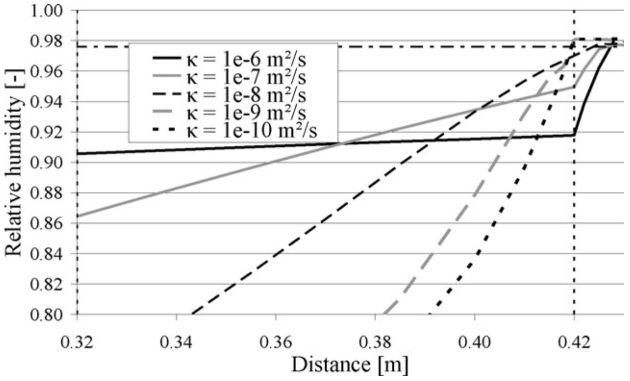

Fig. 3. Sensitivity analysis of moisture diffusivity of thermal insulation in the 691st day of simulation.

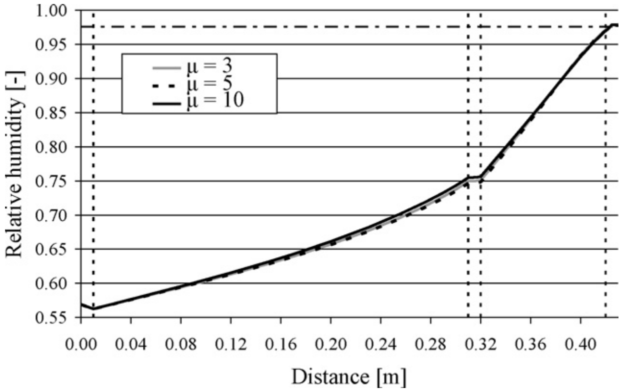

Fig. 4. Sensitivity analysis of water vapor diffusion resistance factor of thermal insulation in the 691st day of simulation.

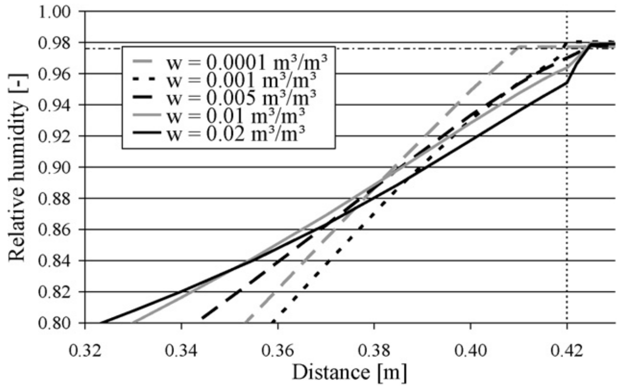

Fig. 5. Sensitivity analysis of hygroscopic moisture content of thermal insulation in the 691st day of simulation.

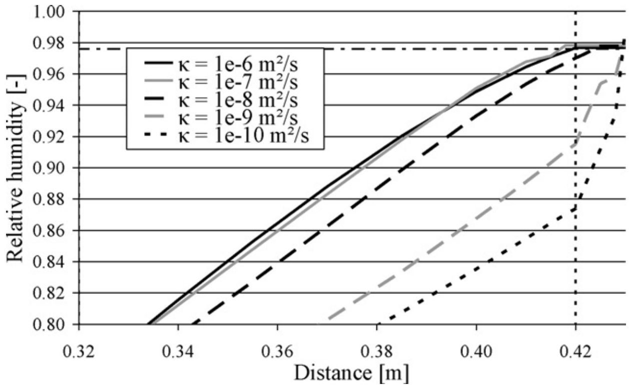

Fig. 6. Sensitivity analysis of moisture diffusivity of exterior plaster in the 691st day of simulation.

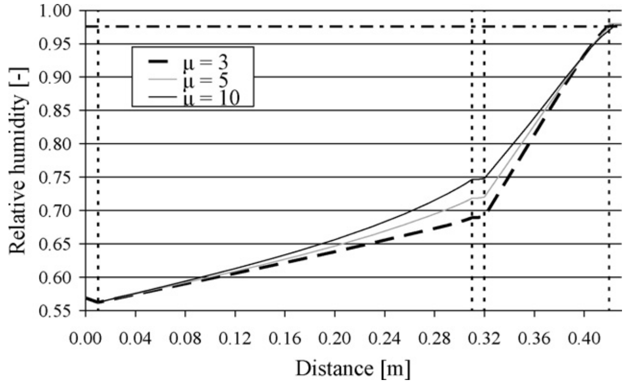

Fig. 7. Sensitivity analysis of water vapor diffusion resistance factor of exterior plaster in the 691st day of simulation.

10^{-9}–10^{-8} m^2/s, maximum hygroscopic moisture content of thermal insulation 0.005–0.02 m^3/m^3, maximum hygroscopic moisture content of exterior plaster 0.001–0.005 m^3/m^3, water vapor diffusion resistance factor of thermal insulation 10 or lower, water vapor diffusion resistance factor of exterior plaster 5 or lower.

Based on the results of sensitivity analysis, prospective combinations of hygric parameters of thermal insulation material and exterior plaster were selected (see Tables 2 and 3 for marking of the particular combinations). Characteristic results are shown in Figs. 9–11. The most suitable combinations from the point of view of the criteria formulated in last paragraph of Section 3 appeared i21p12, i32p22, i32p12, i31p12, i22p22, i31p22, and i21p22. Main criterion of selection of suitable combinations was to choose these

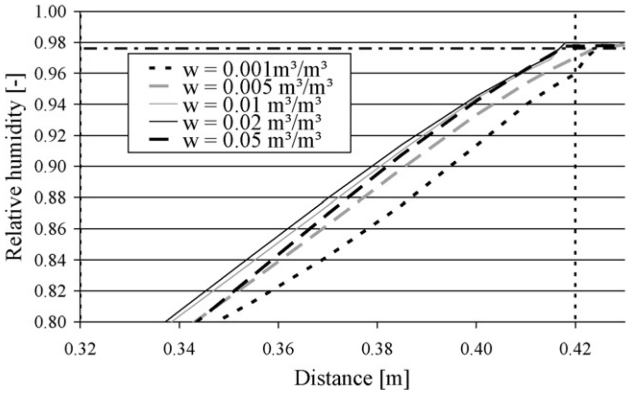

Fig. 8. Sensitivity analysis of hygroscopic moisture content of exterior plaster in the 691st day of simulation.

Table 2
Properties of thermal insulation material.

$\mu = 10$		k_{av} (m^2/s)	
		10^{-6}	10^{-7}
w_{hyg} (m^3/m^3)	0.005	i11	i12
	0.010	i21	i22
	0.020	i31	i32

Table 3
Properties of exterior plaster.

$\mu = 5$		k_{av} (m^2/s)	
		10^{-8}	10^{-9}
w_{hyg} (m^3/m^3)	0.001	p11	p12
	0.005	p21	p22

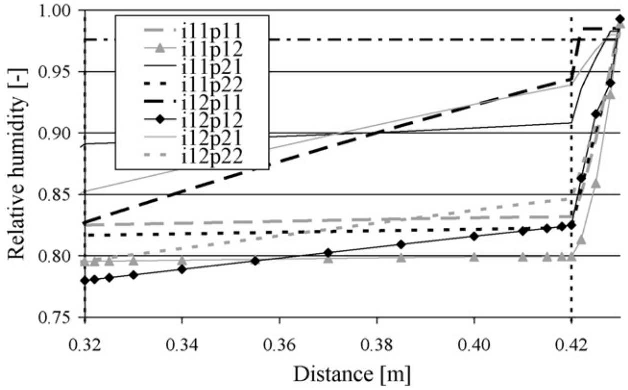

Fig. 9. Hygric simulation of selected types of building envelopes in the 691st day of simulation.

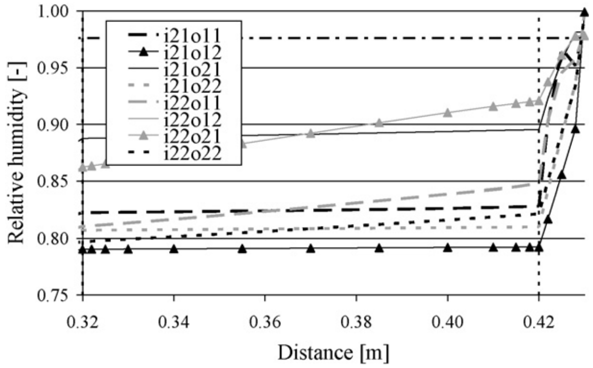

Fig. 10. Hygric simulation of selected types of building envelopes in the 691st day of simulation.

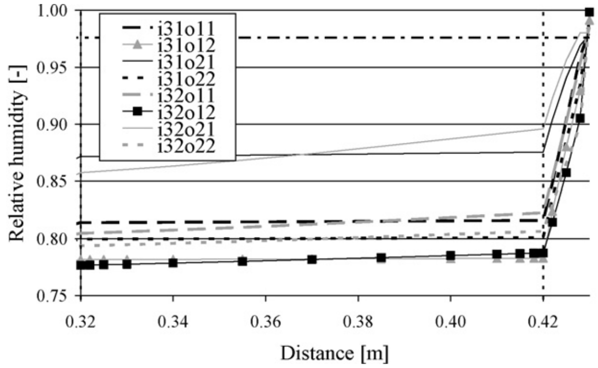

Fig. 11. Hygric simulation of selected types of building envelopes in the 691st day of simulation.

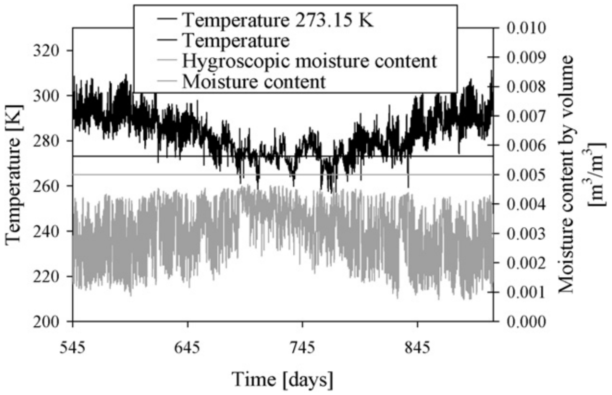

Fig. 12. Hygrothermal simulation of i21p22 building envelope.

which do not contain the liquid moisture in external finish during the critical 691st day of simulation. The external layers of building envelope will be always exposed to the low temperatures in winter, so the only way how to protect them against effect of freezing water is to protect them against the presence of liquid moisture.

For the prospective combinations of parameters a more detailed hygrothermal analysis was done, aimed at both hygrothermal performance and frost resistance at the same time. The moisture and temperature profiles have been recorded every hour for 5 years in the exterior plaster 2 mm under the surface; this position was assumed critical for the appearance of freeze/thaw cycles as water freezing just at the surface may not lead to mechanical damage. A freezing cycle was considered effective only when two conditions were fulfilled at the same time: temperature had to drop below zero and moisture content had to be in overhygroscopic range. Main objective of this part of computational analysis was to find such combinations of properties of thermal insulation and exterior plaster which excluded the appearance of freezing cycles. It was found that only the combinations marked as i21p22, i22p22, i31p22, and i32p22 did not allow appearance of freezing cycles (see Table 4). In other cases there were two or more freezing cycles during the 5 year period. The results obtained for the suitable combinations of material properties were very similar; so they were summarized into one figure (see Fig. 12).

Up to now, all the computational simulations have been accomplished using an average value of moisture diffusivity. This value is commonly obtained using the results of water absorption experiments [26]. In most cases it corresponds to the value of moisture diffusivity for the moisture content equal to about 2/3 of water content at saturation [27]. However, moisture diffusivity is under real conditions highly dependent on moisture content [21], which may affect the hygric calculations in a significant way. According to the shape of moisture diffusivity function [28], it is obvious that moisture transport in overhygroscopic range, which covers most of the moisture transfer, will be slowed down. This will lead to the moisture increase inside building envelope and subsequently to deterioration of hygric behavior. The appearance of freezing cycles can be then expected also in cases, where they were not if a constant value of moisture diffusivity was assumed.

The moisture diffusivity vs. moisture content function, $\kappa(w)$, has often a shape similar to exponential function [28], so we decided to substitute the average value by the function

$$\kappa = k \cdot e^{bw}, \tag{1}$$

where k, b are constants, which determine 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 [28]. The value of constant k was calculated using equation

$$\kappa_{\mathrm{av}} = k \cdot e^{b \cdot (2/3) w_{\mathrm{sat}}}. \tag{2}$$

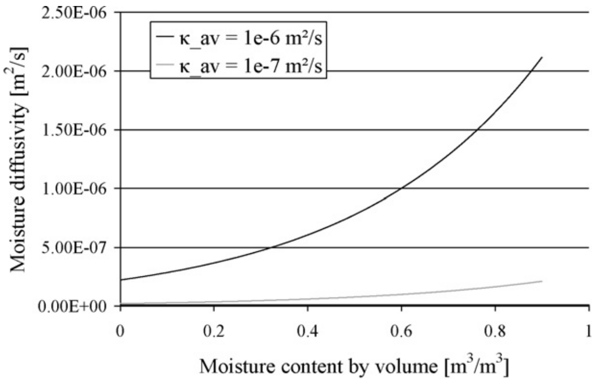

Fig. 13. Moisture diffusivity of thermal insulation as a function of moisture content.

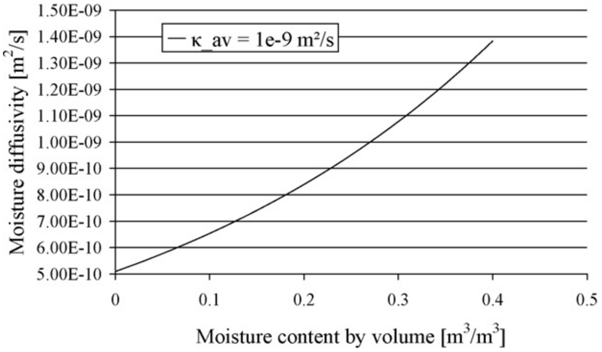

Fig. 14. Moisture diffusivity of exterior plaster as a function of moisture content.

The $\kappa(w)$ functions of thermal insulation material and exterior plaster obtained using the appropriate values of κ_{av} identified before are shown in Figs. 13 and 14.

The results of computational analysis of hygrothermal performance of AAC building envelopes with the prospective combinations of hygric properties of thermal insulation material and exterior plaster identified above, using moisture diffusivity as a function of moisture content this time, are shown in Figs. 15 and 16 (only two representative figures are given because of the almost identical results obtained for two pairs of combinations). Contrary to the previous calculations with constant moisture diffusivity, only combinations marked as i21p22 and i31p22 gave the desired

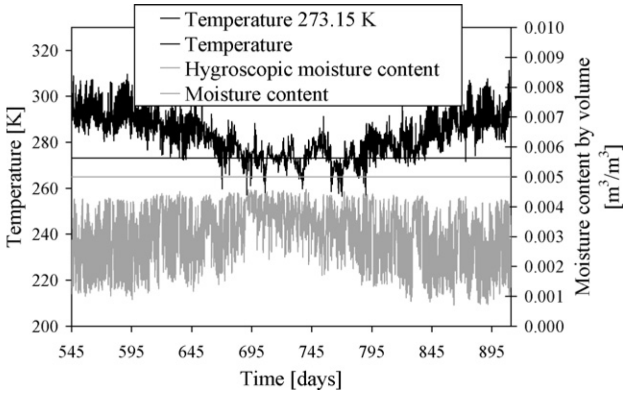

Fig. 15. Hygrothermal performance of i21p22 (i31p22) using moisture diffusivity as a function of moisture content.

Table 4
Number of freezing cycles for the investigated combinations.

	Combinations						
	i21p12	i21p22	i22p22	i31p12	i31p22	i32p12	i32p22
Average number of freezing cycles (annual)	18.4	0	0	16.4	0	19.2	0

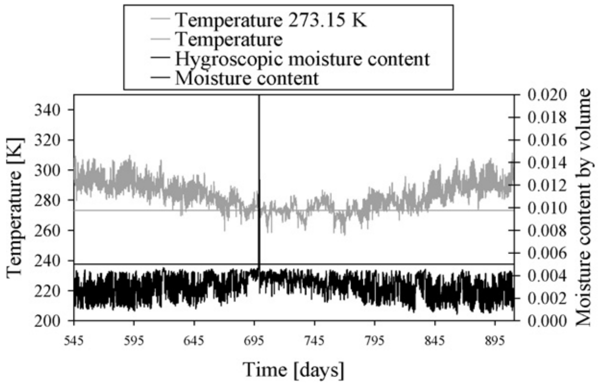

Fig. 16. Hygrothermal performance of i22p22 (i32p22) using moisture diffusivity as a function of moisture content; moisture content peak in 699th day reaches 0.112 m^3/m^3.

results, where not any freezing cycle was observed. In building envelopes marked as i22p22 and i32p22 there were always one or more freezing cycles during the five year period.

A comparison of results obtained in this paper with the work done by other investigators could be done in a limited extent only. The previous computational simulations of hygrothermal performance of AAC-based envelopes were relatively sparse and served primarily to model validation purpose [18–20]. Nevertheless, they indicated the necessity of a reliable knowledge of input parameters of the models, i.e., the moisture and heat transport and storage properties, which was confirmed also in this paper. The in-use performance tests reported in [16] revealed that renderings modified with hydrophobic products were advantageous for AAC substrates. This was in accordance with the results of our computational analysis.

5. Conclusions

The results of computational analysis of hygrothermal performance of AAC-based building envelopes with exterior thermal insulation system aimed at increasing service life in the conditions of Central Europe can be summarized as follows:

- Both the thermal insulation layer and the exterior plaster should be vapor permeable as much as possible. This means that the value of water vapor diffusion resistance factor μ should be as low as possible, preferably lower than 5, for thermal insulation $\mu < 10$ can be sufficient. Low value of water vapor diffusion resistance factor allows very quick transport of water vapor through the material, which sets limits to its possible accumulation and condensation.
- The moisture diffusivity of exterior plaster should be as low as possible. The average value of moisture diffusivity $\kappa_{\mathrm{av}} = 10^{-9}$ m^2/s can be considered an upper limit; it can be achieved, e.g., using hydrophobic agents. A plaster with low moisture diffusivity absorbs liquid moisture (originating, for instance, from rainfall) very slowly; it remains close to the surface, where it can be easily evaporated back to the exterior, and cannot penetrate deeper.
- Contrary to the exterior plaster, moisture diffusivity of thermal insulation material should be very high. For the investigated composition of building envelope $\kappa_{\mathrm{av}} = 10^{-6}$ m^2/s was identified as an optimal value. It means that the insulation material has to be capillary active. Based on that fact we can exclude application of the most common thermal insulation materials such as polystyrene or hydrophobic mineral wool. However, calcium silicate plate or hydrophilic mineral wool could be viable solutions. Capillary activity of thermal insulation material ensures that moisture possibly penetrating through the exterior plaster can be very quickly transported across the insulation layer. A part of moisture content is then removed from exterior plaster, which is exposed to the largest straining. In addition, the distribution of moisture in thermal insulation is almost homogenized thanks to high moisture diffusivity so that moisture in overhygroscopic state is avoided.
- The maximum hygroscopic moisture content of exterior plaster should be around 0.005 m^3/m^3, for the thermal insulation layer it should lay between 0.01 and 0.02 m^3/m^3. Higher w_{hyg} for thermal insulation material (typical for instance for calcium silicate) makes possible existence of water vapor at higher moisture content but it generally leads to higher relative humidity in the load bearing structure. On the other hand, in exterior plaster with lower w_{hyg} value liquid moisture can appear quite early, thus a risk of its freezing in winter is increased.

Based on the above summary, it can be concluded that hydrophilic mineral wool [29] presents the most prospective solution for the thermal insulating layer in an AAC-based building envelope. However, some of its parameters, in particular maximum hygroscopic moisture content, should be modified. The external plasters suitable for the investigated thermal insulation system could be on lime–cement or lime–pozzolana basis and should contain hydrophobic agents. They can be attached to the insulation in a common way, i.e., using wall plaster mesh. This mesh was not assumed during the simulation because it has not any influence on hygric behavior of the plaster or building envelope.

It should be noted that because all the simulations have been accomplished as 1D, the obtained results can be somewhat different from the reality. In 2D or 3D simulations, many factors can be assumed in addition, such as detailed model of construction, influence of surrounding buildings, or interaction between single parts of building envelope, which can lead to more accurate results. However, although we considered only 1D simulations, we chose a spot on building envelope, which was exposed to most critical factors. Therefore, there is a good reason to believe that the presented results included safety reserves.

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