Preventive conservation of the pictorial evidence in the church of Sotterra (Paola, Italy): a microclimatic investigation in a hypogeum environment

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***Abstract* – The conservation of subterranean sites is an issue that poses hard questions, several of which are nowadays still unanswered. In the field of preventive conservation, microclimatic investigation is fundamental as it allows to examine the interaction between environmental conditions and degradation phenomena which occur on the artifacts. In the present study, a nine-months microclimate campaign was conducted inside the church of Sotterra in Paola, in the province of Cosenza (Calabria, Italy). The church, today located six metres under the ground level, represents a unicum since, despite its current location, it was originally built at ground level. The presbytery area preserves important mural paintings which date back from 11th to the 15th century which suffer severe damage due to extreme environmental conditions. The results already obtained from the diagnostic campaign of a previous work have been combined with the thermo-hygrometric values in order to assess the conservation risks of the pictorial evidence.**

I. INTRODUCTION

Subterranean sites, such as catacombs, caves, hermitages, crypts and tombs, are characterized by peculiar environmental conditions which might determine the onset of severe degradation phenomena on the artworks inside the underground space. Their genesis is controlled by humidity and temperature parameters which cause physical-chemical and biological deterioration mechanisms. In the hypogeal sites, high values of humidity values (about 80% and sometimes exceeding 90%), and stable temperatures (between 9°C and 14°C) are generally recorded in temperate zones [1]. According to the literature, even if the maximum water content that masonry can tolerate ranges between 3 and 5 % [2], in the case of subterranean structure the amount of water increases considerably, bringing to swelling, crumbling processes and finally to the formation of lacunae. In addition, moisture is able to convey soluble salts into the porous structure of the wall, leading to crystallization/dissolution cycles under specific thermo-hygrometric conditions [3,4]. Furthermore, the presence of liquid water on surfaces encourages the growth of algae, bacteria and fungi which in the hypogea environment find the optimum conditions for their proliferation [5]. The precarious environmental equilibrium might also be altered by external influences, related to the heavy flows of visitors, the artificial light sources and the air drafts coming from outside which suddenly cause thermo-hygrometric variations and contribute at increasing the crystallization and biodeterioration risk [6]. Moreover, the integrity of the mural paintings preserved inside the subterranean sites has been threatened by past inappropriate restoration interventions, carried out with improper methodologies and materials. It was not uncommon, in the past, the use of cement plaster to restore the material integrity or to prevent the collapse of the paintings. Furthermore, the application of organic polymers for conservation purposes not only caused chromatic variations of the pictorial film but also created an ideal substrate for the growth of microorganisms [6].

Even if the church of Sotterra cannot be properly defined as "hypogeum", it became an underground site due to natural events and nowadays experiences extreme environmental conditions which must be accurately investigated in order to preserve the pictorial evidence inside the building.

The church of Sotterra is located in Gaudimare quarter, 3 kilometres far from the city of Paola, in the province of Cosenza (Italy).

Fig. 1. Church of Madonna del Carmine and, on the right, the entrance to the church of Sotterra.

The building was most likely founded during the Byzantine domination over the Calabria region between the 9th and 10th century. It was only in 1876, during the work of construction of the upper church of Madonna del Carmine, that the church of Sotterra was accidentally rediscovered [7]. As clarified by the archaeological excavation campaign of the late 20th century, the structure was originally built at the ground level and subsequently buried by several landslides which occurred at different times from the 16th century.

Fig. 2. A view from the interior of the church of Sotterra

The presbytery area houses valuable mural paintings which date back from the 11th to the 15th century. The latest paintings, observable above the minor lateral altar, represent the Virgin "Galaktotrophousa" on the left and the saint monk Sant'Antonio Abate on the right and are both attributable to the 15th century. A second decorative phase, datable between the 14th and the 15th century, shows into two frames, depicted on the lateral sides of the altar, the Annunciation theme [8]. The apse mural painting is the oldest (11-12th century) and, according to most sustained historians' hypothesis, it represents the iconographic theme of the Ascension, influenced by the theme of Majestas Domini, with Christ seated on a throne in the semidome, no longer visible due to the poor conservative conditions.

Fig. 3. Wall painting in the apse of the church of Sotterra

The main deterioration processes observed on the paintings surface are: salt crystallization, in the form of efflorescence and sub-efflorescence which have caused swelling of the plaster; lacunae of both the plaster and the pictorial film; biological colonization and calcareous encrustations.

The present study aims to assess the conservative risk of the mural paintings inside the building by comparing the microclimatic data to the results obtained from the diagnostic investigation of the decay phenomena already discussed in a previous work [9].

II. MATERIALS AND METHODS

A. Church description

At present time, the church of Sotterra is located 6.60 meters below the ground level. The access to the building is allowed by an entrance located in correspondence of the external square, built in 2016 to replace the previous access in the churchyard. The passage, characterized by a long corridor, ends with a staircase leaning against the wall of the last span, which allows the direct access to the interior of the church.

The environment is to be defined as confined but it is not totally isolated. In fact, above the presbytery area, in the vault of the first span, there is a hollow of a skylight, created by adapting the aperture made during the discovery of the building in order to come into the church. The latter, remodelled several times during the years, was the responsible for the phenomena of infiltration and rainwater which contributed, in the past, to the worsening of the already precarious state of conservation of the pictorial evidence immediately below it. The aperture of the skylight is protected by a grating and a net that allows the keeping of any residues of various nature that could inadvertently fall inside the building (Figure 4a). Above it, at a higher level, the skylight was built. Although a glass plate is currently placed to protect the hollow, this is raised with respect to the masonry structure, allowing air exchange between the exterior and interior of the building (Figure 4b).

Fig. 4a. Skylight hollow viewed from the inside of the church; Fig. 4b. Skylight viewed from the outside of the church.

The church also has an artificial lighting system consisting of LED lights that are turned on when people are visiting the site. Free access to the church is not allowed, however, guided tours and religious celebrations are occasionally held on special occasions of the year.

B. Microclimatic monitoring

Environmental investigation has been carried out by means of the Data Logger EL-USB-LCD from EasyLog, that measures from −35 to +80 ◦C (−31 to +176 ◦F) and from 0 to 100% humidity (RH) range. The device was placed inside the church on the upper surface of the main altar, in correspondence with the apse in order to obtain information about temperature (T) and relative humidity (RH %). The acquisition interval was set to 15 min. Monitoring was performed for a total of about nine months, from December 2021 to September 2022. Data were subsequently processed to determine the daily, monthly, and seasonal average, minimum, and maximum of both T and RH.

Furthermore, the parameters obtained inside the church were compared with the outdoor climatic data provided by ARPACAL (Agenzia Regionale per la Protezione dell'Ambiente della Calabria). The thermo-hygrometric parameters were collected from the outdoor weather station located in the city of Paola (https://www.cfd.calabria.it/DatiVari/Dati_Storici/Monografie/3060.pdf).

The data recorded by the microclimatic investigation were combined to those obtained from Ion Chromatography, and reported in a previous work [9] with the purpose of determining the conservation risk of the pictorial evidence.

III. RESULTS AND DISCUSSION

During the period under investigation, the indoor temperature range has a minimum of 13°C recorded in January and a maximum of 24°C measured in September (Figure 5). More generally, it is possible to state that the minimum temperatures are reached during January and February while the maximums are recorded during August and September.

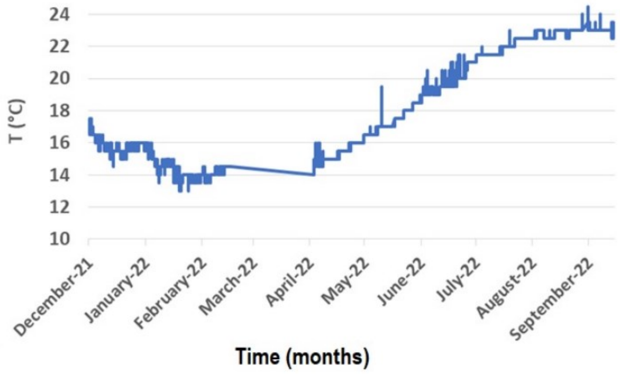

Fig. 5. Temperature values measured inside the church for nine months from Zicarelli et al., 2023 [9].

The indoor temperatures show only gradual variations during the monitoring, with monthly averages fluctuations ranging between 1 and 3 degrees from month to month. In addition, the indoor climate is characterized by minimal daily variation that goes from 0 to 1 degree and rarely from 0 to 1.5 degrees. Only in an exceptional case, on May 15th 2022, the parameters of temperature show a significant increase of 2 degrees within 15 min, related to a massive frequentation of the site.

The microclimate of the church of Sotterra is characterized by high RH values, in line with those of the hypogea environments (Figure 6).

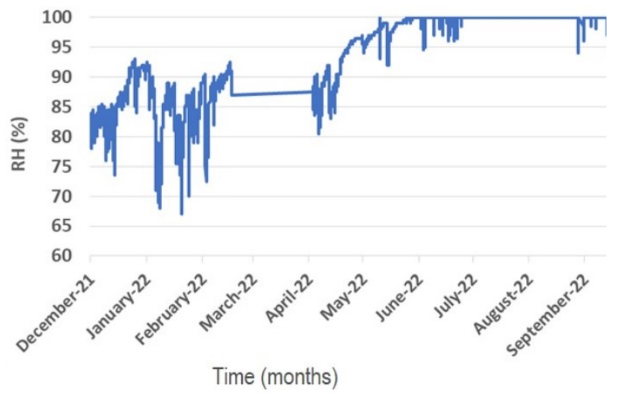

Fig. 6. Relative humidity values measured inside the church for nine months from Zicarelli et al., 2023 [9].

The average RH recorded indoor during the monitoring is 92%. The lowest value is acquired during winter, in

January (67%), while the condition of air saturation is reached in summer, starting from June. The results show wide daily oscillations of the RH values during winter, which sometimes reach 12% variation. During spring, the RH significantly increases, reaching 100% by June and maintaining the condition of air saturation until the first half of September.

The indoor microclimate is characterized by a high thermal stability, even considering the external daily variations of more than 10 degrees (Figure 7).

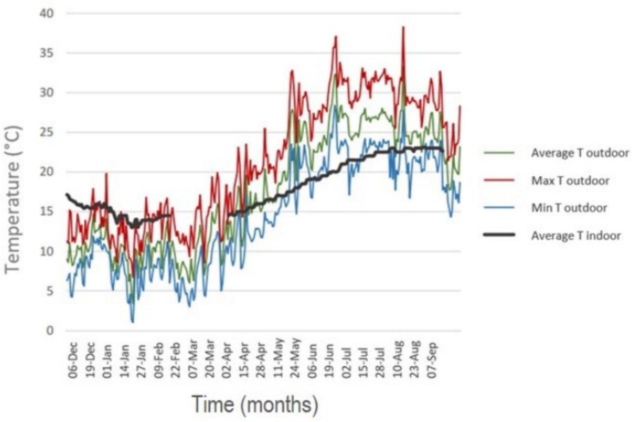

Fig. 7. Temperature values measured in the church and the ones measured outside for nine months from Zicarelli et al., 2023 [9].

The minimum external temperatures are recorded from January to March, with a minimum of 0.9°C measured in January. The maximum outdoor temperature values are recorded during summer, from June to August, with maximum temperature values exceeding 38°C.

Due to the thermal inertia of the building, starting from May and during the summer, the indoor temperature values are lower than the external ones, while on the contrary, in winter the internal temperatures are higher than the ones acquired outdoors.

It is not possible to establish the relationship between the RH values recorded within the church and the external ones due to a lack of data relating to 2021 and 2022 in the ARPACAL archive. Nevertheless, a correlation between the indoor RH and the outdoor T is evident (Figure 8).

Trends of microclimatic data show that at the beginning of the summer period, the RH inside the church increases as the outside temperature increases.

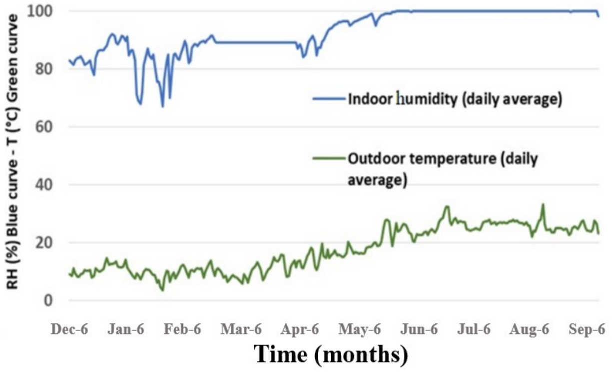

Fig. 8. Daily average humidity (indoor) and daily average temperature (outdoor) for nine months from Zicarelli et al., 2023 [9].

The microclimatic analysis is fundamental in understanding the seasonality and the precipitation mechanism of the saline phases inside the substrate. In particular, crystallization of a specific salt might occur if the ambient RH drops below the equilibrium relative humidity (RH_{eq}) of the saturated solution of a specific salt phase [10]. The ion chromatography investigations on microsamples taken from the mural painting in the apse have shown moderate concentrations of sulphate and calcium ions which suggest that precipitation of calcium sulphate could mainly take place. According to the literature data, gypsum has the highest equilibrium relative humidity, which is 99.96% at 20°C [3], indicating that calcium sulphate is stable even in extreme environmental conditions. Is worth mentioning, however, that the values for the RH_{eq} of a single salt are indicative since actual salt systems are characterized by a mix of ions into solution and their behaviour requires a further deepening. As a matter of fact, the presence of a particular salt phase might drastically affect the solubility of another salt inside the same solution. In this case, although a contribution of nitrates and chlorides was detected, their concentrations are negligible compared to those of sulphate ions, therefore, a minor effect on the alteration of the RH_{eq} of calcium sulphate is expected. Considering that the gypsum is a non-hydration salt phase, the deterioration mechanism is only due to its crystallization pressure and it can not be attributed to hydration pressures.

With regard to the microclimatic data, from a theoretical point of view, precipitation of calcium sulphate occurs starting from the second half of September, when the RH values are lower than 100%. This statement is supported by in situ observations. In fact, from the autumn to spring season, the wall paintings inside the presbytery area are affected by the crystallization phenomenon, in the form both of efflorescence and sub-efflorescence (Figure 9b). The effects of crystallization are particularly visible on the semi-dome area, which is involved in significant swelling processes of the plaster that have caused the loss of the pictorial film (Figure 9a). It can be assumed that this phenomenon is largely related to the air flows coming from the outside and conveyed inside by the skylight placed immediately above, in correspondence with the painting. These likely cause a more rapid evaporation of the aqueous solution inside the wall, leading to the formation of sub-efflorescence.

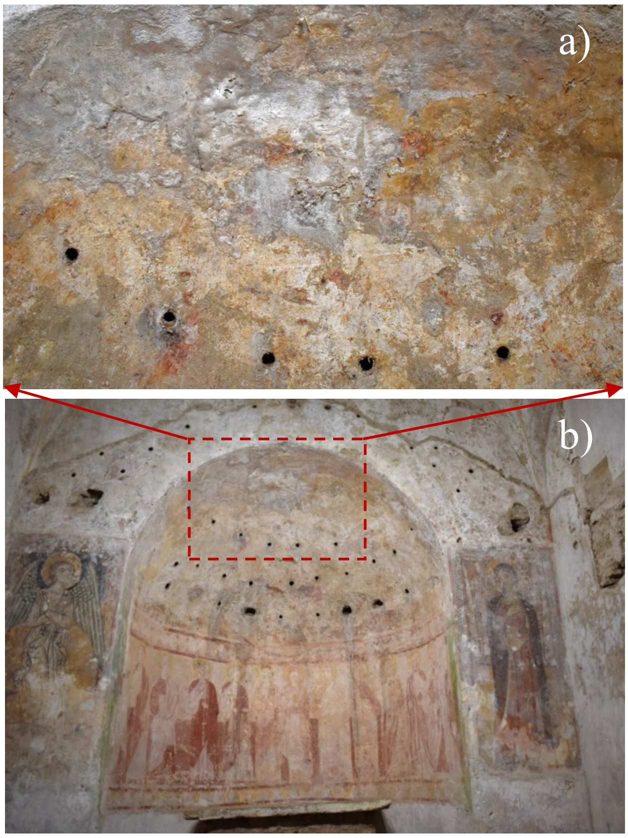

Fig. 9a. Sub-efflorescence and swelling of the plaster in the semi-dome. Fig.9b. Picture of the presbytery area taken on October 14th, 2021.

Fig. 10. Picture of the presbytery area taken on July 7th, 2022.

Otherwise, starting from June, RH values reached the 100%, giving as a result the deliquescence of the salt (Figure 10).

Based on the observation conducted inside the church, the cycles of crystallization and dissolution produced by wetting/drying cycles and oscillations of RH values, occur annually, representing a conservative risk that must be considered. To ensure the preservation of the pictorial evidence and to minimize the decay produced by crystallization phenomenon, theoretically, it is necessary to maintain the RH values permanently above or below the RH_{eq} of the salt phase in the system [4]. Considering that high parameters of RH might cause dissolution processes and microorganism growth, it is possible to conclude that safe microclimatic conditions to avoid salt crystallization have to be set below the RH_{eq} values of calcium sulphate (~99%). This means that wetting/drying cycles that affect the wall inside the church must be limited.

An additional conservation risk that jeopardizes the preservation of the pictorial evidence inside the church of Sotterra is represented by the condensation phenomenon. The latter appears particularly evident by the end of May, when the RH reaches the 100%, and during the entire summer season. When the RH values are close to saturation and high concentrations of carbon dioxide are recorded, a reaction between the condensed water, in droplet form, and CO_2 in the room may take place. The product of the upper described reaction is carbonic acid, which in contact with the calcium carbonate constituting the plaster will form calcium bicarbonate as follows:

$$CO_2 + H_2O + CaCO_3 \rightarrow Ca(HCO_3)_2$$

Otherwise, when the thermo-hygrometric conditions vary the inverse reaction occurs, leading to the evaporation of the aqueous solution from the plaster and finally the re-precipitation of calcium carbonate. The repeated cycles of dissolution and re-precipitation of the carbonate matrix have, as direct result, the decohesion of the pictorial film and the plaster.

As discussed in the introduction section, another conservation risk regarding the wall painting inside the hypogeum environment is the microorganisms growth. In the case of the mural painting in the apse of the church of Sotterra a biological film, bearing a greenish coloration, typical of photosynthetic organisms such as algae and cyanobacteria, is visible in correspondence with the outer lateral edges of the painting. Their proliferation is governed by external factors such as the presence of water and light sources. Although the church is provided by an artificial lighting system, in this case the microbiological growth appears to be linked to a light leak coming from outside and passing through the skylight above the painting. As shown in Figure 11, in the absence of artificial lighting, sunlight illuminates the portion of the wall above the apse and then generates two cones of light on the external edges of the apse painting.

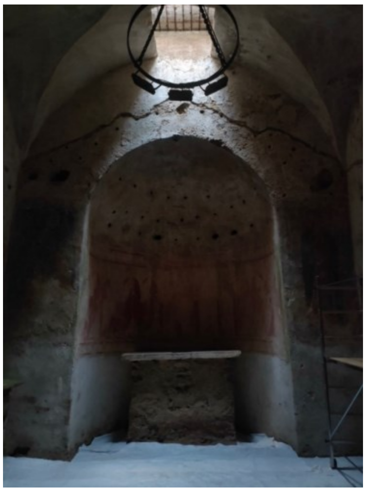

Fig. 11. Light cones visible on the outer edges of the apse painting

In this regard, the area illuminated by the sunlight matches with that colonized by the phototrophic microorganisms, indicating that the presence of this light source has probably encouraged the growth of the biofilm.

In addition, it is worth considering that the already fragile equilibrium could be broken by other external factors such as visitor flow inside the church. In fact, analyzing the monitoring data recorded inside the church of Sotterra, as a result of a high number of visitors on May 15th, the temperature parameters indicate a notable rise of 2 degrees in just 15 minutes. Simultaneously, the relative humidity values exhibit an increase from 97% to 100%, likely attributed to visitors' respiration that led to the formation of a dust layer on the wall surfaces.

The repeated fluctuation of the thermo-hygrometric parameters can accelerate the degradation processes and for this reason must be considered.

IV. CONCLUSIONS

The microclimatic investigation inside the underground church of Sotterra was useful to better understand the complex degradation mechanisms that occur on the surface of the wall painting confined inside the building. The diagnostic results acquired during a previous investigation campaign were combined to the microclimatic data in order to assess the conservation risks of the pictorial evidence. In this regard, the crystallization, condensation and the biological risk must be taken into account. In addition, the flux of visitors inside the church could lead to the oscillation of the thermo-hygrometric values and bring to the accentuation of the previously mentioned risks. For this motivation, the access to the church must be carefully controlled and the number of tourists must be limited.

This study provides useful information on the conservative risks of the pictorial testimonies inside the church of Sotterra and it will serve as a support for future environmental research (e.g. aerobiological surveys, CO_2 measurements, studies on the movements of air masses inside the building etc.).

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