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Simulation of heat and moisture flow through walls covered with uncoated medium density expanded cork

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ABSTRACT

This paper evaluates the influence of the solar heat flux, temperature, and relative humidity on OSB and concrete walls covered with uncoated medium density expanded cork. A boundary element numerical model was used to simulate the coupled heat and moisture transfer through the multi-layer porous solid walls.

The expanded cork hygrothermal properties were determined experimentally. After experimental validation of a building solution using a hotbox, numerical simulations were performed to evaluate the effect of the abrupt change in relative humidity and temperature. It was concluded that the relative humidity variation is only relevant when there are significant weather changes during the course of the year.

Thus, the summer and winter conditions of Bragança (Portugal) and Seville (Spain) were selected to illustrate the hygrothermal behaviour of the walls. Different thicknesses of expanded cork were simulated. The results show that the impact of the short-term environment moisture variation is limited to the outer surface layers. It was also found that the moisture along the medium density expanded cork coated wall is only high when the outer moisture is high and remains high for a long period of time.

1. Introduction

In recent years, the use of building materials of natural origin or/and from industrial waste has been gaining interest [1]. They allow a drastic reduction in the consumption of fossil energy and the CO_2 emissions associated with their production, when compared to conventional materials, thereby leading to a more sustainable construction [2]. One example of the use of by-products and waste from the industry is expanded cork agglomerate, a natural, renewable and fully recyclable thermal insulating material [3]. It is composed solely of cork granules, and made exclusively by the volumetric expansion and exudation of cork and its natural resins under the action of steam from water [4]. The energy used in the industrial process is mainly obtained from the combustion of cork powder, a waste generated by the cork transformation process [5]. Internationally, and in current technical documentation, expanded cork agglomerate is often referred to as ICB (insulation cork board). Compared with other insulation materials, ICB has the lowest value of carbon footprint, with a negative value of -116.229 kg CO_2 equivalent per m^3 of ICB [6].

The use of uncoated ICB as an external layer covering building facades is increasing worldwide, especially in Portugal, Spain, France, Germany, United States, Japan and Saudi Arabia. The hygrothermal performance of the building envelope depends on difference of conditions between the inside and the outside environment. When there is a water vapour pressure or temperature gradient through a wall, transport occurs from the higher to the lower potential [7]. A wall covered with uncoated medium density expanded cork can be exposed to very different climates and, in most cases, to summer and winter conditions that differ considerably. It is therefore relevant to study the hygrothermal behaviour of the wall when subjected to different levels of solar radiation, temperature and moisture gradients, which are determinant factors in reducing energy loss, managing solar gains and providing healthy conditions indoors [8,9].

Two main approaches can be followed to simulate the phenomena: experimental and numerical. Several experimental studies that evaluate the hygrothermal behaviour of buildings and building components can be found in the literature. Medjelekh *et al.* [10] determined the hygrothermal properties of masonry composed of unfired clay bricks. These experimental properties were used to perform simulations of a full-scale wall under different hydric loading scenarios. Moisture and temperature results show a good agreement between the simulation and the experimental evaluations. Busseret *et al.* [11] presented an

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experimental design to estimate vapour permeability and the moisture sorption curve using dynamic measurements and an identification method. Lelievre *et al.* [12] studied the hygrothermal behavior of hemp concrete. Antonyová *et al.* [13] studied the hygrothermal properties of building envelopes to develop a non-destructive method for measuring the temperature and moisture in the space between the insulation panel and the outer wall of buildings, so that the effectiveness of energy saving can be evaluated. Rahim *et al.* [14] used an experimental laboratory facility to investigate the hygrothermal behaviour of a straw concrete wall under static and dynamic conditions of temperature and relative humidity. Odgaard [15] monitored the relative humidity and temperature of two solid masonry spandrels over a period of 2 years and 8 months, to study the effect of installing interior insulation on the spandrels in a historic building with solid masonry walls in Copenhagen. Labat *et al.* [16] studied the dynamic coupling between vapour and heat transfer under real climate conditions, testing a 20 m^2 wood-frame house in Grenoble, France that was fitted with six different wall assemblies, over a period of more than 3 years.

Experimental work is time consuming and can be very expensive. Numerical modelling may be more useful than laboratory testing or insitu measurements since it is cheaper to implement [17]. Different numerical models have been developed over a number of years to simulate the combined transport of heat and moisture, starting in the area of soil sciences, with the studies by Philip and De Vries [18] and Luikov [19]. Their work was then extrapolated to the field of building physics, in which, depending on the chosen potential, the final set of equations varies from one author to another [20].

Krejčí *et al.* [21] performed numerical analyses of coupled heat and moisture transfer in masonry structures by using two computational methods that are based on the diffusion model proposed by Künzel and Kiessl [22]. For both methods, the results of the 2D numerical simulation of coupled heat and moisture transfer in a brick wall showed good agreement with those obtained with the original finite element method, but with a clear reduction of computational time. Abahri *et al.* [23] developed an analytical model for the coupled heat and mass transfer in porous building materials. To validate the proposed analytical solutions the results were compared with those of several numerical simulations that used a finite element method. Good agreement was found. Škerget and Tadeu [24] developed a numerical model based on the boundary element method (BEM) to simulate the coupled heat and moisture flow through a porous solid. To validate the model, the authors used two benchmark examples, one of which was a relatively simple transient linear vapour diffusion while the other was a highly nonlinear coupled moisture and heat transport, and good agreement was found for both. Although in the second case, since the difference between the heat and mass diffusion coefficient has several orders of magnitude, better stability and accuracy was obtained by using the linear variation of the functions throughout the time step model than with the constant variation in terms. Min *et al.* [25] developed a method, based on Lukiov's model to simulate the coupled heat and moisture transport in concrete. The numerical results were compared with the experimental ones and a good agreement was obtained. Škerget *et al.* [26] include the airflow in their coupled heat and moisture model, thereby enabling the simulation of air, moisture and heat flows.

Heat and moisture transfer models are useful when the intention is to evaluate the risk of condensation on building components and any related moisture problems. However, an external building component is also exposed to solar radiation, which increases its temperature. Failure to consider the solar heat flux could underestimate the materials' temperature and thus the heat and mass transport phenomena.

Holm and Künzel [27] used WUFI [28], a computer program which calculates the transient heat and moisture transport in building components, to predict, under natural climatic conditions, the moisture and temperature strains that act on an ETICS with mineral wool insulation. Coons *et al.* [29] used ANSYS CFX 16.1 software to model solar energy as one of the heat sources that affect the external and internal temperatures in residential buildings. The intention was to evaluate the benefits of using a selective solar-beam absorbing paint. The study was undertaken for three cities that represent extreme climates in the United States, under summer and winter conditions. The authors concluded that the positive outcome obtained for the summer season, with a reduction of the cooling loads, has to be balanced against the negative impact in the winter season once the heating loads increase. Kant *et al.* [30] evaluate the thermal behaviour of building bricks containing phase change materials (PCMs), when subjected to solar radiation and ambient temperature. A finite element analysis method was used in a two-dimensional numerical study of heat and mass transfer through the bricks containing PCMs. The simulations, performed using the meteorological data of Rae Bareli for the period 14–16 March 2014, indicate that building bricks with PCMs, when exposed to direct solar radiation, are suitable to be used as passive thermal conditioners in buildings since they stabilise the room temperature and so reduce energy consumption. Cho *et al.* [31] used a finite elements method to experimentally and numerically study the heat and moisture transfer in concrete under real weather data. The model was validated with experimental results. The authors noticed that because of the effects of solar radiation and radiation cooling effect the temperature inside the concrete is 6 °C higher in summer and 2 °C lower in winter. Škerget *et al.* [32] conducted a study on the transient heat and moisture transfer of a multilayer porous solid building components exposed to solar heat flux and submitted to convective heat and mass exchange with the surrounding environment. The BEM numerical model that was used proved to be suitable for the numerical simulation of transient transport phenomena in cases of building envelopes exposed to real weather data.

The main purpose of this study was to evaluate the hygrothermal behaviour, in terms of temperature, relative humidity and moisture content variation, of walls made of OSB and concrete and covered with uncoated medium density expanded cork board, when exposed to real weather data. For this purpose, a numerical model that could simulate the coupled heat and moisture transfer in a building component under solar radiation was used. However, the quality of the numerical results depends on appropriate input data [33,34], and these are not always available, even in the simulation tool databases which often provide only generic data. Thus, a reliable set of hygrothermal properties as a function the material moisture content must be known before a reasonable assessment of the building's energy-related envelope can be made with sufficient accuracy [35,36]. To ensure the accuracy of the numerical results, the properties of medium density ICB were evaluated experimentally and validated by comparing the numerical results with the transient heat and moisture flow through a wall inserted between two chambers of a calibrated hot-box. The properties of all other materials were defined using data from WUFI database.

This paper first presents the numerical model that was used to simulate the hygrothermal behaviour of the constructive solutions. The verification of the numerical model against a benchmark test is presented. The medium density ICB hygrothermal properties were then evaluated and a building solution was validated experimentally. The importance of moisture and heat flow through an OSB wall covered with uncoated medium density ICB was assessed. Finally, the numerical results obtained for Bragança (Portugal) and Seville (Spain) for summer and winter conditions are presented and discussed.

2. Governing transport equations for a two-phase system

The moisture transport phenomena, in a porous solid, of a thermodynamic system comprising the liquid and vapour phases are governed by a series of partial differential equations. If Ω is the domain of the porous solid, bounded by a surface Γ defined by the unit outward normal vector $\vec{n}$, these equations, or the moisture diffusion transport equation, can be formulated as shown below [26,37],