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Detailed territorial estimation of design thermal conductivity for façade materials in North-Eastern Spain

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ABSTRACT

The hygrothermal performance of building envelopes varies based on the temperature and moisture content of their materials. However, multiple building codes adopt constant conductivity values for construction materials based on standardised conditions that do not represent real operating conditions. Currently, a new procedure allows for correcting these normative conductivity values with a limited calculation effort, taking into account the characteristic environmental conditions of each location. This article combines climate records compiled at 313 weather stations distributed in North-Eastern Spain and uses this method to determine the applicable correction factors for materials of masonry façades. The exhaustive characterisation of this geographic area allows for creating correction isopleth maps that may be functionally integrated into building codes to improve the thermal design of buildings at any site of the territory. The results indicate a lower need to correct in mountainous areas, while the Mediterranean coast and the Ebro river valley exhibit larger deviations from normative values with respect to the actual conductivity of the materials. These corrections have been validated in two important cities in this area, Barcelona and Zaragoza.

1. Introduction

The design of the thermal envelope of buildings plays a key role in strategies to reduce energy consumption and CO_2 emissions in the construction field [1–4]. The hygrothermal properties of the materials used in the envelope determine the thermal and moisture transfers established between the interior and exterior environments [5–10]. One of the most important properties is thermal conductivity because it defines the thermal transmittance and resistance of enclosures (*U*-value and *R*-value, respectively), based on which the requirements of the design used in the majority of building codes are established [11–16].

The thermal conductivity of construction materials varies according to their temperature and moisture content, thus modifying the hygrothermal performance of the entire building [17–19]. Therefore, both climatic parameters should be considered for an appropriate thermal design of the building. Ignoring the characteristic climatic conditions of each location can lead to an incorrect selection of construction materials and enclosure design, greater energy consumption, and a lower hygrothermal performance than expected by design [20–22].

However, several building codes establish constant conductivity values, common for all locations and associated with standardised temperature and humidity conditions in the materials, which do not represent the actual operating conditions of the building enclosures [12–14,23,24]. As a result, these standardised conductivity values introduce an additional uncertainty factor in the thermal calculation [25,26]. In practice, this simplification is preferred over other less functional procedures that would allow for adjusting the conductivity values of each material (e.g., software that requires exhaustive input data or laborious analytical calculations, such as those gathered in standard ISO 10456:2007) [27–30].

However, currently a new procedure allows for adjusting conductivity values in a functional manner, using the input data that are typically available [31]. To achieve this goal, the procedure defines for each location a single factor that is able to correct the standardised conductivity values established in building codes. To calculate this conductivity correction factor (CCF), the characteristic environmental conditions of each location are considered, which allows for approximating the design thermal conductivity value of the materials for those operating conditions.

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Previous studies have determined CCF values that are applicable to materials of common masonry façades in a discrete number of locations distributed across Spain (1 location per 9705 km^2) [31]. However, the different climactic conditions in each site result in correction factors that are not representative in zones far from the locations where they were obtained. Therefore, characterising the entire territory with greater detail constitutes a key factor for developing this procedure, which would allow for adjusting the conductivity values and improving the thermal design of any building, independent of its location.

This article develops this new procedure, providing a detailed characterisation of the CCF values that are applicable to materials of masonry façades in an extensive geographical area. Analysis of the climate data gathered from 313 weather stations in North-Eastern Spain provides exhaustive territorial coverage, reducing the distance between the analysed locations and allowing for a more reliable interpolation of the CCF values obtained. The production of isopleth maps based on these interpolations for two regions of the area (Aragón, 1 station per 568 km^2, and Catalonia, 1 station per 151 km^2) makes it possible to improve the thermal design of any building in both regions, even in locations without representative climate data.

The CCF values obtained have been validated for different masonry façade configurations in the main cities of both regions (Barcelona and Zaragoza). To that end the thermal resistance calculated from standardised conductivity values corrected by CCF values has been compared with the results that would be obtained based on the conductivity values adjusted through the standard ISO 10456:2007.

2. Background

The thermal conductivity of construction materials varies with the temperature and humidity of their porous structures. The range of variations depends on the magnitude of environmental changes and on the intrinsic properties of the material [15,25,32–36]. Therefore, each material exhibits a different hygrothermal behaviour considering the variations in its operating conditions.

The thermal conductivity of a material in the operating conditions of the building envelope is described as the design conductivity value, λ_{design} (W/(m K)). These design values should be used for the thermal calculation of the building, thereby characterising its hygrothermal behaviour realistically in each situation [11–14].

However, determining these λ_{design} values is a complex task. The exterior and interior environmental conditions vary over time, according to the climatology of the location and the activity in the building. Similarly, the temperature and humidity of each material varies in every possible configuration of the enclosure, depending on its thickness and the position of the material within the enclosure. In turn, the humidity of materials is not proportional to the relative humidity: the humidity transport mechanisms (i.e., mainly vapour diffusion, capillary flow, capillary condensation, and surface diffusion) are combined differently in each porous structure, leading to a specific sorption function for each material [7,33,37–40]. Other additional aspects, such as solar radiation, wind pressure, and wind-driven rain, can also affect the λ_{design} value of materials.

Currently, there are hygrothermal software and calculation procedures capable of integrating these aspects, allowing for precise calculations of λ_{design} values based on the declared conductivity values provided by the material manufacturer or the normative conductivity values established by a building code (both based on standardised temperature and relative humidity conditions).

To consider all design related aspects, hygrothermal software packages use exhaustive input data, such as climate records gathered in short time intervals, expected indoor conditions, and detailed characterisations of material properties [28–30]. Due to the usual lack of such data, these software packages are primarily used in research projects focused on specific case studies [41–43].

In turn, the standard ISO 10456:2007 provides an analytical method based on dimensionless conversion factors associated to temperature (F_T), moisture content (F_M), and ageing (F_A). Using this method (Eq. (1)), the conductivity λ_2 (W/(m K)) of a material in specific environmental conditions can be approximated from a known reference conductivity, λ_1 (W/(m K)), based on other environmental conditions.

$$\lambda_2 = \lambda_1 \cdot F_T \cdot F_M \cdot F_A = \lambda_1 \cdot e^{f_t(T_2 - T_1)} \cdot e^{f_\psi(\psi_2 - \psi_1)} . F_A \tag{1}$$

The calculation employs temperature conversion coefficients f_t (K^{-1}) and moisture conversion coefficients f_ψ (m^3/m^3), tabulated in the ISO standard for various construction materials. The temperature difference $T_2 - T_1$ (K) and moisture content difference $\psi_2 - \psi_1$ (m^3/m^3) for the material must also be identified between both environmental conditions. When Eq. (1) is used to approximate the λ_{design} value based on the declared conductivity specified by the material manufacturer, a correction factor F_A equal to 1 can be adopted (these declared values typically take account of ageing) [27].

Regardless, the need to determine the temperature and relative humidity of each material in the enclosure leads to a laborious process that must be repeated for any variation in thickness, materials, or layer order considered in the design. In addition, to determine the ψ value, it is necessary to have moisture sorption isotherms that empirically characterise the relationship between the relative humidity of the material and its moisture content [40].

Due to the considerable calculation effort and the necessary input data, neither the ISO standard nor the hygrothermal software are useful in practical applications. For that reason, building codes establish normative conductivity values for construction materials (λ_{norm}) that are constant and independent of operating conditions. To determine their value, standardised conditions (T_{norm} and ψ_{norm}) are adopted, usually coinciding with those used by manufacturers to define their declared values [14,15,23,24]. Thus, although this simplification does not provide a realistic characterisation of the hygrothermal performance of materials, it reduces the complexity of the thermal design and makes its calculation faster.

To reconcile both aspects (i.e., functionality and accuracy), a procedure based on Eq. (1) has recently been developed, which allows for obtaining a simplified estimation of the λ_{design} values with a similar accuracy to that achieved by the ISO standard [31]. For this an adjustment factor is determined, which is only associated to the characteristic climate conditions of each location and can correct the λ_{norm} values established by building codes. The correction factor defined (CCF) is applicable to any material typically present in the analysed enclosure typology (independent of the particular design being considered), allowing for easy implementation in the calculation.

2.1. *Correction factor to functionally approximate the design thermal conductivity*

To determine the CCF value associated with each location, this new procedure uses the formulation of the ISO standard 10456:2007 (see Eq. (1)) and simplifies its calculation by considering a single generalised enclosure that is representative of an entire typology of enclosures (e.g., masonry façades). This generalised enclosure is assumed to consist of a single uniform and generic material, whose intrinsic properties are obtained by weighting the properties of the materials typically present in the enclosure typology being studied. Thus, its properties can be considered