Computational prediction of hygrothermal conditions in innovated AAC-based building envelopes

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Abstract

Hygrothermal conditions in innovated AAC-based building envelopes are studied in the paper, using computational analysis with exactly measured hygric and thermal transport and storage properties as input parameters. The applied computational model of heat and moisture transport in multi-layered systems of porous materials is based on the Galerkin finite element approach. The computer code written in C++ is used in a series of computational simulations. Climatic data corresponding to the test reference year for Prague are used as boundary conditions, so that cyclic wetting and drying occurs in the envelope. The results of computer simulations of moisture and temperature fields are then utilized in the subsequent service life analysis. On the basis of changes of moisture and temperature, particularly the number of wetting-drying cycles and frost cycles the durability of the AAC envelopes is assessed.

Keywords: AAC building envelope, heat and moisture transport, computational simulation, service life estimation.

1 Introduction

Autoclaved aerated concrete (AAC) is a structural material which is commonly used around Europe, particularly as it combines ease of construction with excellent combination of its mechanical and thermal properties. However, the empirical principles employed in construction design until now have led to serious failures which may have serious consequences for the future practical

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applications of the material. In the current durability assessment of AAC-based building envelope systems a complex view is often missing. Precise analyses of hygrothermal performance of the new AAC technologies based on sound scientific knowledge are not performed very frequently. However, AAC-based building envelopes should be designed as a system consisting of AAC, internal and external finishes and possibly also thermal insulation layer, and in this design process, the details have to be solved using suitable methods.

In this paper, computational prediction of hygrothermal conditions in characteristic types of innovated AAC-based building envelopes using long-term simulations of coupled water and heat transport with the measured water and heat transport and storage properties is performed.

2 Computational analysis

The computational analysis was accomplished by computer code TRANSMAT 7.1 [1], which was developed at the Department of Material Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague on the basis of the general finite element package SIFEL [2]. As basic input parameters of the mathematical model, material parameters of used materials, construction detail, initial and boundary conditions and time specification of simulation were required. Description of all input parameters in more detail is given later.

In the computer simulations we focused on a comparison of hygrothermal behavior of several building envelopes based on AAC. Particularly it was building envelope provided with different external and internal finishes only, building envelope with external insulation system and finishes and envelope without any external finishes.

2.1 Mathematical model

Künzel's mathematical model of heat and moisture transport [3] was used in the simulations which can be formulated as

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

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

where ρ_v is the partial density of moisture, φ relative humidity, δ_p permeability of water vapour, p_s partial pressure of saturated water vapour, H enthalpy density, L_v heat of evaporation, λ thermal conductivity and T temperature,

$$D_\varphi = D_w \frac{d\rho_v}{d\varphi} \tag{3}$$

is liquid moisture diffusivity coefficient, D_w capillary transport coefficient.

2.2 Scheme of construction detail

Four variations of building envelope based on AAC were chosen for simulation, in order to analyze the consequences of different material combinations. As a start-up building envelope we chose AAC without any external finish which allowed us to get real image about hygrothermal performance of AAC layer itself. This material combination is marked as Var. 1. In the next simulation we provided AAC with a common lime plaster. This material combination is marked as Var. 2. In the further step we assumed Baumit MVR Uni plaster which is recommended for AAC structures as external finish, material combination is marked as Var. 3. As the last material combination we used AAC provided with external thermal insulation system (mineral wool) and Baumit MVR Uni plaster. On the material interface between mineral wool and AAC an adhesive mortar layer was placed. This material combination is marked as Var. 4. Description of used materials in more detail is given in next subsection. Scheme of construction detail including the dimensions of each layer is shown in Figure 1. In all

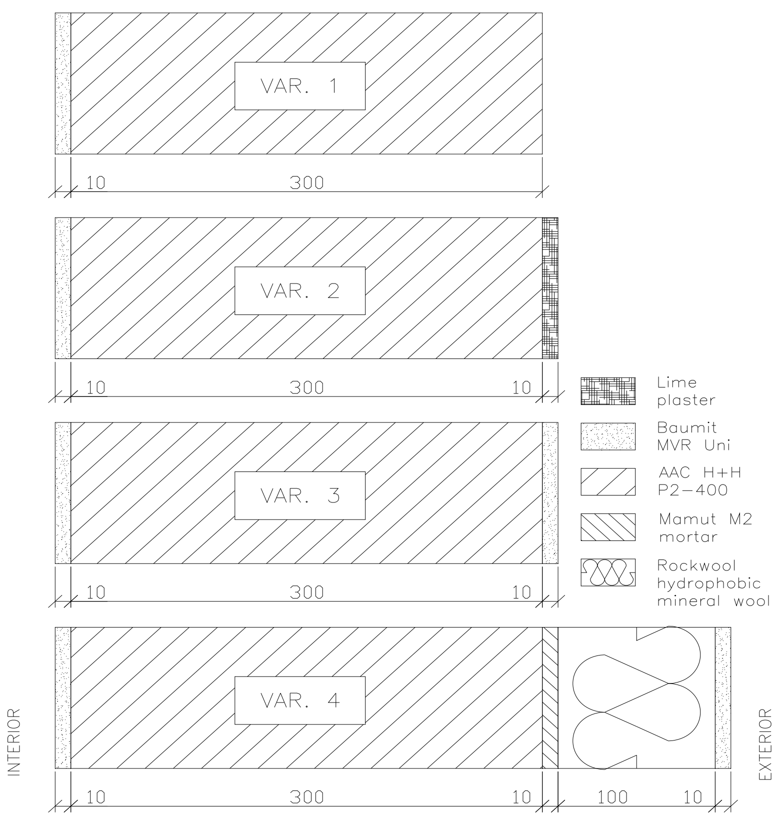

Figure 1: Scheme of analyzed construction detail.

investigated variations we focused on the hygrothermal conditions at a point within the AAC layer just 2 mm under its external surface which can be considered as characteristic position from the point of view of possible frost damage.

2.3 Material parameters

Aerated autoclaved concrete P2-400 produced by H+H Czech Republic, Ltd. was under consideration in this paper. As material for exterior and interior renders we used Baumit MVR Uni Plaster, which is single-layer plaster for exterior and interior surfaces especially recommended for AAC. Another plaster used as external finish was lime plaster [4]. As the thermal insulation we assumed Rockwool hydrophobic mineral wool. For adhesive layer between AAC and mineral wool we used Mamut M2 mortar.

All the material parameters were measured in laboratory of transport processes at the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague [5–7] and are summarized in Table 1. Data for Mamut M2 mortar were measured by M. Jerman and have not been published yet. We used these symbols: ρ – bulk density [kg/m^3], ρ_{mat} – matrix density [kg/m^3], ψ – porosity [%], c – specific heat capacity [J/kgK], μ – water vapour diffusion resistance factor [-], w – moisture content by volume [m^3/m^3], λ – thermal conductivity [W/mK], κ – moisture diffusivity [m^2/s].

Table 1: Material characteristics.

	AAC H+H P2-400	Mamut M2 mortar	Rockwool hydrophobic mineral wool	Baumit MVR Uni plaster	Lime plaster
ρ [kg m^{-3}]	412	1430	270	1402	1650
ψ [%]	80.3	42.6	88.0	44.4	36.0
c [J kg^{-1} K^{-1}]	1250 - 1385	1020	630	1020 - 1780	910 – 1250
μ [-]	3.7 – 14.4	12.4	2.1 – 3.7	4.5 – 12.4	5.1 – 8.9
λ_{dry} [W m^{-1} K^{-1}]	0.094	0.481	0.045	0.443	0.683
λ_{sat} [W m^{-1} K^{-1}]	0.434	2.022	0.246	1.380	1.550
κ [m^2 s^{-1}]	1.12e-9	1.07e-9	2.51e-10	1.59e-9	4.4e-7
w_{hyg} [m^3 m^{-3}]	0.019	0.201	0.007	0.042	0.0495

2.4 Initial and boundary conditions and time interval of simulation

Initial and boundary conditions should be as realistic as possible. This was the reason why we used climatic data in the exterior in the form of Test Reference Year for Prague which contained average data for 30 years. On the interior side we used constant value of relative humidity 55% and temperature 21°C (see Fig. 2). The simulation started on 15th July and took 10 years. The final results show data during the last year.

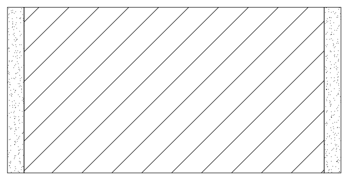

Figure 2: Boundary conditions.

3 Computational results

The results of computational simulations are summarized in a set of figures which describe hygric and thermal performance of studied material of building envelope during a reference year. In all figures we focused on moments when moisture content and temperature reached certain limits simultaneously. In case of moisture content this limit was the value of hygroscopic moisture content (see Tab. 1), in case of temperature the freezing point of water. When these two conditions are fulfilled, contained liquid moisture is getting frozen. This leads to consequent damage of material.

The materials capability to resist to freezing of contained water is characterized by its freeze-thaw resistance which can be measured under laboratory conditions [8]. This was accomplished for AAC and its freeze-thaw resistance was set to 25 cycles [9]. Durability of AAC can be then calculated as quotient of freeze-thaw resistance and number of freezing cycles appearing in the material in building envelope during a year.

3.1 Var. 1 – AAC without any finishes

Hygrothermal performance of AAC without any external finishes is shown in Figure 3. This material combination provided the worst results; we counted 19 freezing cycles during a year. This is caused by relatively long-term keeping high level of moisture content and temperature dropping below zero.

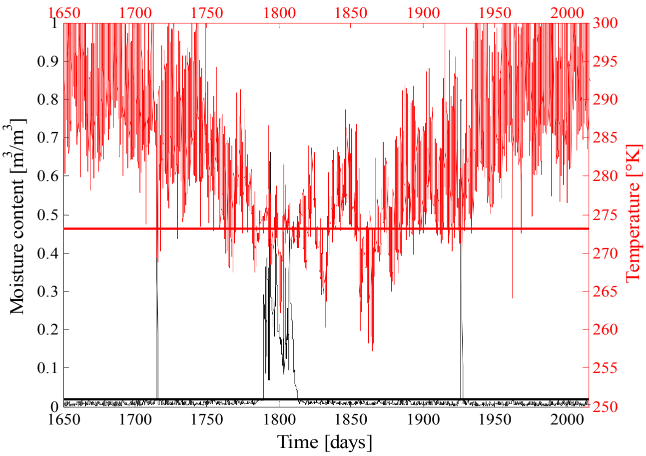

Figure 3: Hygrothermal performance of AAC, Var. 1.

3.2 Var. 2 – AAC provided with lime plaster

Hygrothermal performance of AAC provided with lime plaster is shown in Figure 4. In comparison with Var. 1, number of freezing cycles appearing in AAC during a year was increased to 25 cycles.

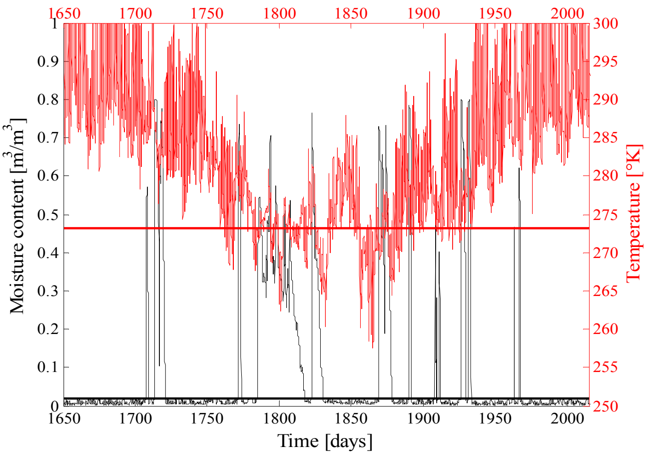

Figure 4: Hygrothermal performance of AAC, Var. 2.

3.3 Var. 3 – AAC provided with Baumit MVR Uni plaster

Hygrothermal performance of AAC provided with Baumit MVR Uni plaster is shown in Figure 5. In this case we did not count any freezing cycles appearing during year. This was caused by low value of moisture content during the whole year.

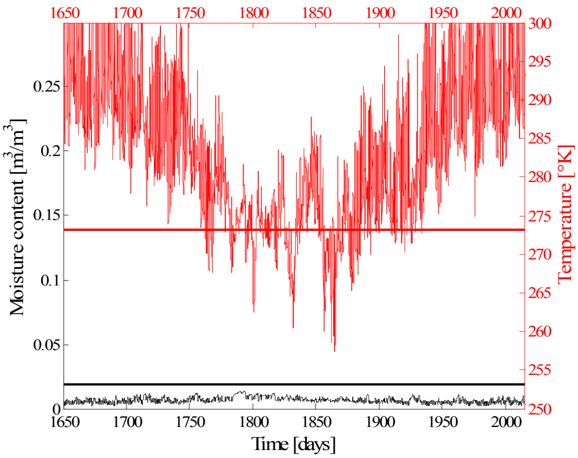

Figure 5: Hygrothermal performance of AAC, Var. 3.

The values of moisture content in external finish were higher than in AAC. However, also in this case not any freezing cycle appeared. Hygrothermal performance of external finish 2 mm under the surface is shown in Figure 6.

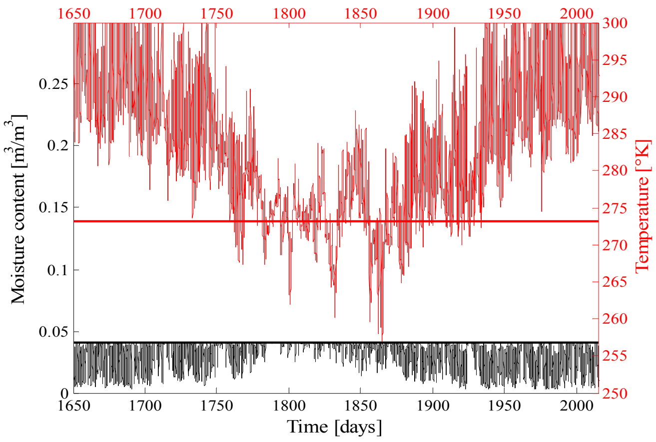

Figure 6: Hygrothermal performance of Baumit MVR Uni plaster, Var. 3.

3.4 Var. 4 – AAC provided with mineral wool

Hygrothermal performance of AAC provided with mineral wool and Baumit MVR Uni plaster is shown in Figure 7. Also in this case there were not counted any freezing cycles. The main reason was the thermal insulation which did not allow the temperature to drop below zero and thanks to hydrophobic modification, the moisture from exterior could not penetrate through the insulation to the AAC layer.

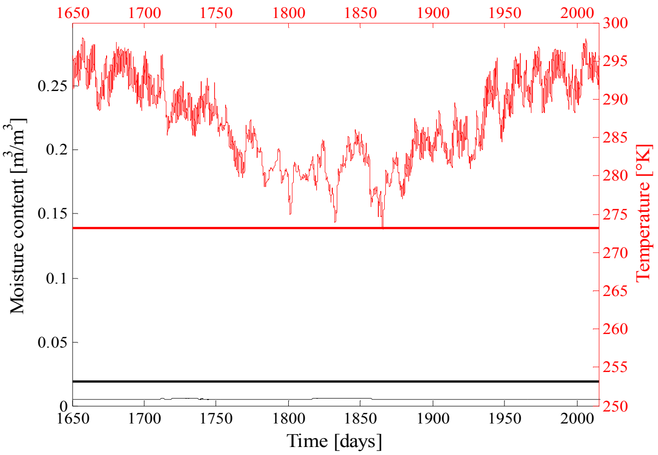

Figure 7: Hygrothermal performance of AAC, Var. 4.

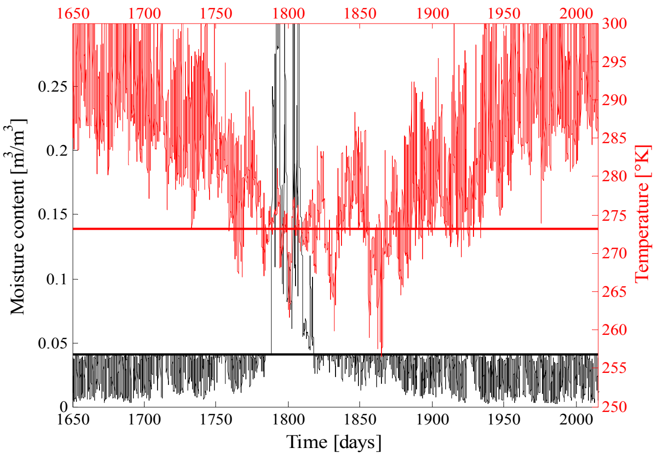

Figure 8: Hygrothermal performance of Baumit MVR Uni plaster, Var. 4.

The AAC layer was well protected because of positive effect of mineral wool, but the negative effects were transferred to external finish. As is shown in Figure 8, we counted 17 freezing cycles during a year.

4 Discussion

The computational results gave clear evidence that building envelopes based on AAC are very predisposed for damage by freezing water if their protection on the exterior side is not sufficient. As it was shown in section 3.1, number of freezing cycles in AAC without any finishes (19) almost reaches values of freeze-thaw resistance. It is caused by high value of moisture content which corresponds to weather conditions, especially the rainfalls. At the same time, there is not any thermal insulation, which could at least prevent the temperature to drop below zero. This fact reduces service life of surface layers of AAC to 2 years at most. So after this time we can expect surface degradation and material crumbling. This proves that application of AAC separately in exterior is inappropriate.

The exterior protection of AAC can be accomplished in two ways. We can either prevent the moisture to reach overhygroscopic range or temperature to drop below zero. Protection against moisture can be easily completed by suitable external finishes. But it is important to use material developed for AAC construction. In section 3.2, common lime plaster has been used, in section 3.3 Baumit MVR Uni plaster developed specifically for AAC. If we compare the results, we can note significant differences. While Baumit plaster reliably protects AAC against moisture content increase, lime plaster does not and 25 freezing cycles are counted which is higher than in unprotected AAC block. Service life of the building envelope with lime plaster is then limited to less than one year. After that time, AAC will start to crumble and fall of together with lime plaster. The main reason of this behavior is apparent. In unprotected AAC there were many very short cycles which were disregarded because there was not enough time for water to get frozen. Presence of lime plaster did not reduce the amount of received liquid moisture because of high value of moisture diffusivity but slowed down water evaporation from AAC which led to extension of time, when the water could get frozen.

Successful protection capability of Baumit plaster consists in low values of moisture diffusivity and thermal conductivity. Amount of received moisture is then reduced on sufficient level and temperature in AAC reaches higher values. The biggest advantage of this material combination is fact, that even in the plaster there are not any freezing cycles. Service life of this building envelope is then not limited by its freeze-thaw resistance.

Application of thermal insulation eliminates both causes of frost damage. Not only it protects against moisture increase but also keeps the temperature in the AAC layer above zero for all the year. Thanks to low moisture diffusivity and thermal conductivity, there is not any indication of creation of freezing cycles. However, this material combination is not considerate to the external finish. Due to low moisture diffusivity, moisture contained in plaster can not be partially taken by AAC block and is kept in plaster for a longer time. This results in creation of 17 freezing cycles during a year. Baumit MVR Uni plaster is classified as a lime-cement plaster, which freeze-thaw resistance was set to more than 103 cycles [10]. Durability of this plaster is then limited by its freeze-thaw resistance to 6 – 7 years.

5 Conclusion

In this paper a very easy predisposition of AAC to frost damage was proved if the AAC layer was left without appropriate external protection. There was clearly evidenced that when AAC was used in building envelope, it was necessary to protect it against impacts of freezing water. We could use either thermal insulation or specific external finishes for such protection. While mineral wool thermal insulation could protect AAC reliably in any case, with external finishes it was quite important which type of plaster was used. According to the results achieved in this paper, we can recommend using plaster developed specifically for AAC constructions or, in general, plaster with low value of moisture diffusivity. But this can be possible only if thermal assessment will be suiting to relevant standard. If it will not, the second best material combination according to results of this paper is to provide AAC block with thermal insulation. But in this case we have to count with reduced durability of external finish when first signs of damage could appear after 6-7 years.

Acknowledgement

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