proceedings

Abstract

Active IR thermography for assessing Moisture Content in Porous Building Materials: application of the Thermal Inertia Method

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Abstract. Moisture in building materials, particularly in cultural heritage structures, can cause reduction of mechanical strength, decrease of indoor comfort and alteration of thermal properties, aesthetic decay, and even material loss. To non-invasively quantify moisture content in porous materials, Active Infrared Thermography was used. The method was applied in the laboratory on brick sample with different moisture contents, as well as on a reference stone sample with known thermophysical properties, to evaluate the thermal inertia as a function of water content using a comparative approach. A heat flux was applied to the sample using a lamp, and thermal inertia was derived from the absorbed heat, influenced by the material's absorption coefficient. An indirect optical calibration enables estimation of this coefficient without applying high-emissivity or high-absorption coatings, preserving the integrity of sensitive heritage materials.

1. Introduction

Infrared Thermography (IRT) is a non-destructive technique used to investigate building structures, particularly cultural heritage assets affected by moisture. Moisture alters the thermophysical properties of building materials, causing various types of deterioration [1], [2]. These issues call for continuous monitoring and, where possible, long-term conservation strategies. This paper aims to apply active IRT to quantitatively measure moisture content in a hygroscopic material. The method is based on evaluating thermal inertia, expressed as effusivity ε [J m^{-2} K^{-1} s$^{-1/2}$] describes a material's ability to spread heat, as a function of water content, using prior knowledge of the material's absorption coefficient. The tested samples are fired clay bricks, a material widely used in historical buildings.

2. Materials and Methods

Tests were performed on 2 modern bricks (UNI 25×12×5 cm), labeled Brick A and Brick B, in dry, moist, and saturated conditions. A sample of Serena sandstone used a reference with known effusivity. To evaluate thermal effusivity via a comparative method [3], samples were briefly heated (~10 s) with a 1 kW lamp, and surface temperature rise was recorded using an IRT camera (180 images at 5 Hz). Assumptions include adiabatic conditions, material homogeneity, and semi-infinite geometry. Evaporative effects were neglected due to a thin film covering wet samples. The surface temperature of each sample, as a function of the square root of time, was then analyzed as follows:

$$T(t) = 2\,[(Q/\varepsilon)\,\sqrt{(t/\pi)}], \quad (1)$$

where Q is the absorbed thermal power [Wm^{-2}], ε is the thermal effusivity [$J\,K^{-1}\,m^{-2}\,s^{-1/2}$], t is the time [s]. By subjecting both samples to the same power input Q for the same duration t, it is possible to compare their temperature increases. Knowing the effusivity of the reference sample ε_{ref}, the effusivity of the unknown sample ε_{mat} can be determined.

Ensuring equal heat absorption Q by both the brick and the reference (Serena stone) is crucial for the comparative method, but difficult in practice due to lamp beam inhomogeneity and, more critically, differing absorption coefficients. The first issue can be mitigated by adjusting the setup (e.g., lamp distance or sample positioning). The second issue can be addressed by either applying identical coatings/paintings to both surfaces, as suggested in previous studies [3], [4], or by estimating the absorption coefficients individually, or at least their ratio, which is the approach introduced in this work. This method is particularly relevant for cultural heritage applications, where surface treatments are generally not allowed.

$$T_{ref} = (2/\pi) \cdot [(Q_{ref} \cdot \alpha_{ref})/\varepsilon_{ref}] \cdot \sqrt{t},\; T_{mat} = (2/\pi) \cdot [(Q_{mat} \cdot \alpha_{mat})/\varepsilon_{mat}] \cdot \sqrt{t}, \quad (2)$$

$$\varepsilon_{mat} = (T_{ref}/T_{mat}) \cdot (\alpha_{mat}/\alpha_{ref}) \cdot \varepsilon_{ref}, \quad (3)$$

where Q_{ref} and Q_{mat} are the incident light power [Wm^{-2}] on the surface of the reference and unknown materials respectively, α_{ref} and α_{mat} are the absorption coefficients of the reference and unknown materials respectively, and it is assumed that the incident light powers (Q_{ref} and Q_{mat}) are equals. An estimation of the absorption coefficients for brick and Serena sandstone was performed using a single photograph taken while the lamp was on. The image included both materials and a reference gray scale chart commonly used in professional photography to adjust luminance level and white balance. The photograph is captured using a wide wavelength sensor with a Bayer filter array. The raw data are interpolated and processed to generate a full-color RGB image [5], after applying different weights to the three-color channels based on human color perception. This RGB image was then converted to grayscale (Figure 1a) by assigning weighted values to the three channels as recommended by standard ITU-R BT.601 (International Telecomunication Union). The complement to 1 of the pixel values in this map was then used to approximate the absorption coefficients of the materials within the frame.
Experiments were conducted on brick samples using both approaches to address the absorption coefficient issue: one painted (Brick B) and one unpainted brick (Brick A) were included in each test. Results were compared in terms of thermal effusivity and the derived moisture content. Moisture Content was expressed as volumetric percentage (MC%), defined as the water volume relative to the total sample volume. MC% was estimated by modeling the thermophysical properties as a function of pore volume progressively filled with water, from dry (MC% = 0) to full saturation (MC% = 34), the latter determined by weight difference between oven-dried and vacuum-saturated samples. To derive MC% from IRT-based effusivity values, a simplified model was used, treating the brick as a mix of: (i) bulk phase, (ii) air, and (iii) water. The volumetric fractions of air and water vary with MC%. Effusivity is defined as:

$$\varepsilon = \sqrt{\lambda\,\varrho\,c_p}, \quad (4)$$

The relevant properties considered [6] were thermal conductivity λ [$W\,m^{-1}\,K^{-1}$], specific heat capacity c_p [$J\,kg^{-1}\,K^{-1}$], and density ρ [$kg\,m^{-3}$]. Quantitative values for λ, c_p and ρ of the bulk phase (i) were obtained through ISO 22007-2 measurements [7],DSC [8], and the gravimetric method, respectively. Properties for air (ii) and water (iii) were taken from literature. A summary of such values is presented in the following Table 1:

Table 1. Thermal properties of the materials used to model thermal effusivity as function of MC%.

Material	λ [W m^{-1} K^{-1}]	ρ [kg m^{-3}]	c_p [J kg^{-1} K^{-1}]
Brick	0.559 ± 0.004	1470 ± 13	797 ± 6
Air	0.02	1.2	1006
Water	0.6	1000	4182

3. Conclusions

Table 2 presents a comparison of the measured thermal effusivity values obtained using the IRT method (with paint, standard method, and without paint), where the absorption coefficient was estimated through photographic approach. The experimental results are then compared to effusivity values calculated from thermophysical properties measured in the laboratory (Figure 1b).

Table 2. Thermal effusivity obtained by IRT and calculation (following equation 5) based on thermophysical properties measured in laboratory from saturation to dry conditions.

Material	ε by IRT (using paint) [J m^{-2} K^{-1} s$^{-1/2}$]	ε by IRT (estimating absorption coefficient) [J m^{-2} K^{-1} s$^{-1/2}$]	ε by laboratory measurements [J m^{-2} K^{-1} s$^{-1/2}$]	MC by gravimetric analysis [%]
Brick A	-	1734	1616	34
Brick B	1865	-	1547	31
Brick A	-	944	1025	10
Brick B	1195	-	915	4
Brick A	-	840	846	0
Brick B	833	-	843	0

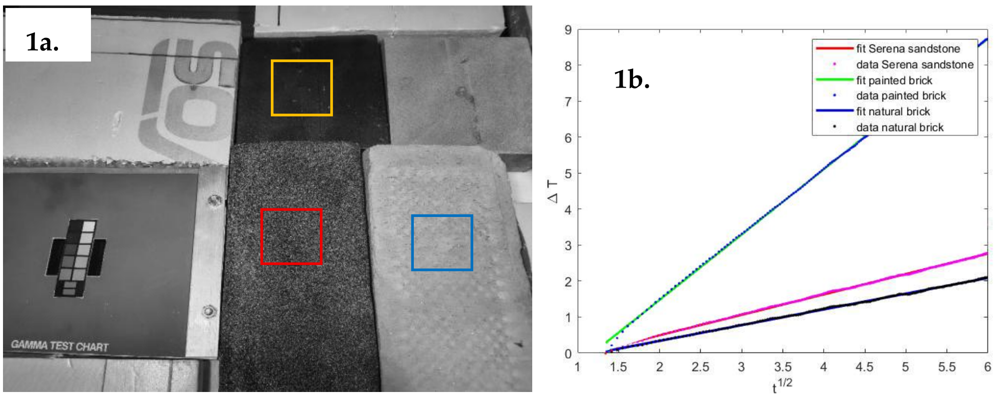

Figure 1a. Grayscale image on the sample normalized with the gray scale chart (on left): orange represents the reference of Serena sandstone, red the painted brick and blue the unpainted brick. **Figure 1b.** Temperature trend in the brick sample and Serena sandstone reference sample.

This study presents a non-destructive method for assessing moisture content in porous building materials, with a focus on cultural heritage. The approach relies on comparative active IRT, correlating moisture content with thermal effusivity. By enabling rapid estimation of the absorption coefficient without the need for surface coatings, the method is particularly suited for in-situ applications, offering quick and repeatable results.

Laboratory tests on fired clay bricks at various moisture levels showed good agreement with reference values under dry conditions. At higher moisture levels, some deviations were observed, though the results maintained a consistent trend. Limitations include heat loss due to evaporation, partially mitigated by a plastic film, and possible inaccuracies arising from non-uniform moisture distribution within the bricks.

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