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Assessment of Cumulative Damage of Selected Building Envelopes Exposed to Various Environmental Effects

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ABSTRACT

Hygrothermal performance of building envelopes based on three different building materials (solid brick, high performance concrete, aerated autoclaved concrete) is assessed under climatic conditions of Prague and Atlantic City. Main objective of the paper is to evaluate the influence of cumulative damage, which was induced by means of natural weathering in 2012-2015 period, on the long-term performance. The performance is assessed using various measures, namely time-of-wetness function, number of freeze/thaw cycles, and annual amount of energy transmitted through the envelope. The results show that thermal performance of the envelopes gets mostly better after weathering as the annual amount of energy is decreased by ~3.5% in average. On the other hand, time-of-wetness function and number of freeze/thaw cycles increase by ~24.1% and ~22.0%, respectively. Based on the results summary it can be concluded, that cumulative damage of materials has an indisputable influence on the hygrothermal performance of building envelopes which might be either negative or positive. A detailed computational assessment is therefore necessary, incorporating not only reference, but also weather-affected material properties.

KEYWORDS
Cumulative damage, computational modelling, hygrothermal performance, weathering, building envelope.

INTRODUCTION

Possibilities of predicting hygrothermal performance of building envelopes are generally known, exploiting capabilities of computational techniques (Oladokun *et al.*, 2017). Such an approach provides relatively fast results without necessity of a construction to be built. Therefore, it is mostly used by building designers or building material producers. However, all computational models are strongly dependent on the quality of input data, the material properties in particular (Goffart *et al.*, 2017). An acquisition of material characteristics is therefore essential and advanced experimental techniques have been developed for this purpose so far, being more or less precise and demanding on time or costs. Unfortunately, it has been mostly ignored that material properties may change upon exposure to environmental conditions. The reason of ignoring this phenomenon, even if it is clear, might be found in the fact that such a kind of experimental investigations is extremely time-demanding and requires considerable storage space which makes it inconceivable for many research groups or departments. The vast majority of computational simulations in the field of building physics is therefore performed using reference material data that remain unchanged during the simulated period (Lakatos, 2017). However, having an indisputable impact on hygrothermal performance of materials, these changes should be included in all serious damage assessment analyses or simulations of hygrothermal performance.

The main objective of this research is to point at the differences in hygrothermal performance of building materials/envelopes that might occur when reference or weather affected data is used within the computational simulations. For this purpose, solid brick, high performance concrete, and autoclaved aerated concrete have been selected as representative load-bearing materials. They had been exposed to natural weathering and induced changes of their hygric and thermal transport and storage parameters were studied. Using computational modelling of coupled heat and moisture transport, subsequent long-term analyses of hygrothermal performance of building envelopes were carried out using reference and weather-affected material parameters in order to emphasize the possible differences.

MATERIALS AND METHODS

Materials

Solid brick (SB), high performance concrete (HPC), and autoclaved aerated concrete (AAC) have been selected as objects of study, representing typical building materials. The material characterization was carried out in the reference state and then after three years of natural weathering between 2012 and 2015. The weather characteristics of this period were continuously recorded using Davis Vantage Pro 2 weather station. The summary of selected weather parameters is given in Table 1, being compared to reference weather parameters of Prague, Czech Republic and Atlantic City, NJ. Climatic conditions of these locations were further considered as the exterior boundary conditions of the simulated walls. The abbreviations used in Table 1 have following meanings: Nov – November, Dec – December, Jan – January, Feb – February, Real – real weather data that were the materials exposed to, TRY – Test Reference Year, PRG – Prague (Czech Republic), ATC – Atlantic City (NJ).

Table 1. Comparison of selected weather parameters.

	Temperature (°C)					Relative humidity (%)					Rainfalls (mm)				
	Real			TRY		Real			TRY		Real			TRY	
	12/13	13/14	14/15	PRG	ATC	12/13	13/14	14/15	PRG	ATC	12/13	13/14	14/15	PRG	ATC
Nov	6.53	6.01	7.93	5.62	7.99	83.22	86.82	79.96	78.19	71.93	27.6	0.4	54.2	24.9	74.1
Dec	0.98	3.25	4.14	1.56	3.47	84.42	81.59	83.62	77.64	71.60	7.2	5.2	24.2	21.3	88.0
Jan	0.34	1.95	3.51	1.83	0.78	84.54	86.89	81.07	77.20	71.01	34.5	16.2	47.2	5.4	69.1
Feb	0.80	4.15	2.01	2.53	2.41	83.07	78.44	77.76	72.44	68.16	40.9	5.4	14.6	16.9	51.3

Table 2. Material characteristics of studied samples.

	SB		HPC		AAC	
	reference	3y-weathering	reference	3y-weathering	reference	3y-weathering
ρ (kg$\cdot$m^{-3})	1831	1860	2273	2330	289	305
ψ (%)	27.9	30.9	12.1	9.6	86.9	87.5
$\mu_{\text{dry cup}}$ (-)	22.1	11.4	106.2	108.3	6.17	5.57
$\mu_{\text{wet cup}}$ (-)	8.8	8.3	86.4	86.8	15.61	15.18
κ_{app} (m$^2\cdot$s^{-1})	$1.08\cdot10^{-6}$	$7.23\cdot10^{-7}$	$2.53\cdot10^{-9}$	$4.02\cdot10^{-9}$	$7.02\cdot10^{-8}$	$3.35\cdot10^{-8}$
c_{dry} (J$\cdot$kg$^{-1}\cdot$K^{-1})	825	813	780	661	1090	1127
c_{sat} (J$\cdot$kg$^{-1}\cdot$K^{-1})	1254	1287	929	772	2813	3032
λ_{dry} (W$\cdot$m$^{-1}\cdot$K^{-1})	0.590	0.541	1.724	2.083	0.071	0.068
λ_{sat} (W$\cdot$m$^{-1}\cdot$K^{-1})	1.735	1.896	2.817	2.754	0.548	0.536
w_{hyg} (m$^3\cdot$m^{-3})	0.00360	0.00896	0.01566		0.00755	

The material characteristics of the studied materials were determined following the procedure described by Černý (2013). The results are summarized in Table 2 (Maděra *et al.*, 2017; Kočí *et al.*, 2017; Kočí *et al.*, 2018b). The meaning of used symbols is as follows: ρ – bulk density (kg·m^{-3}), ψ – total porosity (%), μ - water vapor diffusion resistance factor (measured using dry cup and wet cup methods) (-), κ_{app} – apparent moisture diffusivity (m^2·s^{-1}), c – specific heat capacity (in dry and water saturated state) (J·kg^{-1}·K^{-1}), λ – thermal conductivity (in dry and water saturated state) (W·m^{-1}·K^{-1}).

Computational modelling

The computational modelling of one-dimensional heat and moisture transport was applied to assess the hygrothermal performance of studied materials when exposed to different weather conditions. Comparing the results obtained using reference and weather-affected material properties, one can evaluate the influence of weathering on long-term hygrothermal performance of the investigated building materials.

The computations were performed using the computer code HM Transport (Kočí *et al.*, 2018a) which works on the basis of the general finite element package SIFEL (Kruis *et al.*, 2010). The coupled transport processes were described using a diffusion type mathematical model derived from the Künzel's original formulation (Madera *et al.*, 2017), as it requires only a tight set of input parameters while sufficiently precise results are provided. Besides the mathematical model and material properties, also boundary conditions, discretization mesh and time controller of the simulations are required. Within this paper, a 500 mm thick wall was assumed being exposed to dynamic climatic conditions of Prague and Atlantic City from the exterior side and to constant conditions (21 °C, 55 % RH) from the interior side (see Fig. 1). While Prague is typical with its continental climate, Atlantic City has the oceanic climate as it is located on the east coast of the USA. The weather conditions were applied in the form of TRY which contains long-term average hourly values of temperature, relative humidity, rainfalls, wind direction and orientation, and several kinds of sun radiation. The simulations took 10 years which is long enough to reach a certain kind of dynamic equilibrium.

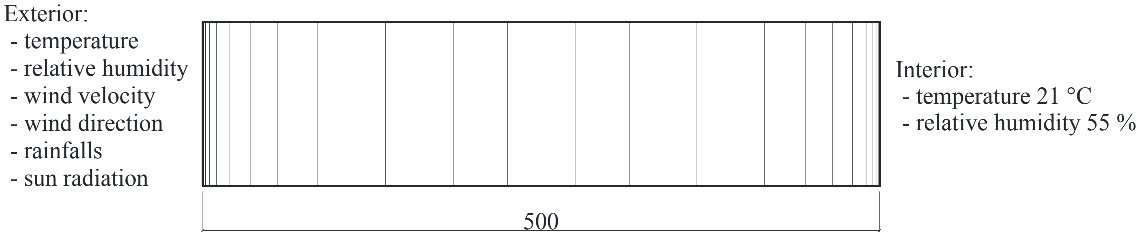

Figure 1. Scheme of the analysed construction detail.

The hygrothermal performance of the wall was assessed by means of time-of-wetness function (ToW) and the number of freeze/thaw (FT) cycles (Koci *et al.*, 2014). These measures were applied to the whole construction detail. Additionally, thermal performance was evaluated by means of quantification of the annual amount of energy transported through 1 m^2 of the particular envelopes (further denoted as Annual EB). It was calculated as

$$Q = \int_{1.Jan}^{31.Dec} q(t)\,dt, \tag{1}$$

where

$$q(t)=\lambda(w,t)\frac{\Delta T(t)}{\Delta x}. \tag{2}$$

In Eq. (2), $\lambda(w,t)$ is the moisture dependent thermal conductivity as a function of time ($\mathrm{W\cdot m^{-1}\cdot K^{-1}}$), $\Delta T(t)$ the temperature difference (K) between two nodes defining the boundary element and Δx is their distance (m). The hourly values of $\lambda(w,t)$ and $T(t)$ were obtained as the results of computational modelling.

RESULTS AND DISCUSSION

The results of computational simulations revealed that the hygrothermal performance of studied materials is definitely affected by their weathering. However, the influence may be positive as well as negative, depending on the material, climatic data and the measure investigated. The summary of hygric and hygrothermal performance is given in Table 3.

Table 3. Summary of hygric/hygrothermal performance.

		Prague		Atlantic City	
		ToW (h)	FT cycles (-)	ToW (h)	FT cycles (-)
SB	reference	350.02	30	3380.64	38
	3y-weathering	406.22	35	3478.49	42
HPC	reference	155.06	8	850.70	7
	3y-weathering	197.06	14	1240.70	8
AAC	reference	76.08	9	651.74	13
	3y-weathering	93.10	9	847.73	15

The hygric performance measure, ToW function, determines the sum of time when liquid moisture is present in any of nodes of the computational mesh (see Fig. 1). For this sake, the decisive value of relative humidity was considered to be 95 %. Approximately 8 times higher values in average were obtained when the weather conditions of Atlantic City were assumed. This finding agrees with the weather parameters presented in Table 1 showing much higher amount of rainfalls in Atlantic City than in Prague. However, more interesting is the fact that ToW values got higher after weathering in all the investigated cases. For instance, ToW of solid brick increased by ~16 % under climatic conditions of Prague and by ~27 % and ~22 % in case of high performance concrete and aerated autoclaved concrete, respectively. Except for solid brick, the relative increase of ToW was even higher under Atlantic City weather conditions. In case of high performance concrete, the ToW changed from 850.70 to 1240.7 h which represented an increase of about 45 %.

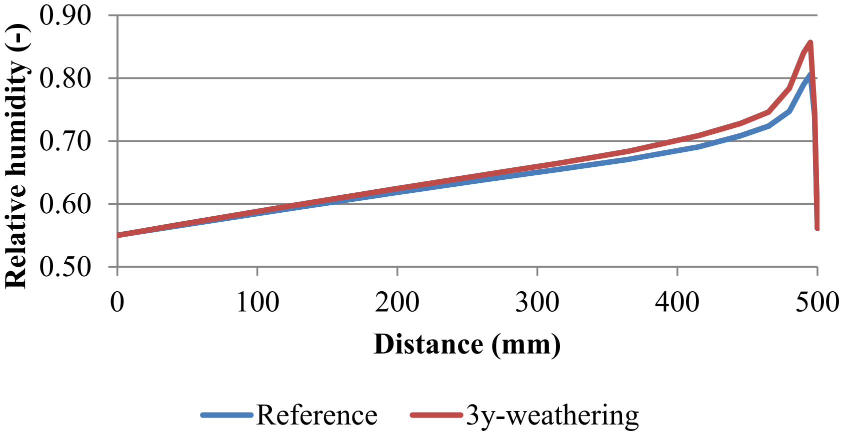

Figure 2. Comparison of moisture profiles: HPC, Atlantic City, Aug 10, 15:00

These changes can be explained mostly by the decrease of moisture diffusivity of studied materials, which led to retaining moisture for longer periods. The changes of hygric performance can also be demonstrated by a comparison of moisture profile before and after weathering. In Fig. 2 the moisture profiles of HPC under Atlantic City's climatic conditions as of August 10 are captured. The differences in this case reached more than 5 % of RH.

Closely related to hygric performance of materials is a risk of creation of freeze/thaw cycles that might cause a serious damage. The possibility of creation of FT cycles appears only when moisture is contained in the liquid phase and, at the same time, the temperature drops below zero. The principles of ice formation in real porous structures are, of course, more complex, incorporating other aspects such as pore characteristic, freezing temperature and duration, mechanical straining, or presence of chemical compounds. However, this measure serves well as a comparative indicator. Alongside with worsening of ToW values, also the number of FT cycles increased as it is shown in Table 3. It can be therefore concluded, that weathering of materials negatively affects their hygrothermal performance and thus might have also a negative impact on their durability. The rate of worsening depends on the type of material, as well as on specifics of the climatic conditions.

Table 4. Summary of thermal performance.

		Prague		Atlantic City	
		Average thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Annual energy balance ($kWh \cdot m^{-2}$)	Average thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Annual energy balance ($kWh \cdot m^{-2}$)
SB	reference	0.59253	98.66	0.59309	81.78
	3y-weathering	0.54811	92.34	0.54932	76.60
HPC	reference	2.12483	250.55	2.12764	207.41
	3y-weathering	2.15129	253.05	2.15426	209.49
AAC	reference	0.07276	13.98	0.07359	11.72
	3y-weathering	0.06908	13.29	0.06983	11.12

Unlike hygric performance, the thermal performance of studied materials got mostly better after weathering. It can be ascribed to the increase of porosity due to formation of microcracks which subsequently contribute to decrease of thermal conductivity. The opposite phenomenon can be observed in the case of high performance concrete, of which porosity decreased most likely due to secondary hydration processes. However, more sophisticated method such as SEM or XRD would be necessary to provide a detailed explanation. The summary of thermal conductivity changes is provided in Table 4: the annual energy balance of brick and aerated concrete was improved by ~6.4 % and by ~5.0 %, respectively. On the other hand, the energy transmitted through 1 m^2 of high performance concrete got higher by ~1.0 %. All these findings correlate with the changes of thermal conductivity.

CONCLUSIONS

A study of the influence of weathering on the hygrothermal performance of selected building envelopes was presented in this paper. In the first step, the samples made of solid brick, high performance concrete, and aerated autoclaved concrete were exposed to natural weathering and the weather-induced changes of their material properties were investigated. Subsequently, computational analyses of coupled heat and moisture transport of walls made of these materials were carried out in order to assess the impact of weathering on their long-term hygrothermal performance.

The natural weathering of materials led to changes in microstructure which was reflected also in their transport and storage parameters and thus in their hygrothermal performance. While the hygric performance got worse, being proved by an increase of ToW and FT values, the thermal performance got slightly better. As the formation of microcracks contributed to the increase of porosity, the lower thermal conductivity resulted in better thermal insulating properties of the studied materials except for HPC of which porosity decreased due to secondary hydration processes.

Based on the results presented in this paper it can be concluded, that weathering of materials and cumulative damage of theirs have indisputable influence on their long-term hygrothermal performance. Since the effects can be positive as well as negative, depending on the specific measure and climatic conditions, the cumulative damage should be included in computational simulations that are supposed to provide precise results.

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