Journal of Cultural Heritage 16 (2015) 113–118

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Case study

Microclimatic monitoring of a semi-confined archaeological site affected by salt crystallisation

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ARTICLE INFO

Article history:
Received 16 September 2013
Accepted 4 February 2014
Available online 4 March 2014

Keywords:
Microclimate
Semi-confined environment
Archaeological site
Salt crystallisation
Sodium sulphate

ABSTRACT

The aim of the research is to investigate the role of the microclimatic conditions and their variations on the decay due to salt crystallisation, observed in a semi-confined archaeological site, in an urban area. A microclimatic monitoring was carried out in the site to detect temperature and relative humidity and their respective variations. Statistical methodology was conducted to examine the microclimatic data with seasonal, monthly and daily analyses. Different zones of the site were monitored and a microclimatic zoning was detected. The outside environment influences the most external zones of the site, while in the confined ones a high relative humidity was detected in all the seasons. The comparison between the hygrothermal conditions monitored in the site and those thermodynamic favourable to salt crystallization revealed a very harmful risk of salt damage for the archaeological structures.

1. Research aims

The archaeological structures are very vulnerable with respect to changes in microclimate. Often shelters are used for their protection to mitigate temperature variations, wetting-and-drying cycles and wind velocities as in [1]. However, if shelters were not prudently designed, they can cause conservation problems both for microclimatic changes [2–4] and compatibility with the archaeological materials [5–7]. Shelters create a semi-confined environment, so far little investigated [8], that does not prevent exchanges of matter and energy with the outside thus allowing the transport of pollutants [4] or other effects like greenhouse effects [3,4]. Shelters can cause problems especially when they were built with cementitious materials in a polluted environment in which the formation of soluble salts is an usual phenomenon [6,7].

In order to assess the implications of the microclimatic variations on the decay due to salt crystallisation of an archaeological site located in a semi-confined environment, a campaign of microclimatic monitoring and a statistical elaboration were carried out.

2. Introduction

Temperature changes cause differential stress in the materials, especially in those more susceptible, like archaeological structures [9]. If the temperature drops, freeze-thaw cycles can occur in porous materials which have a critical saturation degree [10]. A high humidity is responsible for the deterioration of a lot of materials such as wood and paper but also stone in which the risk of biological attack can be produced especially when associated with $T > 20\,^{\circ}C$ [9]. When high humidity is combined with pollutants, it may favour certain chemical reactions, such as the transformation of marble in gypsum [11,12] and also salt crystallization [6]. Microclimatic changes may favour the transport of pollutants through thermophoresis, diffusiophoresis and Stefan flow [13]. In particular salt crystallization in porous building materials is one of the most important agents of decay in historic monuments and archaeological sites [14,15]. A high ventilation enhances the evaporation of the aqueous solutions promoting the growth of subflorescences inside the stone pores [16–18] with potential damage of porous materials, according to Everett's law and its derived relationships [19,20]. The variations of hygrothermal conditions can cause condensation-evaporation cycles with a consequent migration of dissolved salts and recrystallization elsewhere [9,10]. Alkaline sulphates are very dangerous salts and they can be found in the presence of cement, used very often in restoration work during the 19th and 20th centuries [21,22], especially in a polluted atmosphere. Sodium

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http://dx.doi.org/10.1016/j.culher.2014.02.001

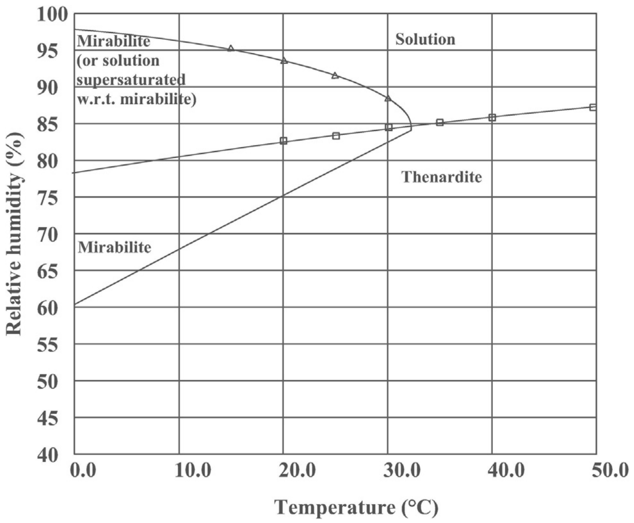

Fig. 1. Phase diagram for sodium sulphate. The continuous lines indicate the boundaries of the stable phases. Triangles and squares are experimental data for mirabilite and thenardite, respectively [23].

sulphate, used in salt crystallization tests [16,17,23], can crystallize in different forms, depending on hygrothermal conditions that are established. The anhydrous phase Na_2SO_4 (thenardite) precipitates directly from a solution over 32.4 °C and 84% RH while the hydrated phase $Na_2SO_4 10H_2O$ (mirabilite) under 32.4 °C and 84% RH (Fig. 1). If many fluctuations of hygrothermal conditions take place, many phase transitions of the sodium sulphate can occur. Following these fluctuations, high damage can be caused to porous stones by the development of high crystallization pressures [16,23].

3. Materials and methods

3.1. Description of the case study

The case study is an archaeological site located in Cagliari (Sardinia, Italy); it is a multi-layered complex dated from the Republican Roman period until the Middle Ages [24].

The area is characterized by the presence of the remains of walls built with limestone blocks enclosing rectangular areas (Fig. 2). The lithotype used for the archaeological structures is the so-called *Pietra Cantone*, a biomicritic limestone, very similar to *Lecce stone*, part of the *Cagliari Limestone formations* [25,26]. This lithotype is not very compact and it is easily alterable; it is very porous with a porosity between 30–35%, with pores mainly concentrated in the range of $r = 0.1$–$5.0\ \mu m$; there are also pores with $r > 5.0\ \mu m$ and, to a minor extent, with $r < 0.1\ \mu m$. This microstructure is likely to favour the phenomenon of salt crystallization as suggested by Everett's law and its derived relationships [19,20,27]. This lithotype is very sensitive in the presence of water, in fact its mechanical strength is 10.1 MPa in dry samples and decreases to 5.4 MPa in wet ones [28].

The archaeological site was discovered in 1985 during works to construct an office building and in 1987 a concrete roof was erected on the archaeological structures in order to use the area above as a car park [24]. This created a semi-confined environment because, on both sides of the site, there are pillars with openings which allow exchanges of materials and energy with the outside (Fig. 2).

After the excavation, the area was abandoned and no maintenance was done on the car park for more than twenty years.

In 2010, work for the conservation of the area was carried out. Both the concrete roof and the limestone structures were in an alarming state of decay with debris and cracks on the cement ceiling and pillars, but the most dangerous decay was due to salt crystallization and the consequent pulverization and detachment of materials. A successive excavation to clean the area from the debris was carried out. Cleaning campaigns to remove salts from the structures were also performed with the application of sepiolite-cellulose pastes. In 2012, a false ceiling to block the infiltration from the ceiling was built but, despite this conservation operation, the dangerous decay persists, the structures show a strong pulverisation and are totally contaminated by salts. In fact the source of moisture that produced the stagnation of water coming from outside and the source of salt crystallization was not removed and water can enter the site through the openings, from the cistern and probably for capillarity from the ground. The pillars and walls are totally contaminated by salts which could damage the archaeological structures. The main salt contaminating the archaeological structures and the modern concrete has been recognized, by X-ray diffraction, as sodium sulphate [27]. Furthermore, from the survey conducted in 2012, a differential decay inside the site appeared (Fig. 2): the structures closest to the openings showed the greatest damage with intense phenomena of pulverization, detachments and a little thickness of efflorescences, while in the most confined ones there was only dust, very thick efflorescences and no detachment phenomena [29]. The microclimatic monitoring was carried out in order to study the effect of the hygrothermal variations on the decay due to salt crystallization and to understand how the observed decay is correlated to the microclimatic zoning.

3.2. Methods

The microclimatic monitoring was performed for five months (from February to June 2012) in order to have a representative period in which hygrothermal seasonal variations can be investigated. It was carried out using eight miniaturized data loggers. They were positioned in different points inside the site (Fig. 2): next to the structures with the greatest value (the mosaic, point X), next to the openings (points Y) and in the zones in which the efflorescence phenomena were most evident (point Z).

Data loggers allow us to measure continuously the air temperature and relative humidity. They were placed at least 1 m from any source of direct radiation and not directly exposed to air draughts. They constitute a fully integrated system with temperature (thermistors NTC 10k) and relative humidity sensors, signal conditioning, digitization and registration. The measurement field of sensors is −25 °C ÷ +85 °C for temperature and 0% ÷ 95% for relative humidity, with accuracy of ±0.2 °C in the range between 0 °C and 70 °C and ±3.0% RH at 25 °C for relative humidity. The data were acquired every half an hour.

A climatic station was placed outside to monitor the external temperature and relative humidity every five minutes. The measurement field of the station is −40 ÷ +65 °C for temperature, with accuracy of ±0.5 °C and 3% for relative humidity.

The data from the data loggers were elaborated by statistical methods using a spreadsheet. Seasonal, monthly and daily analysis were carried out in order to understand the relative variations of T and RH and their implications on salt crystallisation. For each data logger a seasonal analysis was performed. Thermo-isoplets and hygro-isoplets are useful to show the possible microclimatic zoning and the differences between the outside environment and the site. The hourly mean monthly values were calculated and put in a diagram with months as the X-axis and hours as the Y-axis. Areas of different colours represent the average temperature and relative humidity.

The implications of daily and monthly variations of temperature and relative humidity on salt crystallisation in the structures were evaluated calculating the number of the probable phase transition that can cause high stress in the material [16,17,23]. The couples