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Infrared thermography analysis of the ancient soapstone quarry in Chiavenna

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Abstract

The research aims to characterize the thermal behavior of a rock mass forming a little hill at the confluence of two glacial valleys in the Italian Alps, known since centuries for the particular warm microclimate and its botanical-archeological park. The characterization from a thermophysical point of view is done both with laboratory tests exploiting infrared thermography coupled with petro-physical characterization and in the field long term thermographic survey. Methods based on infrared thermography allowed to measure thermal diffusivity, conductance and specific heat. The measurements aim also to evaluate the use of thermographic methods for the early detection of falling rocks and to study the characteristics temperate local microclimate.

1. Introduction, an overview of the studied area

Thermographic analysis is more powerful when a mathematical model for heat diffusion inside the inspected solid structure is assumed, but to obtain specific indications on the way infrared images must be recorded (frequency, spatial resolution, time) it is necessary perform specific tests on the materials of which the object of study is made [1].

As well thermographic testing is widely used to analyses inner structures of both building and rocky wall in architectural [2], archaeological [3] or geophysical applications [4,5], many variables, including optical non homogeneity and thermal characteristics, make these applications still difficult. They can be partially overcome by selecting the appropriate heating method or to exploiting the natural ones. Choosing these last as similar as more possible to the ones that allow analytical solution the use of approximate solutions of the heat diffusion models allows the determination of heating procedures in order to obtain thermal images representative of the inner parts of the wall. Some authors developed methods of dynamic thermography for the analysis of discontinuities based on the study of the dynamism of heating and cooling processes [2]. The results show that some problems applying the thermographic procedure to wide surfaces are still present.

Valchiavenna extends into the Central Alps, at the north of Como Lake in northern Italy up to the Swiss boundary, and includes the territory crossed by two valleys: the Val San Giacomo NS directed, and the Val Bregaglia EW directed, both tectonically controlled and remodeled by glacial processes. These characters make it a study area of particular interest both for its centrality in the Alpine arc and for its geological and geomorphological representativeness. The studied site is located within the city of Chiavenna, in the archaeological and botanical park known as “Parco Paradiso” where plant biodiversity, geomorphology of the Alpine environment, archeology and history of the technological tradition combine in a museum and naturalistic educational path. The Park is included in the natural reserve of the "Marmitte dei Giganti". Inside the park, there is a trench quarry, developed since the Roman age due to the extraction of soapstone which has boosted for centuries the local economy. In fact, the extraction, processing and trade of lithic materials suitable for various types of use is strongly rooted in the local culture. The outcropping rock belongs to the ultramafic body of the Chiavenna Unit, characterized by a wide local lithological variability, from peridotite to chlorite schist, with calc-silicate boudins and talc schists, the latter exploited for soapstone extraction. Few mechanical joints interrupt the continuity of the rocky mass, that for most of the outcropping, is of high- medium mechanical quality.

As concerns its thermo-mechanical behaviour, qualitatively the soapstone has characteristics intermediate between stone and metal, showing properties of both materials. The almost total absence of pores makes this stone practically unwettable it shows a metal-like high conductance but a high degree of thermal capacity.

Inside the park a botanical garden includes numerous plant species some of which are normally found in a Mediterranean climate. It is not unlikely that the particular microclimatic conditions of the park derive precisely from the heat accumulation properties of the soapstone hill, which has large surfaces of vertical rock facing south, making the absorption of solar radiation optimal, particularly in the winter months [6]. The dimensions of the hill, 140 x 200 meters, 50 m high, and the particular orography of the alpine valleys place these particular situations outside the scale grid of meteorological models. Under these conditions, only the study conducted at the local level can lead to highlighting particular phenomena of thermo-resistance of the territory that could be applicable on a larger climate model for the understanding of climatic phenomena at the macroscale level.

With these premises, the research develops through different phases on laboratory an in field. The preliminary phase of this research has been the study of thermo physical characteristics of the soapstone intact rock. So, we present here the main work at a laboratory scale on a series of cores, drilled from both sides of the quarry. The artificial heating has been planned to be as uniform as possible to approach the ideal case of the semi-infinite solid of homogeneous and isotropic materials. The results obtained in this phase allowed us to plan the phase of on the field survey that will end in 2022 winter.

Fig. 1. *View of the soapstone quarry trench in Chiavenna - Italy. The canyon is due to the secular working of excavation of local population.*

2. The use of thermography for natural and artificial wall inspection

Most difficulties in thick wall analysis are due to the heat diffusion inside the materials, often characterised by low thermal diffusivity. The walls of ancient buildings and statues on which the research group has worked for years [1,8,9] are normally more than 300 mm thick and allow to consider for medium time heating (minutes) as semi-infinite solid [7]. The case of rocky wall isn't so far from this rude approximation. Infrared thermography is not easily applicable for investigating the inside of both masonry and rocks in such conditions because of the difficulty in obtaining thermal images representative of the temperature distribution in the nonhomogeneous inner layers. The heat transfer has to be as one-dimensional as possible and perpendicular to the surface. Geomaterials like stones and, similarly, solid bricks have a low thermal diffusivity of 10^{-6} to 10^{-7} m^2/s so the heat penetration requires a long time to obtain a returning signal at the surface that could be detected by infrared thermography. Moreover, the superficial inhomogeneity, like as stains or vegetation, modify the heat transfer from the surface to the inner zones and from inside to the surface during the cooling phase. Nevertheless, infrared thermography testing is improved by the analysis of a proper mathematical model of the structure in the preliminary phase of study. The mathematical model of heating, even if it is simplified, has to take into account the thermal and optical characteristics of the materials, which determine the surface temperature and the actual in situ environmental conditions. In the approximation of a semi infinite isotropic plate the problem is to fix the superficial temperature or the incoming flux of energy working on experimental conditions, in this case it's possible to get the relative solutions for homogeneously structure with thermal diffusivity assumed to be equal to that of a sample drilled out from the quarry wall. As a rock mass joint has thermal behaviour different from the intact rock, the active thermography appropriately identifies different elements of the wall and the technique allows for the detection of the presence, persistency and, in certain conditions, the opening features of joints. For outdoor wide areas heating by artificial radiation has been excluded. But in some cases solar loadings can be considered as constant flus heating.

2.1 Lab test in simplified heat transfer conditions

A preliminary phase of laboratory tests was carried out on a set of cores in order to determine:

- Thermal characteristics of local soapstone
- The correspondence between the proposed heat transfer models and the actual phenomenon
- The influence of boundary conditions (convection exchange, lateral diffusion) in one-dimensional heat diffusion assumptions.

Lab tests were carried out in order to verify the approximation done. A heating plate (40x 20 cm) with power of about 25 kW/m^2 was used to control the temperature on one side of the core and the spread of the heat was observed by means of a termocamera on the perpendicular side (fig. 2).

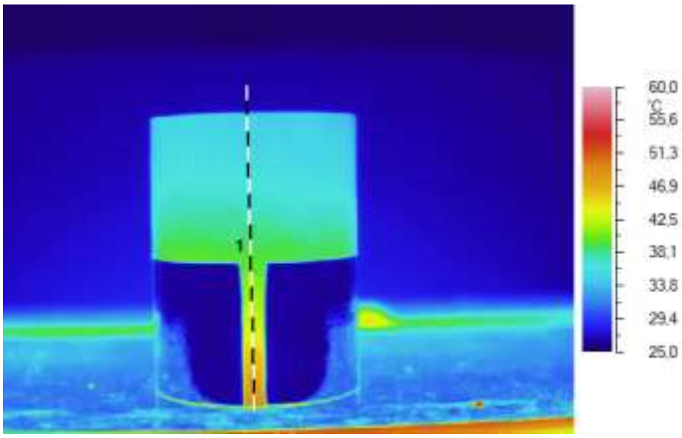

Fig. 2.*: One of the soapstone core during the heating by warm plate, colder sides of the core are covered by an aluminium tape that reduce emissivity and lateral heat dissipation. During the test the steel plate was covered by a fiberglass insulator mat in order to reduce the convection by hot air raising (80°c).*

The well-known solution of the heat transfer equation [7] had been used to fit the experimental temperature data as functions of distance x from the heated surface and time *t* of the semi-infinite solid (eq. 1) in the case of superficial temperature Ts constant. Figure 3 shows the temperature along a vertical profile at different time. Lasting the total test 600 seconds after about 300 s a remarkable raise (+ 0.15°C) in temperature has been observed at the top of the core and so data have been considered no more significant for the analytical solution given by eq. 1.

$$T\ (x,t) = T_s + (T_i - T_s) erf\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{1}$$

2.2 Models for the on Field Application

Contrary to what happens in lab tests, heating in field conditions can occur by solar loading with a supplementary increase in environmental air temperature. In this case, the heating was obtained through direct solar irradiation. In order to estimate how deep it is possible to investigate inside the quarry wall and the time required to reach it, we therefore used the well-known expression to determine the evolution of the temperature inside the wall in case of constant flow heating Q [7]. In eq. 2 is reported the solution for the superficial temperature T(x=0, t). In our case the direct insolation for the stone absorption coefficient (about 500W/m^2).

$$T = T_0 + \frac{Q2\sqrt{\alpha t}}{k\sqrt{\pi}} \tag{2}$$

Where k, thermal conductivity was measured by evaluating the time required for heating in transmission obtained with very intense (4000 W/m^2) and uniform halogen lamp irradiation on thin cores (20 mm).

3.2 Laboratory results

Thermal, optical (spectral LW emissivity and VIS-NIR reflectance) and elemental (XRF) analyses have been performed in laboratory on samples with different sizes obtained from six cores (75 mm diameter, different thickness around 100 mm) drilled from both sides of the quarry. Analyses have been planned on several slices from the same core to evaluate the variation of the properties from the rock surface, exposed to secular weathering, to the inner part of the rock until a depth of 25 cm corresponding to the maximum deep of drilling.

The thermal conductivity and specific heat have been measured using different methodologies (mixing calorimeter and constant heating). The results obtained (4.9±0.18 W m^{-1} K^{-1} and 0.908±0.008 J g^{-1} k^{-1} respectively) are comparable to those reported in technical literature of the same type of rock for Finnish deposits [10].

From data shown in figure 3 we stress that the core thickness and the rapidity of the heat propagation in this kind of material are high enough to justify the approximation of a semi-infinite solid in the experiment only during the first 5 minutes in our experimental set-up.

Figure 3 does not resemble the representation of a propagation of heat with constant surface temperature, in fact the starting point (lenhght = 0) evolves over time. Actually the 0 position refers to the 0.386 mm height of this core, that represents the first pixel clearly attributable to the stone sample and not to the discontinuity, in term of emissivity, of contanct layer with the warming plate. Our strong assumption that the contact temperature is maintained at the plate setted temperature (T = 80°C) has been attributed to the central part of the disc in contact with the heated plate and not observable at the edge on view.

Lateral heat loss for convection is negligible with respect to the heat flux inside the core. This method allows the determination of a thermal diffusivity value of 2.0×10^{-6} m^2/s with an incertitude of 1×10^{-7} m^2/s (mean over the values obtained by the best fit at different times, 10, 30, 60, 90 and 150 s), which is close to the only value found in literature [10].

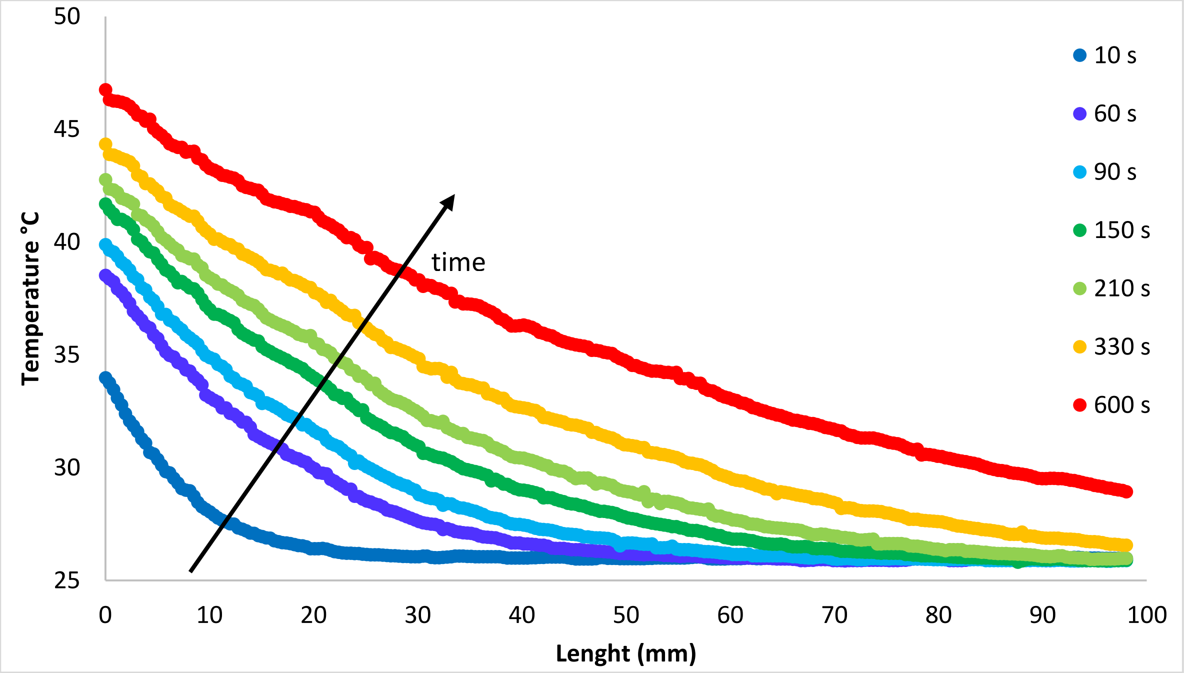

Fig.3 *Temperature evolution along the vertical profile showed in figure 2 for 10, 60, 90, 150 210, 330 and 600 seconds. Data recording rate: 10 s, the 0 position refers to the 0.386 mm height of the core, the first pixel clearly attributable to the stone sample. This is due to the strong discontinuity of the data present in the first layer in contact with the plate.*

3.3 In situ measurements and early detection

The geometry of the quarry is particular: very narrow and north-south oriented and therefore with the parts exposed only for a few hours during the morning (the west part) and a few hours after noon the east wall respectively. These conditions made it possible to consider solar radiation as a constant and short duration impulse in time.

By using the same type of modeling but assuming a constant flow of heat, that due to insolation, the time necessary to obtain a signal distinguishable from the background noise coming from a depth of 80 mm was estimated. With the experimental values found in the laboratory tests, a time of about two hours was found to be sufficient for the soapstone wall inspection. This increase is enough to produce a signal on the surface detectable by thermography when reflected by the presence of a discontinuity inside the rocks in order to put in evidence the detached shield of rock otherwise not easily detectable from long distance observation of operator.

In-situ thermographic acquisitions are currently on the way by means of two LW microbolometers. The first one collects thermograms over the whole eastern wall of the quarry every two months for at least two consecutive days at three different times of the day (9:00, 13.00, 17:00); from these data it is possible to map the areas of the rock walls of the quarry subject to stronger thermal stress. The second instrument is dedicated to the monitoring, with 72-hour-long cycles, of a few-square-meters-large shield of rock on the western wall, which is suspected of possible detachment.

Figure 6 shows a thermogram acquired at 15:25 PM on March 29 2022 on the western wall of the quarry depicting a fractured area which can be identified by the dark V on the right enhanced HDR thermography obtained from the sequence of that day.

HDR images in visible photography are realized from a series photographs taken with different exposure settings [11]. This series of photographs are combined into a single HDR image, which represent an extended range of the luminances present in the scene. In this work the HDR thermal images were obtained in a different way from that described for the visible [12]. The issue in thermal imaging is to enhance the ability of the thermal camera to fully span a scene with an extended range of infrared emissions [13]. To achieve this, the range of the thermal scale of a single grey level thermal image was adjusted to improve the visibility and the contrast of the thermal features in the scene. The procedure was repeated considering equal and subsequent temperature ranges so as to cover linearly the entire thermal range present in the scene. A set of 3-images, in this case, was obtained by thresholding the different featured areas and combining them into one single gray level image with a specific temperature scale as shown in Fig.6 (right image).

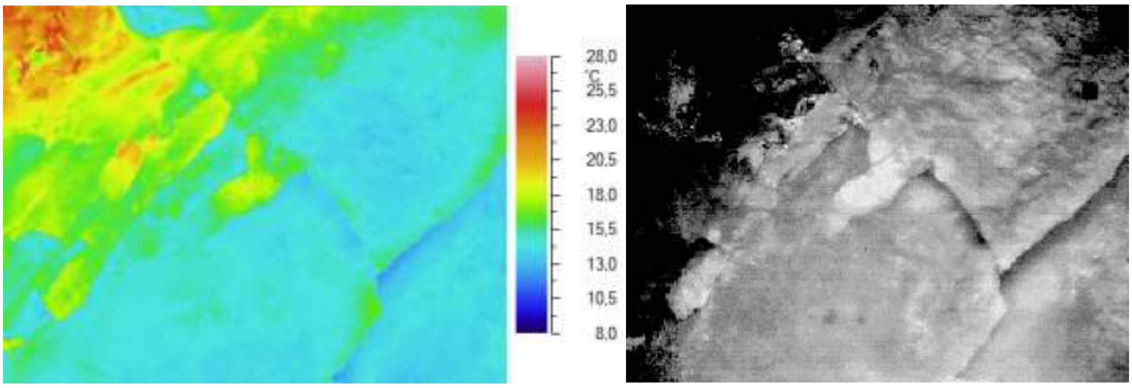

Fig. 4. *Left: thermogram during maximum insolation and, right, HDR thermography of western wall putting in evidence two major line of fracture of the upper part of the rock.*

3.4 Elemental analysis

XRF analyses on core drillings were made considering 10 slices, referring to different depth of the coring, out of 8 core samples (; for each considered slice, 4 measuring point were chosen near the edge of the flat surface at the four "cardinal direction" of the slice, for a total of 40 spectra.

The X-ray source used was MINI-X2 X-ray tube (Amptek, Bedford, MA, USA) with a maximum power of 4 W (50 kV, 200 µA) and a transmission rhodium anode. The X-ray detector was a complete SDD spectrometer (XGL-SPCM-DANTE-25 model) from XGLAB Bruker Nano Analytics, with 17 mm^2 active area, 500 µm thickness and 12.5 µm Be window.Working parameters were 40 kV and 0.06 mA, with an acquisition time of 200 s. The main element detected were Fe, Ni, Mn, Cr, Ca,Ti, K and Zn; net counts of Kα line were calculated normalised to the net counts of Rayleigh scattering of Rh (20.022 KeV). The mean values obtained for each slice show that the average composition is constant when considering various depths.

4 CONCLUSIVE REMARKS

The main limit in using thermographic technique is due to short penetration of heat in geomaterials; this reduces the monitored thickness just to few centimetres. Another limit is related to the ease of use of this technique; a thermographic shot of a natural surface always shows thermal anomalies and it's necessary to study simple heat diffusion models in order to find out the ones related to the inner structure and those to the surface characteristics such as vegetation o stains. It's the operator who has to find the best experimental environment to make the pathology visible in thermographic analysis. Following these considerations we included some experimental cases.

The research investigates both the thermophysical properties of the particular type of rock (soapstone) known for centuries for its particular thermal properties and the microclimate of the whole hill. Soapstone is a very interesting material of historical interest and appears widely commercialized in the pre-industrial world [16], however only a few studies have dealt with characterizing it from the point of view of its macroscopic features.

The first aim of the research is to characterize the lithic material from a thermophysical point of view both with laboratory tests and field surveys. Measurements of thermal conductivity, specific heat, and specific weight have been performed with traditional methods, whereas thermal diffusivity is estimated by applying simple analytical solutions of heat diffusion equation in constant flux heating condition [1,3].

The second purpose is to develop monitoring set-up for the early detection of falling rocks. The thermographic campaign lasting a year follows seasonal change in solar loadings in order to determine both the duration and intensity of this natural heating for the safety purpose. Passive IRT has been recently utilized for the identification of open cracks, loosened rock zones, fractures and failures, unstable cliffs, and pseudo-karst caves in rock slopes using both unmanned aerial vehicle and hand-held instrumentation [14,15,17].

Finally, the third goal is to identify the environmental characteristics that have allowed the development of the characteristic temperate microclimate, thus providing an important case study in the context of current global climate change.

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