ACTA IMEKO
ISSN: 2221-870X
October 2018, Volume 7, Number 3, 20 - 23

Infrared Thermography technique (IRT) for the evaluation of the hydric behavior of building stones

Giulia Forestieri[1], Mónica Álvarez de Buergo[2]

[1] Facultad de Ingeniería, Universidad de la Sabana, Campus Universitario del Puente del Común, Chía, Cundinamarca, Colombia
[2] Instituto de Geociencias IGEO (CSIC-UCM), Spanish Research Council – Complutense University of Madrid, Madrid, Spain

ABSTRACT
The water distribution into stone specimens in laboratory conditions is evaluated through the infrared thermography method (IRT). Porous building stones samples (calcarenite and sandstone) are examined under stable laboratory conditions (controlled temperature and relative humidity) in order to simulate the same hydric behavior in real scale of material systems *in situ.* Hydric tests monitored through IRT are performed in order to analyze the capillary water absorption and evaporation transport phenomena into stone samples. IRT technique allows to record thermal images at different intervals of time highlighting the internal capillary and evaporation rise heights, responsible for the majority of decay processes occurring in masonries. The geometric shape of the damped area and the time of spreading are directly related to the open porosity of the investigated stone materials. Hydric tests are repeated for each splitting plane of the specimens (faces), in order to obtain useful results that could be applied for real masonries. Results demonstrate the usefulness of IRT as a non-destructive and portable technique in the field of new construction and for restoration purposes, as well as its importance in characterizing the physical stone features and the effectiveness of applied conservation treatments.

Section: RESEARCH PAPER

Keywords: building stones; non-destructive tests; infrared thermography; hydric behaviour

Citation: Giulia Forestieri, Mónica Álvarez de Buergo, Infrared Thermography technique (IRT) for the evaluation of the hydric behavior of building stones, Acta IMEKO, vol. 7, no. 3, article 5, October 2018, identifier: IMEKO-ACTA-07 (2018)-03-05

Editor: Sabrina Grassini, Politecnico di Torino, Italy

Received February 28, 2018; **In final form** September 14, 2018; **Published** October 2018

Funding: This work was supported by "Programa de Geomateriales 2 (S2013/MIT-2914)" and by "Fondi 5 per mille D.P.C.M. 23/04/2010"

Corresponding author: Giulia Forestieri, giulia.forestieri@unisabana.edu.co

1. INTRODUCTION

Hydric tests are very important in the characterization of the porosity of stones, especially in terms of the movement of water through the pore system, which is the main factor controlling water uptake and its transport inside the stone itself. In particular, the open porosity of stones and their effective pore size determine the movement of water, as obtained by authors who based their research on the comparison of pore size distribution values of various building materials [1].

In this study, the infrared thermography technique (IRT) is used to better individuate the water absorption/desorption of different stones simulating real conditions. A not so frequent approach is pursued focusing on water exchange properties of capillary rise uptake and evaporation of two different stones, with the aim of simulating masonry prototypes in laboratory as well as integrating traditional standardized techniques with non-destructive IRT [2], [3], [4].

2. MATERIALS AND METHODS

Two types of building stones are investigated and tested by different techniques.

2.1. Stone materials

For the stone selection, different criteria are considered: the historical importance and the role of building stone materials in the Calabrian (southern Italy) context; the main schools of stonemasons and the related architectural models; the role of the quarry activity in the past and how it still influences the Calabrian quarry market through the presence of active quarries [5].

Two lythotypes of sedimentary stones are selected:

1) San Lucido calcarenite (CS), a medium porous Miocenic calcarenite quarried in "Motta Lupo" quarry in San Lucido (39°18' N and 16°03' E), with micritic matrix and visible fossils. CS is classified as "biopelmicrite" and "with pores" [6] and its carbonate content is quite high,

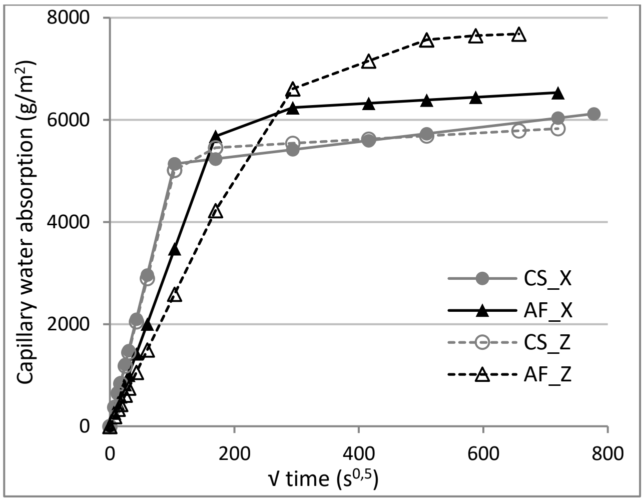

Figure 1. Capillary water absorption (g/m^2) vs. square root of the time (s^{0,5}) along the two investigated directions (X and Z).

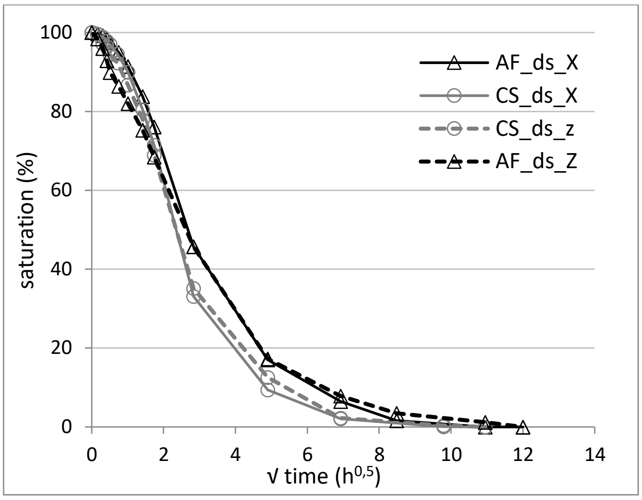

Figure 2. Water desorption curves. Saturation (%) vs. square root of the time (h^{0,5}) along the two investigated directions (X and Z).

reaching 94 % at the maximum. It is also known as "Mendicino stone" and due to its architectural importance has been investigated by many authors [7], [8].

2) Fuscaldo sandstone (AF), a porous Miocenic sandstone quarried in outcrops located in Fuscaldo (39°24' N and 16°01' E). AF contains silico-clastic matrix (50 %) and clasts (50 %), it is classified as "graywacke" and "with many pores" [6]. It is also commercially known as "sweet stone" due to its easy workability and principally employed as building material for structural elements such as buildings, arches and portals of many Calabrian historical centres [5].

32 cubic specimens (50 ± 5 mm side), are prepared for each lithotype, and their spatial coordinates (X, Y and Z) marked according to the quarrymen's convention that is related to the anisotropy of the stones [9].

2.2. Experimental procedure

Specimen dimension is measured with a Mitutoyo digital caliper with a precision of ±0.01 mm. Measurements are recorded along each of the three orthogonal directions and averaged.

The stone porosity structure is evaluated by means of mercury intrusion porosimetry (MIP) with an Autopore IV Micromeritics mercury porosimeter, being the measured pore diameter range between 0.001 and 400 micrometers.

The hydric tests performed are: i) capillary water absorption; and ii) desorption; iii) porosity accessible to water, real and bulk densities. The first one is carried out longitudinal and perpendicular to the anisotropic planes of stone specimens (X and Z). Specimens are placed in a water sheet of 3 (±1) mm height and the weight increase is measured at the time intervals indicated by current standards [10] until reaching constant mass. The capillary coefficients C1 (along X), C2 (along Z) and the mean value Cc are calculated. The second hydric test consists in determining the water desorption content (Wi(Ds)) [11]. After reaching the saturated conditions through the capillary test, the same specimens are let to drying under constant laboratory conditions, and their weight water content is registered and plotted as a function of time. Open porosity is obtained employing an evacuation vessel for the water absorption by total immersion test under vacuum [12].

During the hydric tests, in order to provide thermal maps of the specimen surface areas in a black and white scale, in relation to a temperature scale and to visualize the moisture distribution by water movement (absorption, evaporation) into samples, an IRT camera (Thermacam B4 - Flir Systems) is used. Water areas present lower temperatures that can be detected by IRT. The detection of water is registered as a thermal difference and IRT images provide the measurement of the change of temperature due to the presence of water [13].

3. RESULTS AND DISCUSSION

Open porosity, pore size distribution and hydric parameters are reported in Table 1 while the capillary absorption curve and the kinetic of desorption are plotted in Figure 1 and Figure 2, respectively. The first part of each curve of Figure 1 defines the capillary water absorption, while the second part defines the water saturation.

According to the values reported in Table 1 and as shown in Figure 1, CS shows the highest values of capillary absorption. While AF demonstrates a different hydric behaviour according to the sample orientation, in contrast to CS that shows similar absorption curves along the two investigated directions. According to Figure 1, AF absorbs water more quickly along the X direction than when oriented with the Z axis parallel to the capillary rise direction.

By analysing Figure 1 it is evident that CS absorbs water more quickly than AF (if comparing the first part of the curve of the two stones), while AF absorbs the major water quantity due to its higher open porosity (the second part curve), coherently to the porosity values reported in Table 1. The difference of the capillary suction rate between CS and AF is related to the pore diameter and open porosity [14]. CS, due to the presence of macroporosity, absorbs water faster than AF, characterized by microporosity (Table 1) [15]. The difference in the absorbed water quantity is to be related to the open porosity: as AF exhibits higher open porosity than CS, it absorbs more water [1]. Thus, capillary test curves perfectly plot what expected by the open porosity values obtained by the MIP test.

As well as for the capillary absorption, CS displays higher evaporation rate than AF (Figure 2) during the desorption process. Within the first 3 hours the saturation is still about 90 %, for both materials. After the evaporation of the water from their surfaces, a pretty fast drying rate still keeps due to the internal

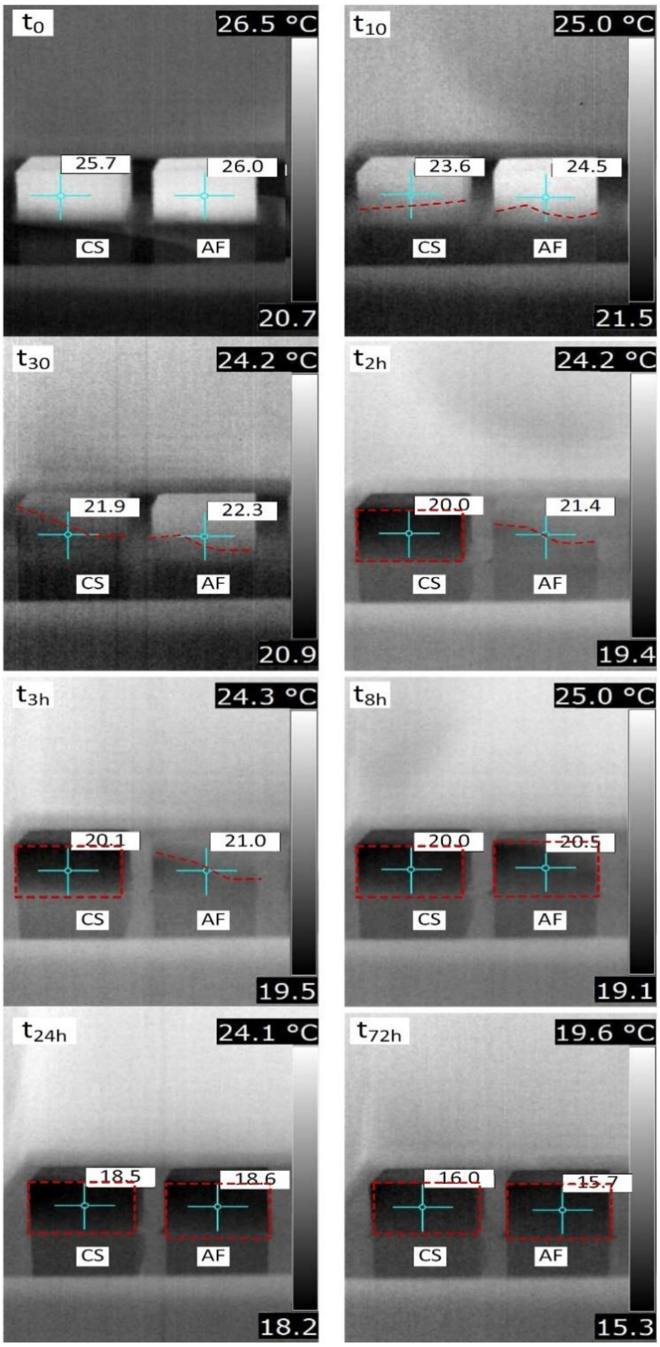

Figure 3. IRT thermal images taken during the capillary water absorption test along the X direction of San Lucido calcarenite (CS) and Fuscaldo sandstone (AF).

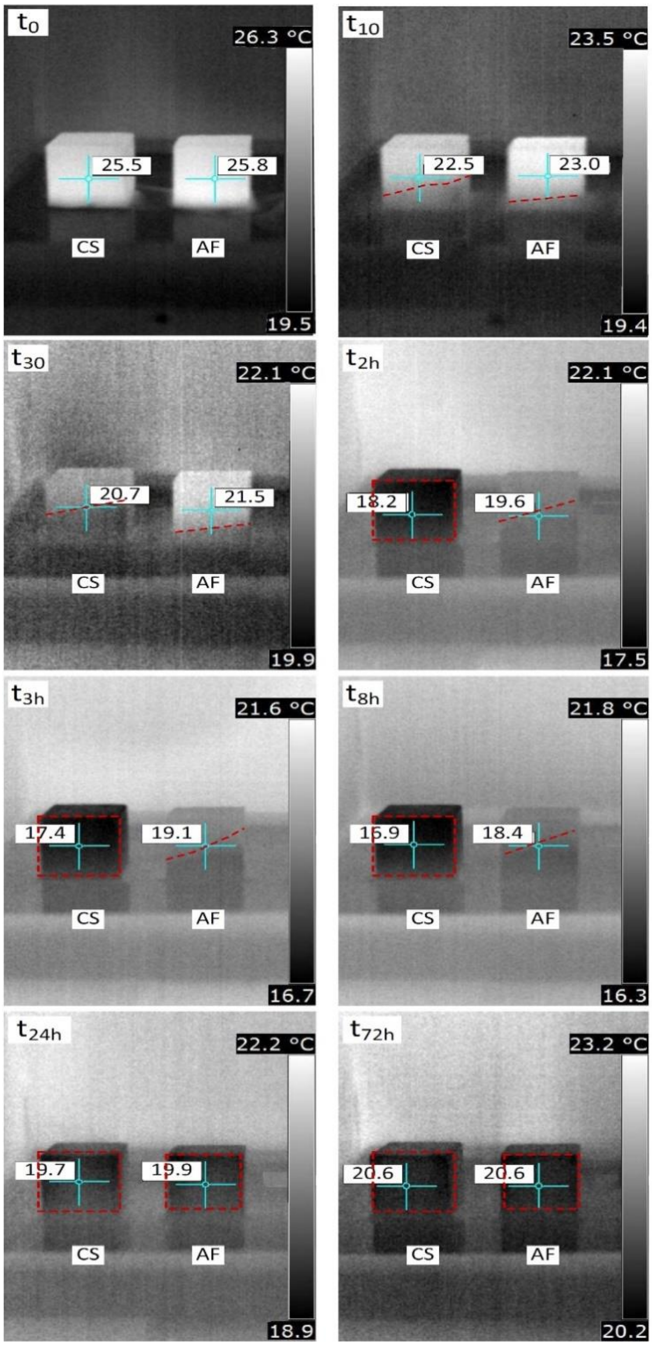

Figure 4. IRT thermal images taken during the capillary water absorption test along the Z direction of San Lucido calcarenite (CS) and Fuscaldo sandstone (AF).

absorbed water: within 21 hours (interval of time from 3 h until 24 h) a 60 % of their water content is lost. Probably, this high percentage is due to a good connectivity of the porous system [1]. After this point, there is an abrupt change in the drying rate with a constant saturation of 10-15 %. Thus, it could be summarized that each stone presents the same hydric behaviour during the absorption and desorption process: the higher the water absorption velocity, the higher the water desorption velocity and vice versa [16].

IRT thermal images, obtained during hydric tests are shown in Figure 3 and Figure 4. IRT thermal maps show a clear correlation among porosity, water absorption and evaporation. The cooling down of the damp areas on the specimen surface is the effect of the water (both in liquid and vapour phase) transport phenomena. IRT images provide the measurement of the change of temperature due to these effects. On CS surface, the wet area is larger than on AF specimens; the regular shape is due to the liquid, which regularly fills up all the open pores at disposal. The largest area is due to the rapid absorption of the drop by the surface rich in macropores, where water capillary spreading is faster. On AF specimens, the wet area has undergone the largest increase during the observation time, nevertheless the shape becomes irregular and the contour line is unreadable and vague, so that it is difficult to measure. This behaviour can be attributed to the pore size distribution. The extension and shape of the wet moisture over the intervals of time changed for any tested materials, depending on their surface characteristics. Moreover, comparing hydric absorption process

Table 1. Test results of San Lucido calcarenite (CS) and Fuscaldo sandstone (AF). Porosity values: Macro (> 5 µm) and micro (< 5 µm) porosity [15], open porosity to mercury (P_o) values in percentage obtained by the MIP test. Hydric parameters: open porosity to water (Po_w), capillary coefficients along X (C_1), along Z (C_2) and mean value (C_c) expressed in $g/m^2s^{0.5}$, water content evaporated (Wi_{Ds}) expressed in %, obtained by the capillary absorption and evaporation tests.

Samples	> 5 µm (%)	< 5 µm (%)	Po (%)	Po_w (%)	C_1 ($g/m^2s^{0.5}$)	C_2 ($g/m^2s^{0.5}$)	C_c ($g/m^2s^{0.5}$)	Wi_{Ds} (%)
CS	31.4	68.6	21.0	20.1	49.4	48.3	48.9	2.5
st. dev.	*1.0*	*0.2*	*0.7*	*2.3*	*10.1*	*3.4*	*0.8*	*0.3*
AF	3.0	97.1	13.0	16.1	33.5	24.9	29.1	1.9
st. dev.	*0.9*	*0.8*	*2.5*	*0.8*	*9.4*	*5.8*	*6.1*	*0.1*

along the two investigate directions trough IRT images, it can be observed how along Z the water uptake (Figure 4) is more irregular and slower than along X (Figure 3), especially for AF.

This fact indicates that water rises with higher difficulty inside samples along Z due the foliation planes orientated perpendicularly to the flux direction [17]. In the case of CS, no significant differences are detected for the two directions, coherently to the similar values obtained for the capillary coefficients C1 and C2 (Table 1) and to the quite parallel slope of the curves reported in Figure 1.

4. CONCLUSIONS

IRT images result suitable and effective tests to evaluate the absorption capability and the evaporation of liquid water into building stones together with the performed hydric tests. The presented techniques allow to measure different characteristics of the exterior layer of stone building materials. IRT shows good results indicating the variation into stones by measuring the changes of the surface temperatures due to absorption, diffusion and evaporation of water. The most influencing factor during the capillary test is related to pore features, especially in the very exterior layer of the materials, where the water exchanges occurs much more frequently than in the inner part of the stone. AF shows a more anisotropic hydric behaviour than CS and absorbs more water than CS, coherently to the porosity values and the pore size distribution. Each stone presents the same hydric behaviour during the absorption and desorption process.

Results obtained are useful when considering decay processes due to the water uptake, like salts or ice crystallization. For what concerning the hydric behaviour variability along the investigated directions, the way in which stones are positioned in construction could influence the capillary rise and, consequently, their durability. To minimize decay induced by water ingress and at the same time to improve stone durability, it is suggested to place (or lay) stones with their higher anisotropic hydric behaviour vertically along the Z axis, where the water uptake registered is lower. In the case of AF, as resulted more anisotropic than CS from a hydric point of view, this stone should be positioned along the Z axis in order to minimize the water content by capillary absorption. Moreover, IRT might be used as an important non-destructive technique to evaluate the performance of conservation interventions and materials, in compatibility to the original materials on the level of the structures. Indeed, IRT recording thermal maps of real surfaces could provide useful information on the differential behaviour of the various materials on the masonry scale regarding the water impregnation and evaporation phenomena, which control decay effects in porous media.

ACKNOWLEDGEMENTS

This study is supported by "Geomateriales 2 programme (S2013/MIT-2914)" and by "Fondi 5 per mille D.P.C.M. 23/04/2010".

REFERENCES

[1] E. Molina, G. Cultrone, E. Sebastián, F.J. Alonso, L. Carrizo, J. Gisbert, O. Buj, The pore system of sedimentary rocks as a key factor in the durability of building materials, Eng. Geol. 118 (2011) pp. 110-121.

[2] N. P. Avdelidis, A. Moropoulou, P. Theoulakis, Detection of water deposits and movement in porous materials by infrared imaging, Infrared Phys. Tech. J. 44, 3 (2003), pp. 183-190.

[3] A. Tavukçuoğlu, A. Düzgüneş, E.N. Caner-Saltık, Ş. Demirci, Use of IR thermography for the assessment of surface-water drainage problems in a historical building, Ağzıkarahan (Aksaray), Turkey, NDT&E Int., 38, 5 (2005), pp. 402-410.

[4] N. Ludwig, E. Rosina, A. Sansonetti, Evaluation and monitoring of water diffusion into stone porous materials by means of innovative IR thermography techniques, Measurement (2017), dx.doi.org/10.1016/j.measurement.2017.09.002.

[5] G. Forestieri, A. Campolongo, M. Ponte, Analisi storica e materica del materiale lapideo nel territorio di Cosenza, Proc. of 2nd History of Engineering International Conference, vol.1, Apr. 22-23, 2016, Naples, Italy, pp. 213-222.

[6] G. Forestieri, M. Álvarez de Buergo, M. Ponte, Idoneidad de rocas como material constructivo y restauración mediante la evaluación de su comportamiento hídrico y fíisco-mecánico, Proc. of ECPC National Congress, vol.1, Nov. 16-19, 2015, Málaga, Spain, pp. 23-27

[7] F. Rodolico, Le pietre delle città d'Italia, Second Edition, Le Monnier, Florence, 1995, pp. 427-429.

[8] G. M. Crisci, A. M. De Francesco, C. Gattuso, D. Miriello, Un metodo geochimico per la determinazione della provenienza di lapidei macroscopicamente omogenei. Un esempio di applicazione sui monumenti del centro storico di Cosenza, Arkos 2 (2003), pp. 52-59.

[9] G. Forestieri, D. M. Freire-Lista, A. M. De Francesco, M. Ponte, R. Fort, Strength anisotropy in building granites, Int. J. Archit. Herit. 8 (2017), pp. 1-13, doi.org/10.1080/15583058.2017.1354096.

[10] EN 1925, Natural stone test methods - Determination of water absorption coefficient by capillarity, Italian standards, Milan, 2000.

[11] NORMAL 29, Measurement of drying index, ICR CNR, Rome, 1988.

[12] EN 1936, Natural Stone Test Methods - Determination of real density and apparent density, and of total and open porosity", Italian standards, Milan, 2001.

[13] N.P.Avdelidis, A.Moropoulou, "Applications of infrared thermography for the investigation of historic structures", J. Cult. Herit. 5 (2004), pp. 119-127.

[14] S. Siegesmund, H. Dürrast, Physical and Mechanical Properties of Rocks, in: Stone in Architecture. Properties, Durability, 5th Edition. S.Siegesmund, R.Snethlage (editors.). Springer, Berlin, 2014, pp. 107-224.

[15] F. De Quervain, "Technische Gesteinskunde. Lehrbücher und Monographien aus dem Gebiete der exakten Wissenschaften", Mineralogisch-geotechnische Reihe, Bd 1, Birkhäuser, Basel, 1967.

[16] R. Fort, M. Álvarez de Buergo, M.J. Varas-Muriel, M. Gomez-Heras, "Anisotropy indices and the effects on the hydric behaviour of natural stone", G.R.A. 12 (2010), EGU2010-6830-1.

[17] G. Forestieri, M. Ponte, "Evaluation of hydric behavior into porous building stones by means of Infrared Thermography (IRT)", Proc. of IMEKO International Conference on Metrology for Archaeology and Cultural Heritage, October 23-25, 2017, Lecce, Italy, pp. 269-273.