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Method for Quantitative Assessment of Moisture Content of Porous Building Materials Based on Measurement of Thermal Inertia with Active Infrared Thermography †

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Abstract: The presence of moisture in masonry is crucial because it causes and exacerbates various deterioration mechanisms, such as crystallization of salts, mechanical stresses due to freeze–thaw cycles, biological degradation, etc. The assessment of the water content is critical for cultural heritage buildings; thus, on-site non-invasive techniques have been proposed over time. An innovative active thermographic procedure is proposed and tested in a laboratory to assess the amount of moisture via a non-destructive approach. The methodology is based on heating a brick specimen together with a reference sample which has known thermophysical properties. Evaporation is inhibited by an impermeable film applied to the samples. The trends in the surface temperatures of both materials are recorded using infrared thermography and compared with each other: the calculation of the thermal inertia of the wetted material is retrieved from the comparison of the temperature trends in both samples. The water content value is thus determined from the thermal inertia of the sample.

Keywords: thermophysical properties; active infrared thermography; water content of porous materials

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1. Introduction

Masonry structures, particularly cultural heritage buildings, are prone to deterioration due to moisture. The presence of moisture can lead to various adverse effects such as salt crystallization, mechanical stresses from freeze–thaw cycles and biological degradation [1]. The conservation of historical buildings requires a thorough analysis of moisture dynamics within the masonry. However, traditional invasive methods of water content assessment, such as gravimetric measurements [2], are not always appliable, mainly in listed heritage buildings. An alternative approach based on infrared thermography (IRT) allows one to observe the thermal effect of moisture by measuring surface temperatures. IRT is a non-contact, non-destructive technique that visualizes surface temperatures exploiting the infrared radiation emitted by any object [3]. Traditional IRT only provides qualitative information on moisture presence without quantity details. State-of-the-art active IRT detects the temperature of a surface stimulated by a controlled thermal source in order to induce evaporation [4]. The thermal response over time, together with the implementation of mathematical algorithms, allows for the assessment of the thermophysical properties affected by moisture. Nonetheless, it only gives qualitative indications about the presence of moisture. This paper introduces an innovative active thermographic procedure to measure the water content of a material. The thermal inertia of a porous building material is influenced by water content. Laboratory testing on brick samples demonstrates that the water content of porous materials can be assessed with a high level of accuracy from the determination of thermal inertia. This procedure opens a path to the evaluation of moisture content in cultural heritage buildings.

2. Materials and Methods

Thermal inertia is evaluated by means of thermal effusivity measurement, which is carried out in IRT via a comparative method [5,6]. The wet specimen (brick) and a reference material ("pietra serena" sandstone) are subject to heating by activating a 1 kW lamp for a short time, typically around 10 s. For thick samples, following the semi-infinite approximation, the surface temperature trend over time (Figure 1) can be evaluated with the following equation:

$$T(t) = 2\frac{Q}{\varepsilon}\sqrt{\frac{t}{\pi}} \quad \varepsilon = \sqrt{\lambda\rho c_p} \tag{1}$$

where Q is thermal power, t is time, ε is thermal effusivity, λ is thermal conductivity, ρ is density and c_p is specific heat capacity at constant pressure.

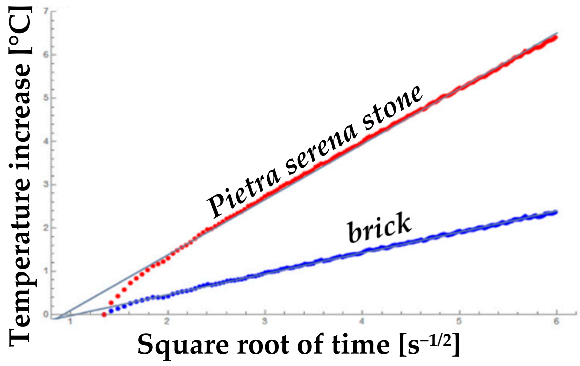

Figure 1. Temperature trend in the tested materials. The slopes of the linear temperatures increase depending on the different thermal emissivities.

Both samples are varnished with a high-emissivity paint in such a way that they absorb the same thermal power. The IRT camera records the trend in the surface temperature at a sampling rate of 5 Hz. The thermal image (Figure 2) collects the average surface temperature variation during the application of the thermal stimulus on both the material with an unknown thermal effusivity (brick, on the left) and the reference material (pietra serena stone, on the right).

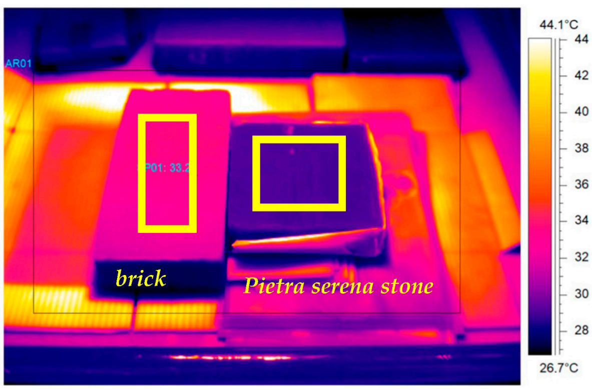

Figure 2. Thermal image of the tested materials. The yellow boxes are the regions of interest where the average temperatures for each frame were collected.

From the thermal effusivity of the reference material, the thermal effusivity of the unknown material is determined by means of the equation below:

$$\varepsilon_{unknown} = \varepsilon_{reference} \frac{T_{reference}}{T_{unknown}} \tag{2}$$

In this simplified model, the heat exchange with the environment and the evaporation on the surface of the wet material are not considered. Specifically, the latter is prevented by the application of a thin plastic film that is easily removable from surfaces without causing damage and is thin enough to ensure a negligible thermal resistance. Two standard-size bricks, measuring 12 × 25 × 5 cm^3, were measured: one coming from Venetian Arsenal building (brick A) and a contemporary manufactured brick (brick B). The samples were measured using the abovementioned methodology at different levels of water content; a correlation between the differences in thermal effusivity and the water content is therefore established. Concurrently, thermal effusivity is also calculated according to the following relationship:

$$\varepsilon = \sqrt{\lambda\, \rho\, c_p}\ \left[\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1/2}}\right] \tag{3}$$

where λ is thermal conductivity, ρ is density and c_p is specific heat capacity. Thermophysical properties of both bricks were measured in the laboratory under dry conditions. Thermal conductivity measurements were conducted via transient plane source method, according to ISO 22007-2 standard [6]. c_p was determined by means of Differential Scanning Calorimetry [7]. ρ was measured using the gravimetric method. While complex models have been proposed in the literature [8], for this study a simplified thermophysical model was used, which considered the bricks as three-component composite materials. The model is based on weighted averages between the bulk, air and water components, allowing for the parametric recalculation of these properties as a function of water content. To determine the open porosity, which represents the volume that can be filled by absorbed water and corresponds to the volumetric water content at saturation conditions, gravimetric analysis was performed. This involved comparing the weight of the oven-dried material to that of the material in saturation conditions. By assessing these various thermophysical properties, a comprehensive understanding of the behavior of the bricks under different moisture conditions was achieved, as summarized in Table 1.

Table 1. Thermophysical properties of the specimens [1].

Material	Specific Heat [$J \cdot kg^{-1} \cdot K^{-1}$]	Density [$kg \cdot m^{-3}$]	Thermal Conductivity [$W \cdot m^{-1} \cdot K^{-1}$]	Open Porosity [%]
Brick A (dry)	797 ± 6	1470 ± 13	0.559 ± 0.004	34 ± 1
Brick B (dry)	796 ± 2	1680 ± 14	0.64	32 ± 1
Serena Stone	818 ± 2	2480 ± 10	2.36 ± 0.02	-
Water	4182	1000	0.6	-
Air (at 25 °C)	1006	1.185	0.02	-

[1] Uncertainty is given as standard deviation for laboratory measured values only.

Using the established relationships and the measured thermophysical properties, it becomes possible to correlate the effusivity value measured using IRT on the wet material with a specific absorbed water content.

3. Results

The proposed methodology was applied to "brick A" and "brick B", encompassing various water content levels ranging from saturation to approximately 15–20% of the samples volume. However, it was observed that, even at lower humidity levels, accurate sample preparation that ensured homogenous water distribution within the brick became difficult due to the water gradient between the core and the outer surface of the bricks. To evaluate the effectiveness of the proposed methodology, Table 2 presents a comparison between the actual water content measured through gravimetric analysis and the results obtained using the proposed approach for both brick samples. This comparison enabled a quantitative assessment of the water content.

Table 2. Evaluation of water content of brick samples using IRT and standard method (gravimetric).

	Brick A				Brick B			
Water content (IRT method) [%]	34 ± 0.3	30 ± 0.3	26 ± 0.2	20 ± 0.1	35 ± 0.4	29 ± 0.3	22 ± 0.3	13 ± 0.1
Water content (gravimetric method) [%]	36 ± 0.3	28 ± 0.3	23 ± 0.2	16 ± 0.1	32 ± 0.3	26 ± 0.2	19 ± 0.2	13 ± 0.1

4. Conclusions

A novel approach for the assessment of the water content of porous materials via IRT has been proposed. This methodology has been tested and evaluated in a laboratory and the results have been compared with a standard method. The foundation of this approach lies in modeling the thermophysical properties of the materials as a function of water content. On the one hand, encouraging outcomes were achieved via simplified models; on the other hand, an accurate modeling of the minero-petrographic characteristics of bricks would be helpful in order to determine the thermal conductivity. Bricks can contain diverse types of inclusions, some of which have a crystalline structure and may respond differently depending on the direction of thermal flux (e.g., Quartz). Moreover, water fills the pores and is in contact with various inclusions; such aspects lead to significant variations in thermal conductivity. To enhance the proposed IRT method for future applications, thermal conductivity could be obtained using finite element modeling, employing a two-dimensional geometry derived from observations of thin sections of bricks, or X-ray tomography. However, the current approximation would make the methodology promising and available for field or large-scale trials as a complement or support to other standard methods.

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References

1. Camuffo, D. *Microclimate for Cultural Heritage: Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*; Elsevier: New York, NY, USA, 2013.
2. *UNI 11085:2003*; Beni Culturali–Materiali Lapidei Naturali Ed Artificiali–Determinazione Del Contenuto D'acqua: Metodo Ponderale. UNI: Milano, Italy, 2003.
3. Maldague, X. *Theory and Practice of Infrared Technology for Nondestructive Testing*; Wiley: Hoboken, NJ, USA, 2001.
4. Grinzato, E.; Rosina, E. Infrared and thermal testing for conservation of historic buildings. In *Nondestructive Testing Handbook: Infrared and Thermal Testing*; Maldague, X., Ed.; ASNT: Columbus, OH, USA, 2001; Volume 3.
5. Grinzato, E.; Bison, P. Building material characterization by using IR thermography for efficient heating systems. In *Thermosense XXX*; SPIE: Bellingham, WA, USA, 2008; Volume 6939.

6. *ISO 22007-2:2015*; Determination of Thermal Conductivity and Thermal Diffusivity—Part 2: Transient Plane Heat Source (Hot Disc) Method. ISO: Geneva, Switzerland, 2015.
7. *ISO 11357-4:2014*; Differential Scanning Calorimetry (DSC)—Part 4: Determination of Specific Heat Capacity. ISO: Geneva, Switzerland, 2014.
8. Torquato, S. *Random Heterogeneous Materials—Microstructure and Macroscopic Properties*; Springer: New York, NY, USA, 2002.