A THERMOGRAPHIC SURVEY FOR THE MONITORING OF MOISTURE IN POROUS STONE

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Abstract: In this work, infrared thermography was employed as a monitoring technique during water capillary rise tests on a choice of porous stones in the laboratory, as well as in situ on a cleaned porous stone surface of a historic building. While the emissivity values of the investigated materials were considered for the thermographic survey, other investigative techniques, such as mercury intrusion porosimetry and water sorption analysis for studying the stone in terms of their microstructure and isothermic behaviour respectively, were additionally used for the laboratory investigation on quarry samples. Results, such as water absorption coefficient and percentage, total porosity and isothermic behaviour were presented and discussed, in an attempt to explain the thermal images from the capillary rise tests. Furthermore, correlation between the thermal contrast and the imbibed water percentage for each sample obtained from the capillary rise tests was also presented in an attempt to show how powerful the action of water inside a porous stone is. Lastly, an in field thermographic survey on a cleaned historic stone surface, using a wet micro blasting method, was also carried out. Representative samples were collected from the investigated surface with the intention of studying their microstructure by means of mercury intrusion porosimetry and water sorption analysis.

Introduction: The infrared inspection of buildings for heat loss was one of the first commercial uses for thermography [1]. Since then, the use of infrared thermography in monitoring of buildings, monuments and large structures has been extensively and effectively used. Published work in the field of building thermography [2-5] has been carried out using both thermographic approaches. Qualitative, as well as, quantitative analysis (employing usually the active approach) has been attained. Together with the use of thermography in the inspection of electrical and mechanical installations, the building area is considerably acknowledged [6].

In this research study, infrared thermography was used for the assessment of moisture [7] in porous stones in the laboratory; their porous nature was also investigated in terms of their microstructure. Furthermore, their emissivity values [8] were determined in the laboratory and were considered for the interpretation of the thermal images obtained during monitoring of the water capillary rise tests. An in field thermographic survey on a cleaned historic stone surface, using a wet micro blasting method, was also performed. Characteristic samples were collected from the stone surface in order to examine their microstructure by means of mercury intrusion porosimetry and water sorption analysis.

Experimental: The emissivity values of the different types of stone were determined in the laboratory in accordance with the ASTM standard E1933–97 [9]. Batches of three specimens were measured using long wave infrared thermography (8-12 μm), at a temperature of 40°C. A non-contact thermometer (Gann IR40) was also utilised for confirming that the examined specimens were in a thermal equilibrium state while inside the chamber (Binder FD-115). The infrared thermographic system (Avio TVS 2000 Mk II LW) was then adjusted in order to determine the emissivity values of the examined stone. To overcome the problem of moisture (porous materials), the samples were first heated at a temperature of 70°C for a period of 24 hours and then were stored in a desiccator for at least two hours [10]. Description of the examined samples and their average emissivity values are shown in table 1.

Sample	Description of Sample	Average Emissivity Value (T = 40°C & λ = 8-12μm)
GPLSR	Grey porous limestone from the fortifications of the Medieval City of Rhodes, Greece	0.87
YPLSR	Yellow porous limestone from the fortifications in the Medieval City of Rhodes, Greece	0.81
WPLSC	White porous limestone from the Venetian fortifications of Heraklion in Crete, Greece	0.82
O-YPSP	Kapandritis Stone (fine-grained calcite) from the Bank of Greece historical building in Piraeus	0.71

Table 1: Description of investigated samples

Infrared thermography (Avio TVS-2000 Mk II LW, 8-12μm) was employed, for the monitoring of capillary rise tests on porous stones in the laboratory. The capillary rise tests were performed for the determination of the water absorption percentages and coefficients of the examined samples in a tank filled with ~3mm of water.
The water absorption coefficient was calculated as:

$$C = \frac{m_i - m_d}{A\sqrt{t_i}}$$

Where, according to BS EN 1925 standard [11]: C has units of $gcm^{-2}s^{-1/2}$, m_i is the successive masses of the specimen during testing (g), m_d is the mass of the dry specimen (g), A is the area of the side immersed in water (cm^2), and t_i is the time (s) of the absorption.
Given that water absorption tests by capillary rise determines pores with radii ranging from 10^{-3} to 10^{-7} m, additional techniques were utilised for supplementary results [7, 12]. Mercury intrusion porosimetry (range of pores from ~10^{-4} to 10^{-9} m) and water sorption analysis (range of pores from ~10^{-7} to 10^{-9} m) were also used. The first (2000 series porosimeter by Fisons Instruments), allowed the calculation of the total porosity, total cumulative volume, pore radius average, bulk density, and surface area. Each sample was submerged in a confined quantity of mercury and was tested up to a pressure of 1,800 bar. Sorption analysis was completed using a CISorp Water Sorption Analyser, under steady conditions of temperature (25°C) and pressure (1 atm), using the gravimetric method, across the range of 0 to 90% Relative Humidity.
An outdoor thermographic survey on a historic building porous stone surface was also examined. Due to the difference between the thermal diffusivities of moist and dry stones [7], infrared thermography was capable of imaging areas that presented qualitative variations in respiration behaviour (i.e. moisture impact), appearing as surface temperature fluctuations on the thermal image(s). The same thermographic system that was used for the laboratory tests was employed for the in field investigation.
Results & Discussion: The results obtained from the water capillary rise tests (i.e. imbibed water % and water absorption coefficient) are presented in table 2. Furthermore, water absorption curves of the investigated porous stones in the laboratory, along with representative thermal images of the samples, are shown in figure 1.

Sample	Imbibed Water (%)	Water Absorption Coefficient ($gcm^{-2}s^{-1/2}$)
GPLSR	8.21	0.0378
YPLSR	22.683	0.6057

WPLSC	9.533	0.0525

Table 2: Results obtained from the capillary rise tests

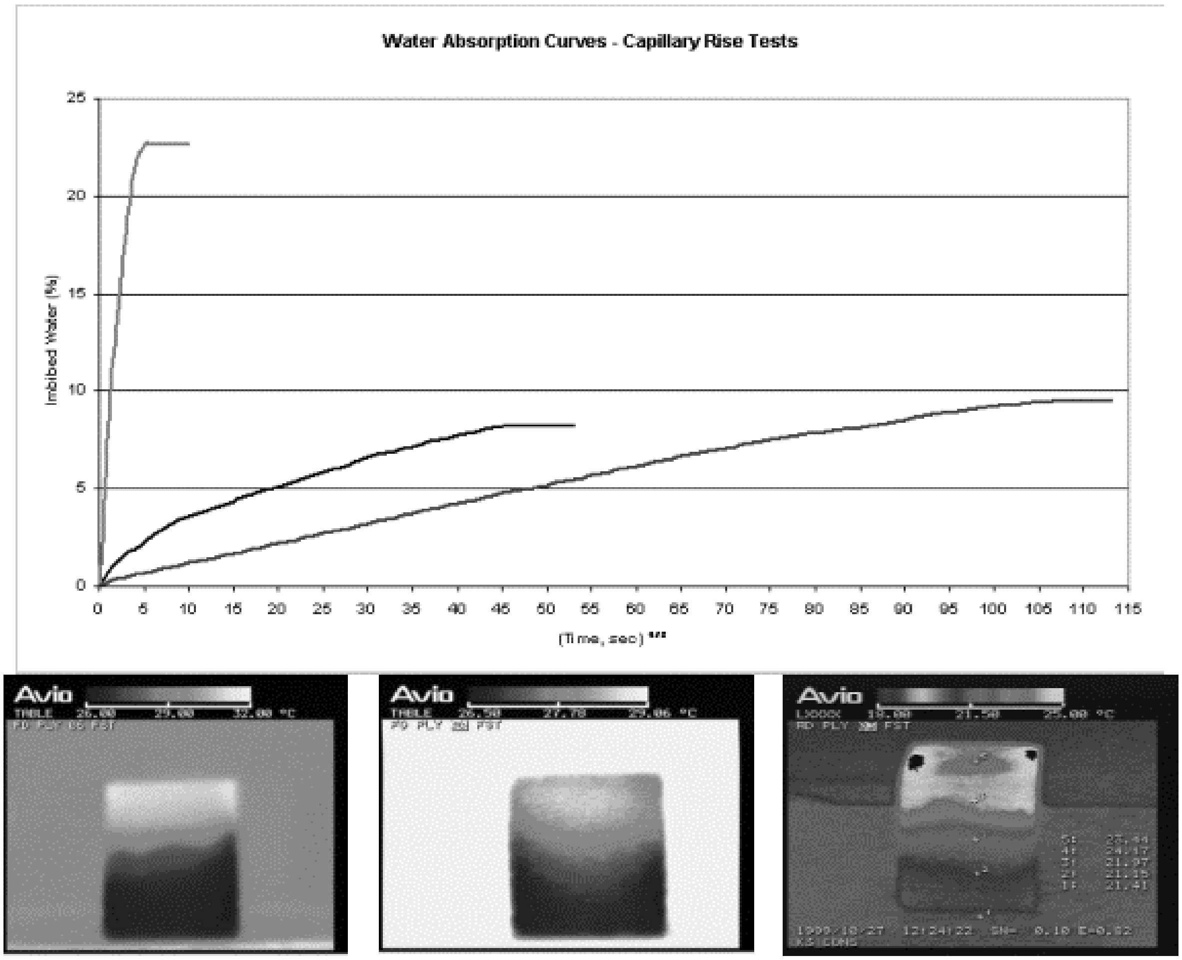

Figure 1: Water absorption curves and thermal images of examined porous stones

The investigated samples present a different behaviour as far as their capillarity is concerned. Although samples GPLSP and YPLSR are found in the fortifications of the Medieval City of Rhodes, they present a totally different behaviour. This is because of their separate origin (i.e. different quarry). The third examined stone, sample WPLSC, presented a relatively intermediate moisture % and a low water absorption coefficient. The presented thermal images show the influence of water inside a porous structure. Since water has a specific heat of approximately five times greater than stone, an area contaminated by water presents lower temperature values that can be detected by thermography.

The microstructural behaviour of the stones was further investigated with the use of the other techniques (i.e. mercury intrusion porosimetry and sorption analysis) as well. The results from the mercury intrusion porosimetry tests of the porous stones GPLSR and YPLSR (table 3) were in agreement with the results obtained from the capillary rise tests. In particular, they presented different total porosity values and surface area, while their pore size distributions graphs showed that YPLSR has large amounts of large pores, explaining in a way the high water absorption coefficient and percentage [7]. Sample WPLSC on the other hand, showed a large total porosity value (similar behaviour to sample YPLSR, but a similar surface area to sample GPLSR; nonetheless, the pore size distribution graph showed that WPLSC holds relatively more amounts of smaller pores. A representative pore size distribution graph (sample YPLSR) is presented in figure 2.

Sample	Total Cum. Vol. (mm^3/g)	Bulk Density (g/cm^3)	Porosity (%)	Pore Radius Average (μm)	Surface Area (m^2/g)
GPLSR	76.2	2.45	18.7	45.11	2.03
YPLSR	163.5	2.37	38.7	33.29	0.84
WPLSC	190.5	1.88	35.8	7.52	2.99

Table 3: Mercury intrusion porosimetry results

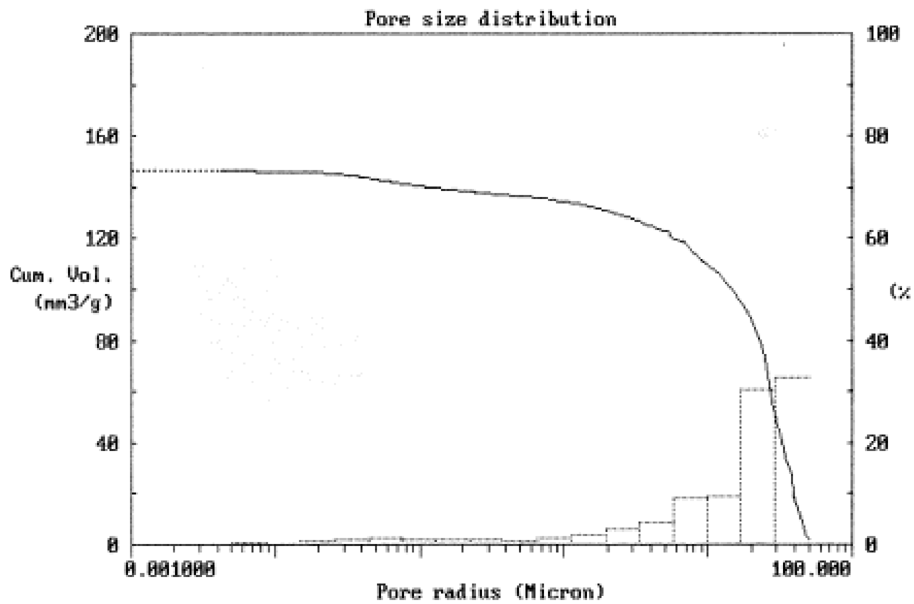

Figure 2: Pore size distribution of sample YPLSR

Since sorption analysis includes pores with radii from 10^{-7} to 10^{-9} m [12] the moisture contents that were observed from the curves reveal the affect of water – vapour condensation in porous stone. Sample WPLSC showed great moisture content due to the presence of smaller pores as already defined by the mercury intrusion porosimetry tests. The other two stones also presented predictable behaviour, i.e. moisture % according to their amounts of small pores detected by porosimetry. A representative isothermic plot (sample GPLSR) is presented in figure 3.

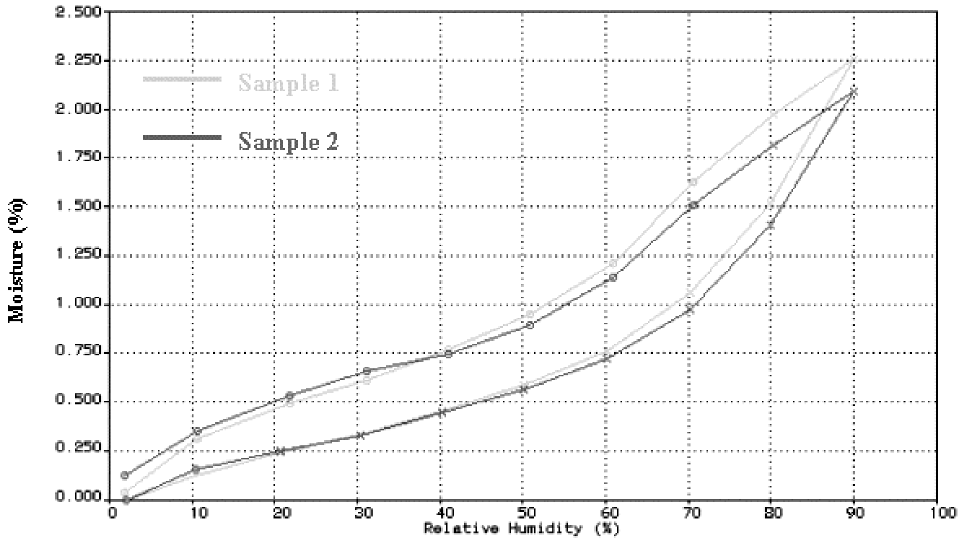

Figure 3: Isothermic curves of sample GPLSR

The overall belief is that moisture detection in a porous stone system is attainable by the use of thermography. Furthermore, thermography can monitor the water movement in a porous structure and detect its impact by recording temperature variations on its surface. In figure 4, the temperature differences (ΔT) that were obtained from the thermographic survey, along with the imbibed water percentage of each sample, after the completion of the capillary rise tests, are shown. This indicates how powerful the action of water inside a porous stone is.

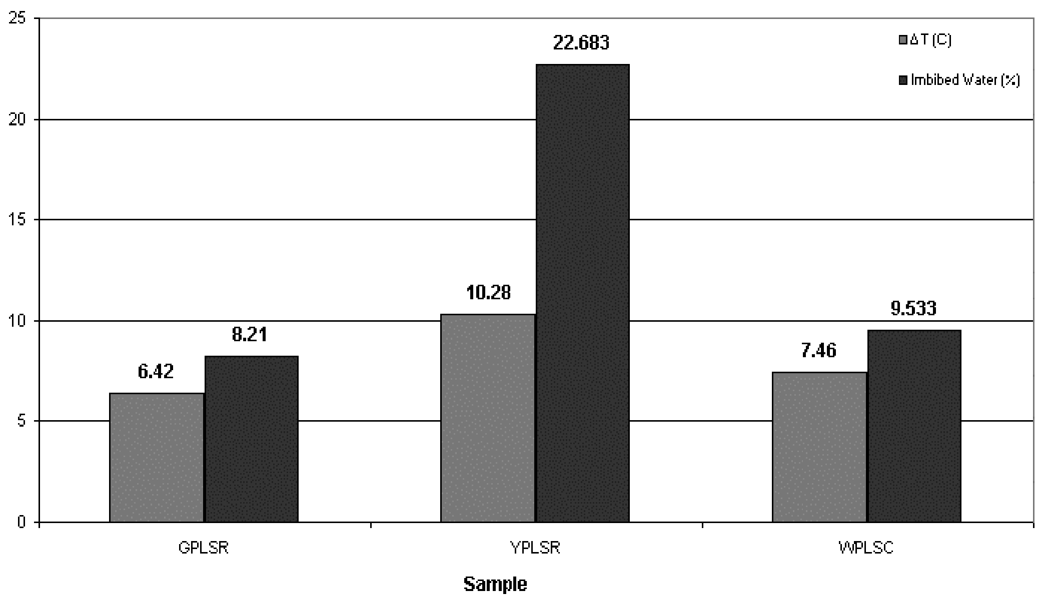

Figure 4: ΔT and Imbibed Water % of investigated porous stones after the capillary rise tests

For the outdoor thermographic survey, infrared thermography was employed with the intention of evaluating the morphology and moisture withholding on a selective architectural surface (figure 5) after a wet micro blasting cleaning application [13]. A porous stone surface (Kapandritis stone) at the Bank of Greece Historic Building in Piraeus was investigated. The applied cleaning intervention was a wet micro blasting method where spherical particles of calcium carbonate, with diameter lower than 80μm, were springing with a maximum function pressure of 0.5 bar on the architectural surface.

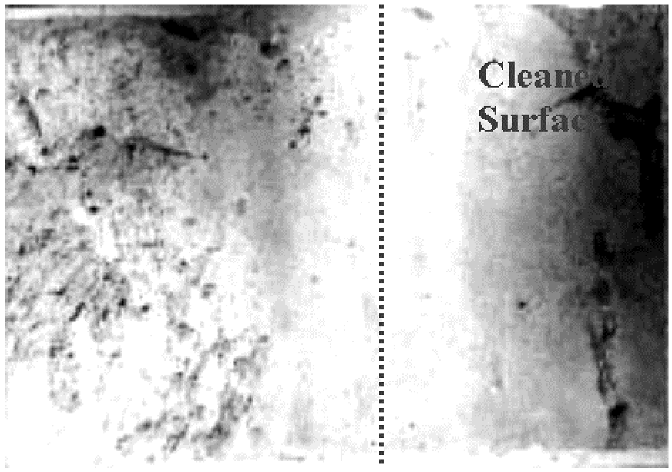

Figure 5: Photograph of investigated surface at the Bank of Greece historic building in Piraeus

In the thermal image, presented via the histogram, at the Kapandritis stone surface at the Bank of Greece Historic Building in Piraeus (figure 6), the cleaned surface is presented on the right hand side, whereas the left side presents the untreated area of the stone. Despite the fact that the cleaned surface – moisture withholding is on the right hand side of the thermal image, cold areas on the upper left side of the image were also detected. This is due to the capillarity movement of water inside the porous stone.

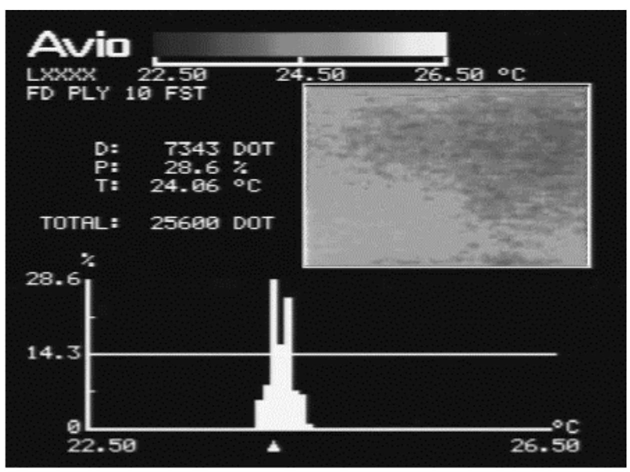

Figure 6: Histogram of Kapandritis porous stone surface at the Bank of Greece historic building in Piraeus

The histogram also reveals quite tight temperatures distribution of the examined surface, indicating temperature consistency at the porous stone surface. Nonetheless, the moisture transfer through the pores from the cleaned to the untreated area of the stone demonstrates the improperness of the applied cleaning method for this specific material and application, but nonetheless indicates how thermography can detect moisture movement inside a porous stone.
The results from the microstructural investigation on samples that were collected from the surface are presented in table 4 (porosimetry results) and figure 7 (sorption analysis). The microstructural study indicated focal variations in pore size distributions, i.e. large amounts of micro, medium or

macro pores were observed among the examined samples. Furthermore, the presence of macropores can be attributed to salt crystallisation decay, since the historic building is exposed to an aggressive marine environment. For this reason, the active to total porosity ratios (P_{act}/P_{tot}), which give an indication as far the susceptibility of the stone to salt decay is concerned, were calculated. Usually, when a stone has a large ratio (i.e. > 50%) it presents great susceptibility to salt decay [14]. Table 5 shows the ratios of the examined samples.

Sample	Total Cum. Vol. (mm^3/g)	Bulk Density (g/cm^3)	Porosity (%)	Pore Radius Average (μm)	Surface Area (m^2/g)
O-YPSP1 before cleaning (P_{tot})	14.1	2.59	3.6	0.18	0.78
O-YPSP2 before cleaning (P_{tot})	8.8	2.57	2.3	0.03	0.49
O-YPSP1 after cleaning (P_{tot})	29.5	2.56	7.5	0.26	0.55
O-YPSP2 after cleaning (P_{tot})	43.1	2.40	10.3	0.25	0.60
O-YPSP1 before cleaning (P_{act})	6.4	2.59	1.7	0.02	0.36
O-YPSP2 before cleaning (P_{act})	3.4	2.57	0.9	0.04	0.16
O-YPSP1 after cleaning (P_{act})	16.0	2.56	4.1	0.33	0.26
O-YPSP2 after cleaning (P_{act})	27.6	2.4	6.6	16.77	0.30

Table 4: Mercury intrusion porosimetry results of Kapandritis stone

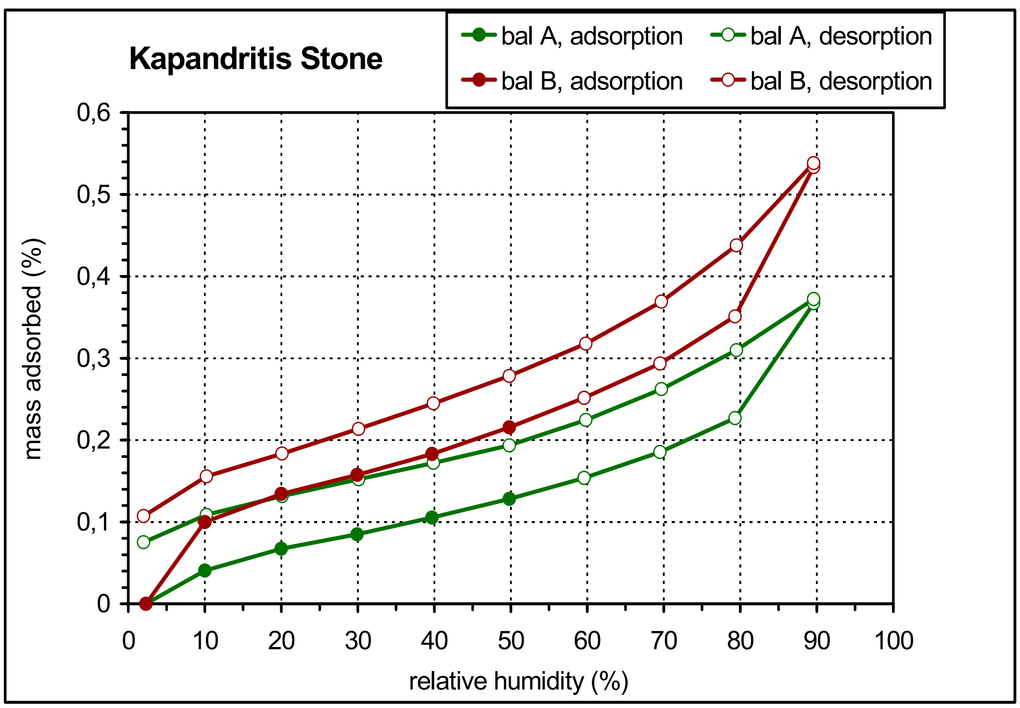

Figure 7: Isothermic curves of Kapandritis stone samples

Sample	**P_{act}/P_{tot} Ratio**
O-YPSP1 before cleaning	47.2
O-YPSP2 before cleaning	39.1
O-YPSP1 after cleaning	54.6
O-YPSP2 after cleaning	64.1

Table 5: P_{act}/P_{tot} Ratios for Kapandritis stone

Finally, it is also worth mentioning that mineralogical and other analysis techniques were used for the investigation of this type of stone [15]. It is therefore a near-future aim of the authors to investigate the Kapandritis stone in terms of capillary rise tests, isothermic behaviour and by means of mercury intrusion porosimetry on quarry samples that will be acquired from the Kapandritis area in Attica, Greece.

Conclusions: In porous stone, the presence of moisture that arises as a result of capillary movement, water sorption and condensation can initiate important signs of deterioration. The results of this work indicate that water detection in porous stone by means of infrared thermography is feasible due to the difference between the thermal diffusivities of dry and wet areas. The advantages of the technique are that it investigates rapidly large areas, i.e. historic buildings, for moisture assessment in a qualitative procedure and that it gives straightforwardly interpretable results. Its disadvantage is that its indisputable success is also dependent on the microstructural characteristics of the investigated stone, which means that laboratory experiments, as in this work, must be prearranged prior to in field surveys. Nonetheless, thermography should be considered as an important NDT & E approach for the monitoring of moisture in porous stone.

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