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Thermal delay provided by floors containing layers that incorporate expanded cork granule waste

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ABSTRACT

This paper reports the computation of the thermal delay provided by concrete floors built with layers of cork and lightweight screed that incorporate expanded cork granule waste. The heat transfer by conduction across these multilayer systems is simulated analytically under unsteady boundary conditions.

The thermal delay is computed for multilayer concrete floors with varying numbers of layers and layer thicknesses. The mass density and thermal conductivity of the various materials were determined experimentally. Given its heterogeneity, the specific heat of the lightweight screed was obtained indirectly using both the experimental results and the analytical model.

The results obtained show the potential of these composites in applications for increasing the thermal performance of concrete floors, in particular the thermal delay and thermal resistance. The results show that the contribution of the insulating lightweight screed material's properties to thermal delay is more relevant in systems composed of few layers. The constructive solutions composed of a greater number of layers present higher thermal delay value.

1. Introduction

Heating and cooling energy requirements have become more important in recent decades, as borne out by the policies that are being implemented (e.g. Directive 2010/31/EU of the European parliament on the energy performance of buildings [1]). The energy performance of a building is influenced by several factors, such as indoor and outdoor climate conditions, design, thermal characteristics of the building envelope, internal loads (solar and internal heat gains) and HVAC (heating ventilation and air-conditioning) systems. The design of a passive building must consider certain parameters in order to provide good thermal comfort conditions for users for the lowest heating energy cost [2]. The building envelope is one of these parameters since it significantly affects the indoor conditions [2]. Researchers have therefore been studying the thermal properties of building elements in order to understand how they contribute to interior comfort for the lowest life cycle cost [2] and to define the thermal performance of occupied and naturally ventilated houses [3]. Pereira et al. [3] investigated the correlations between the percentage of discomfort hours and the equivalent thermal transmittance, thermal capacity and thermal delay values of the envelope's components. They concluded that the number of discomfort hours is lower in buildings with a higher thermal capacity and thermal delay envelope values, and that the thermal property with the best correlation to discomfort hours is thermal capacity. The transmission rate of heat transfer through the envelope elements that separate the air-conditioned space and the outside air depends on how the thermal bridges are dealt with [4] and on the insulation level of the flat envelope. Under steady state conditions the building envelope should provide high thermal resistance. However, as real conditions are mostly unsteady, in addition to providing good thermal resistance building elements should have the thermal capacity to attenuate and delay external temperature fluctuations. Simões et al. [5] used an analytical model, validated with experimental results, to show the importance of cork layers in the thermal delay conferred by multilayer wall systems. Mathieu-Potvin and Gosselin [6] computed numerically the thermal shielding exhibited by an exterior wall containing layers of PCMs. Yilmaz [7] evaluated the thermal performance of two buildings, in order to show the importance of thermal mass in hot dry climates.

The flat opaque elements are characterized taking into consideration both the thermal transmittance (U-value) and their thermal capacity [8,9]. In fact, over the last few years thermal capacity is increasingly cited as an important saving energy aspect that also improves a building's comfort levels [8–12]. Greater thermal capacity enables indoor thermal comfort to be achieved using less energy for climate control.

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Thermal delay is one of the parameters that may be used to predict the dynamic thermal behaviour of building elements [8]. Antonopoulos and Tzivanidis [13] defined thermal delay as the time needed for the mean indoor air temperature to rise above the mean value of the outdoor temperature oscillations by a specified amount under specified building heating. Their paper proposes a finite-difference solution of a system of coupled differential equations describing the transient heat transfer and energy balance in buildings; this is used to calculate the time delay for a wide range of climate conditions and a variety of fully-insulated and non-insulated buildings. Few years later, Antonopoulos and Koronaki [12] presented a procedure for estimating the thermal delay of typical buildings in which the effect of the indoor mass provided by partitions and furnishings was examined. They demonstrated that the indoor mass promotes an increase of up to 40 percent in thermal delay. In another work, [8], the same authors correlated the dynamic parameters, i.e. the effective thermal capacitance, the time constant and the thermal delay, in terms of the thickness of exterior wall layers and the percentage of every envelope element. They concluded that knowing the thermal contribution of each part of the envelope is important to improve the prediction of the dynamic thermal behaviour of buildings in the design phase. Kravvaritis et al. [14] developed a 'thermal delay method' based on the 'T-history' method used to measure the thermal properties of phase change materials (PCMs). The proposed method was used to measure PCMs' thermophysical properties, i.e. phase change heat, temperature and the corresponding heat capacities. Simões et al. [5] presented an analytical formulation to compute thermal delay in multilayer systems with insulating materials, such as cork, mineral wool and expanded polystyrene. The results prove that the contribution of the insulating material's properties to thermal delay is more relevant in systems composed of few layers. The same study shows that a longer thermal delay occurs for construction solutions composed of layers with low overall thermal diffusivity and larger insulation thickness.

Multilayer systems composed of different materials seem to be a rational choice for use in the building envelope, particularly when thermally and acoustically optimized solutions are required [12,15,16]. Additionally, the current environmental context demands energy conservation along with the use of low impact materials with high technical performance [17]. Cork, as a natural resource that is renewable and recyclable, fulfils these requirements [18]. Cork is obtained from the bark of the cork oak, *Quercus suber* L., and is a low density material with excellent thermal and acoustic properties. It can be used in cork-gypsum composite in partitions [19], for stoppers and insulation corkboards [20,21], in a cement paste [22], cork agglomerates [23,24], cork-gypsum decorative materials [25] and sandwich panels [26].

Furthermore, in granular form cork waste can also be used as aggregate in lightweight concrete mixtures [27,28], offering solutions with improved thermal and acoustics properties.

The work described here computes the thermal delay provided by floors containing cork and lightweight screeds incorporating expanded cork granule waste. It uses one-dimensional analytical solutions where the time variable is catered for by using a frequency domain approach. These solutions have been previously proposed and validated against experimental results by the authors [5,29]. The technique uses the Green's functions for harmonic heat plane sources. The solutions are formulated as the combination of surface terms that arise within each layer and at each interface so as to satisfy temperature continuity and normal fluxes between layers.

These transient thermal simulations are applied in various multilayer systems, built up by superimposing layers of concrete, lightweight screed layers incorporating expanded cork granule waste, and layers of expanded cork agglomerate. These multilayer systems are assumed to be subjected to sinusoidal temperature variations at one of the external surfaces.

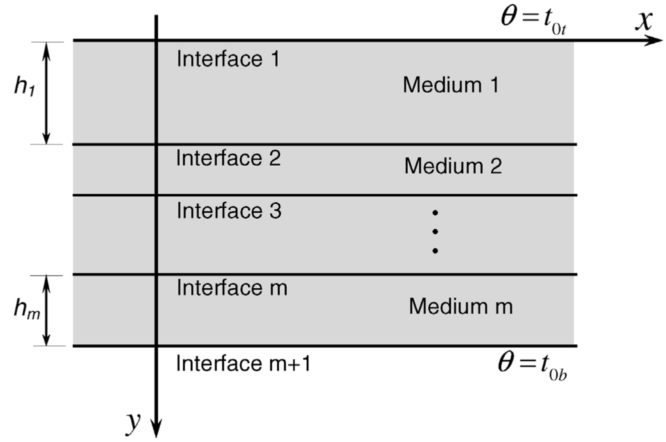

Fig. 1. Geometry of the problem.

This paper first briefly describes the analytical model used to simulate the transient heat conduction. Then, the concrete mixtures used are listed and the experimental evaluation of the physical and thermal properties of the materials is presented. The specific heat of the lightweight screed is obtained indirectly by using both the experimental results and the analytical model. Laboratory tests were performed to validate the analytical results. Finally, the thermal delay is computed for different multilayer systems. The variables studied were the number and type of layers, and the thickness and positioning of the lightweight screed.

2. Analytical solutions

The analytical solutions are briefly explained. A full description of these equations can be found in one of our previous papers [5], where the 3D and the 2.5D solution for multi-layered systems has been proposed and validated against experimental results.

Thus, consider a multilayered system built from a set of m plane layers of infinite extent, as shown in Fig. 1. This system is subjected to temperatures t_{0t} and t_{0b} at the top and bottom external surfaces. The layers are assumed to be infinite in the x and z directions. The thermal material properties and thickness of the various layers may differ.

The transient heat transfer by conduction in each layer is expressed by the equation

$$\lambda_j \left(\frac{\partial^2}{\partial y^2} \right) T(t, y) = \rho_j c_j \frac{\partial T(t, y)}{\partial t}, \tag{1}$$

in which t is time, $T(t, y)$ is temperature, the subscript j identifies the layer, λ_j is the thermal conductivity, ρ_j is the density and c_j is the specific heat. These thermal properties are constant in each layer and do not change from point to point.

The solution is defined in the frequency domain after the application of a Fourier transformation to Eq. (1)

$$\left(\frac{\partial^2}{\partial y^2} + \left(\sqrt{\frac{-i\omega}{\alpha_j}} \right)^2 \right) \hat{T}(\omega, y) = 0, \tag{2}$$

where $i = \sqrt{-1}$, $\alpha_j = \lambda_j / (\rho_j c_j)$ is the thermal diffusivity of the layer j, and ω is the frequency.

The total heat field is found by adding the surface terms arising within each layer and at each interface, as required to satisfy the boundary conditions at the interfaces, i.e. continuity of temperatures and normal flows between layers.