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The influence of moisture content on the thermal conductivity of external thermal mortars

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HIGHLIGHTS

- Experimental campaign on 17 thermal mortars at different moist states.
- Thermal mortars with different lightweight aggregates, binders and admixtures.
- Influence of the moisture content on the thermal conductivity.
- Analytically and experimentally thermal conductivity correlations.

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ABSTRACT

The growing European interest on building sustainability has driven the establishment of the 2012/27/UE Directive. Mortars with thermal conductivity lower than 0.2 W/m·K (thermal mortars) can have an important role in the energy efficiency of buildings. The thermal conductivity is a fundamental parameter to characterize the hygrothermal performance of mortars. Nevertheless, its measurement is complex due to its large dependency on several factors and its dynamic behaviour. In the present paper, an experimental campaign is carried out to evaluate the influence of the moisture content on the thermal conductivity of 17 thermal mortars. Moreover, correlations between thermal conductivity analytically estimated from standards and experimentally measured are assessed. The results showed that the thermal conductivity is significantly dependent on the moisture content. However, most of the building standards use fixed conductivity values for normalized conditions. Therefore the discussion of relevant influence factors on thermal conductivity of thermal mortars can help designers and professionals to evaluate the hygrothermal performance of in-service buildings facades with thermal mortars, when subjected to real exposure conditions.

1. Introduction

Building energy performance has become a crucial issue to evaluate the sustainability of a building. The heat transfer between the inside of the building and the outdoor environment is very dependent on the thermal performance of the building envelope during the building life cycle [1].

Therefore, it is very important to know how to measure and estimate the design and declared values of major thermal properties of building materials. However, the heat transfer through the walls is usually heterogeneous, has time-varying nature (dynamic) and is affected by many external factors, and thus its calculation is very complex but necessary to assess the building energy performance.

It has been frequently confirmed by many researchers in recent decades that the thermal properties of building materials are significantly affected by the moisture content and not so significantly by temperature [2–6]. It is worth referring that most of these studies have focused on insulation materials with a porous structure with large moisture storage capacity. Furthermore, other researchers, such as Jakob [7], have established additional relationships such as: thermal conductivity *versus* dry bulk density, which was corroborated by other studies [8–10]; and thermal conductivity *versus* ageing [11]. However, constant thermal conductivity values are usually established by most of buildings standards, which do not represent the real in-service conditions [12,13]. In this context, the EN ISO 10456 [14] standard considers the variation of thermal conductivity in function of conversion coefficients for the following three key factors: temperature, moisture content and ageing.

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Acronym list

C	Portland cement (CEM II/B-L 32.5N or CEM I 42.5R)
L	aerated lime
F_a	fly ash
Sa_1	silica aerogel (bulk density 66.96 kg/m^3)
Sa_2	silica aerogel (bulk density 305.58 kg/m^3)
E_c	expanded clay (bulk density 431 kg/m^3)
G_c	expanded cork granules (bulk density 101 kg/m^3)
P	perlite
A	admixtures
w/b	water/binder ratio
T_{mean}	mean testing temperature [°C]
ΔT_{23}	temperature variation [°C] for a reference temperature of 23 °C
λ_{exp}	thermal conductivity [W/m·K] obtained experimentally
λ_{dry}	thermal conductivity [W/m·K] at dry state
λ_1	thermal conductivity [W/m·K] of the first set of conditions
λ_2	thermal conductivity [W/m·K] of the second set of conditions
λ_T	estimated value for thermal conductivity [W/m·K] with temperature correction
λ_Ψ	estimated thermal conductivity [W/m·K] considering only the moisture effect
Ψ	moisture content volume by volume [m^3/m^3]
f_i	conversion coefficient for temperature (i = T), moisture content volume by volume (i = Ψ) or ageing (i = a)
F_i	conversion factor for temperature (i = T), moisture content (i = Ψ) or ageing (i = a)
f_i	conversion coefficient for temperature (i = T), moisture content volume by volume (i = Ψ) or ageing (i = a)
i_1	temperature (i = T), moisture content volume by volume (i = Ψ) or ageing (i = a) for the first set of conditions
i_2	temperature (i = T), moisture content volume by volume (i = Ψ) or ageing (i = a) for the second set of conditions
m_i	specimen mass at each moisture state i [kg]
m_{dry}	specimen mass at the dry state [kg]
ρ_{water}	water density, equal to 1000 [kg/m^3]
V	total volume of the specimen [m^3]

Moreover, the relationship between moisture content and thermal conductivity is affected by the type of material. Within the masonry materials group, the thermal conductivity variation with the moisture content is wide, with the inorganic and timber materials as the most and the least influenced materials, respectively [15,16].

There are several standards relating to thermo-physical property measurements, as discussed by Clarke & Yaneske [17]. However, there is still no consensus on the procedure of thermal conductivity material determination, in particular in the moist state. In fact, several steady and transient methods can be used to measure the thermal conductivity of materials. These methods can lead to different results of thermal conductivity. It is expected that by applying steady-state methods one can overestimate the actual energy consumption (dynamic) of building up to 40% [18,19].

This paper focuses on the influence of moisture content on the thermal conductivity of a set of thermal mortars, in order to understand more accurately the extent to which thermal conductivity is influenced by the boundary conditions and thermal mortar composition. This type of coating is not specifically covered by building codes. The analysed mortars have different lightweight and insulating aggregates (silica aerogel, expanded cork granules, and expanded clay), with low bulk density values and can be classified as T1 or T2 in accordance with European standard EN 998-1 [20] since they present a thermal conductivity lower than 0.2 W/m·K.

2. Materials and methods

The present work the impact of the moisture content and thermal mortar composition on the thermal conductivity is studied through both experimental and analytical approaches.

2.1. Experimental campaign

Bearing in mind that the thermal conductivity decreases as the density goes down [17,21,22,23], cement-based thermal mortars with different compositions were produced using several aggregates, binders, admixtures and additions, under laboratory controlled conditions (Table 1).

Lightweight aggregates, such as expanded cork granules and expanded clay (Figs. 1a and b), were incorporated as replacement of sand to reduce the bulk density in the hardened state and improve the renders' thermal performance [24–26]. Furthermore, two types of hybrid silica aerogel were selected as the main aggregate (Fig. 1c). This innovative high-porosity material is mainly composed of air and is extremely lightweight, with excellent thermal properties [27,28]. More details about the sol-gel process of these aerogels and its incorporation in the mortar can be found in [29].

Aerial lime and fly ash were used as cement partial replacement of two types of cement binder (CEM II/B-L 32.5N or CEM I 42.5R). The incorporation of admixtures allows increasing the porosity and improving the bond of the components in the fresh state (air entrainers, resins and rheological agents) [30–36]. The perlite filler addition also contributes to a better thermal performance of the mortar [37,38]. Mortars were produced with a constant binder:aggregate volume ratio of 1:4, and mixed with a drill as suggested by Silva et al. [39]. Cylindrical specimens, with 20 mm high and 60 mm diameter, were stored at a constant temperature of 20 ± 2 °C, 7 days in a sealed polyethylene bag (relative humidity of around 95 ± 5%), and 21 days in a chamber with a relative humidity of 65 ± 5%, as indicated in EN 1015-11 [40].

Table 1 also shows the bulk density and the thermal conductivity. All samples meet the requirements specified in EN 998-1 [20] to be considered as thermal renders, as they present a lower thermal conductivity, for thermal classes T1 and T2, below 0.1 and 0.2 W/m·K respectively. The bulk density of these mortars, measured according to [41], is between 367 and 836 kg/m^3, and therefore they can be classified as lightweight mortars [20].

The thermal conductivity was measured using the commercial Isomet 2114 [42] surface probe (Fig. 2a) by a transient test method, according to ASTM D5930-09 [43]. This hand-held device applies dynamic methods for the calculation of thermophysical properties, which among other advantages is less time-consuming [44,45] than other stationary methods. The measurement is based on the analysis of the temperature response of the analysed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater with a direct thermal contact with the surface of the sample. Periodic registers are made in function of time and the specimen's temperature. The thermal conductivity was