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Improving the thermal performance of concrete-sandwich envelopes in relation to the moisture behaviour of building structures in boreal conditions

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ABSTRACT

The excellent thermal performance and low cost of concrete-sandwich walls have made them widely applied in residential buildings. However, their standard composition may require additional insulation in boreal and arctic climates, where improvements in thermal insulation are achieved mainly by applying additional insulation layers on the envelope surface. Although thick insulation will substantially improve the heat capacity of a structure, elevated temperatures and entrapped humidity can lead to favourable conditions for the initiation of mould growth. The present study simulates the thermal performance of a model house wall structure in relation to increased mould growth risk. The results indicate that added insulation may have a negative impact not only on the structure and material properties of structural elements, but also on the environmental health and comfort of residents. Furthermore, climate conditions are shown to be a significant factor in identifying an optimal insulation design based on thermal performance and structural health.

1. Introduction

The building of low-energy houses has been promoted due to increasing energy costs and the constant effort of national and international institutions to lower the energy consumption of residential houses due to various environmental issues. Improving the thermal resistance of residential buildings is typically performed by applying additional insulation layers to the external surface of a building envelope. This action represents one of the easiest ways for a building to reach a higher thermal resistance and ensure lower energy consumption costs. In addition to cost and comfort benefits, additional construction layers typically cause a different response in the way humidity and heat are exchanged. Automated air exchange and thermal and humidity conditions also play major roles in a healthy indoor environment [1]. Specific combinations of temperature and humidity promote mould growth, which may lead to allergic reactions and other health issues for inhabitants [2,3], as well as influence the behavioural properties of structural elements [4–7].

There are three main ways to obtain data concerning a given physical phenomenon in building engineering: on-site measuring, lab tests, and numerical analysis. In recent years, the growth of numerical analysis has been induced by the rapid development of simulation methods and the availability of software that supports numerical analyses [8–11] (i.e., the Finite Element Method [12,13]). Despite the probability of biological activity in wetted and poorly aerated structures, the present policy seeks to promote low-energy, high-closure housing [14]. The capabilities for measuring indoor air quality have significantly improved over recent years [15,16]. However, these results have not been systematically linked to specific flaws in building practises, attempts to control structural contamination by mould spores, the prevention of moisture build-up and absorption, or design guidelines.

The modelling of biological activity on building structures to predict possible health issues for inhabitants has undergone stringent development in recent years [17,18], partially due to the increased focus on energy issues of housing and popularity of low-energy and passive houses. Numerous studies have presented mathematical models that express the risk of mould growth based on environmental factors [19–22]. Consequently, different results have been obtained with each mould-growth prediction model [23], which have commonly focused on the relation between temperature and humidity over an exposed time in long-term

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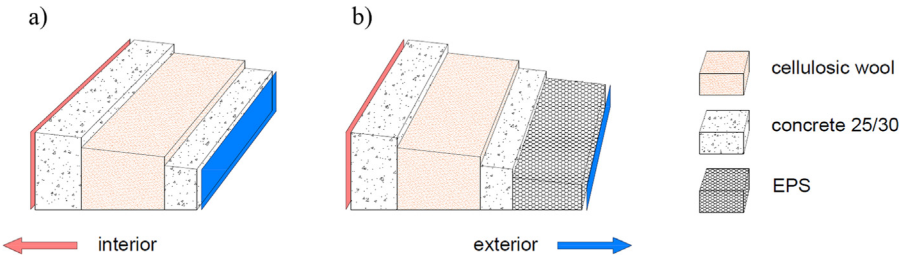

Fig. 1. Analysed wall structure; (a) core sandwich wall; (b) core sandwich wall with an additional insulation layer.

laboratory tests or on-site measurements [24,25]. In many cases, the validation of these models has been based on small sets of experimental data, while the impact of structural models and selection of building materials of house structures going unanalysed. The aim of the present study is to analyse the effect of an additional EPS insulation layer to improving thermal resistance and mass transfer, and in turn the impact of increased insulation on mould growth risk in a concrete sandwich wall subjected to boreal weather conditions. The analysed structure is displayed in Fig. 1.

2. Thermal performance of wall structure

The wall of examination in this study is made of concrete-sandwich prefabricated elements. Its two concrete layers are made of C25/30 filled with 180 mm of cellulosic wool insulation. The additional insulation layer applied on the external surface of the structure is made of an extruded polystyrene (EPS) sheet. The initial thermal transmittance (U-value) of the envelope is 0.209 W/m^2 K, with the thermal bridge achieving a linear thermal transmittance of 0.059 W/m K in the vertical corner of the envelope.

With regard to costs and construction demands, thermal resistance can be improved by applying an additional insulation layer on the external surface of the wall's envelope. In this study, added insulation is considered only on the external surface, with the thicknesses of the additional layers ranging from 10 to 200 mm. Thermal analysis was performed using the multi-physical program COMSOL Multiphysics®. Each of the nine analysed cases included the same core element (concrete sandwich) as the initial structure (case 0), though with additional insulation layers of varying widths (cases 1–8). The designs of the analysed cases are displayed in Table 1. The following schematic (Fig. 2) shows the thermal flow of analysed cases 0, 4 and 8.

The following equation was applied for the evaluation of the thermal bridge (ISO 10211:2007(E)):

$$\psi = L_{2D} - U_1 \times l_1 - U_2 \times l_2 \qquad (1)$$

The results obtained in the thermal analysis are shown in Table 2.

3. Mould growth model

Although the analysed structure is made of inorganic material, mould growth and its related health issues cannot be fully eliminated. During manufacturing, the transportation of elements, and the building of a construction, a great amount of spores can accumulate in and on structural elements, which may cause the gradual potential risk of mould growth initiation over the lifespan of a structure. Unsuitable combinations of heat and moisture (HM) can initiate mould growth [26,27], which can lead to allergic reactions or other health issues. The effects of temperature and humidity under unfavourable conditions also decrease the expected structural lifespans of materials [28]. The relationship between temperature and humidity and favourable and unfavourable conditions for the initiation of mould growth can be expressed by a mathematical formula of critical relative humidity RH$_{\text{crit}}$ (2), which is a function of temperature T [25,29] and understood for porous materials as equilibrium with relative humidity of the air in its pores, defined by sorption isotherm of the material. A graphical expression of Eq. (2) is shown in Fig. 3, which demonstrates that extremes in temperature and overly dry conditions do not tend to initiate mould growth despite the presence of mould spores. Fig. 3 and Eq. (2) detail the reference conditions for material sensitivity classes 1 and 2 (see below).

$$\text{RH}_{\text{crit}} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0, & \text{when} \quad 0 \le T \le 20 \\ 80\%, \quad \text{when} \quad 50 \ge T > 20 & \\ \text{no growth is assumed} \quad \text{when} \quad 0 > T > 50 & \end{cases} \qquad (2)$$

An essential element for the initiation of mould growth along with favourable climate conditions is exposure time. If a structure is subjugated to favourable conditions for extended periods of time, the risk of mould existence increases. In other cases where temperature is lower or higher than set values, or humidity is sufficiently low, the risk of mould growth decreases. The risk of mould growth is expressed qualitatively by Ojanen et al. [25] by seven levels of mould growth, with 0 indicating no growth, 1 indicating small amounts of mould on the surface (microscopic), 2 indicating several local mould growth colonies on the surface (microscope), 3 indicating visual findings of mould on the surface (under 10% or less than 50% coverage of mould) (microscopic), 4 indicating visual findings of mould on the surface ranging from 10 to 50% mould coverage or more than 50% coverage (microscopic), 5 indicating more than 50% coverage (visual), and 6 indicating heavy and full-growth coverage. Mould growth intensity, modified from [25], is expressed in the following equation:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{1}{168\exp(-0.68\ln T - 13.9\ln RH + 66.02)} k_1 k_2 \qquad (3)$$

Table 1
Thermal properties of the simulated wall structure.

	Internal surfaces surfaces	C25/30		Insulation		C25/30		EPS		External surface
	[m^2 K/W]	d [m]	λ [W/m K]	d [m]	λ [W/m K]	d [m]	λ [W/m K]	d [m]	λ [W/m K]	[m^2 K/W]
Case 0	0.130	0.100	1.6	0.180	0.04	0.070	1.6	–	–	0.04
Case 1–8	0.130	0.100	1.6	0.180	0.04	0.070	1.6	0.01–0.20	0.04	0.04