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TOOLS FOR THE KNOWLEDGE OF THE BUILT HERITAGE

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CRITICAL ANALYSIS OF RESTORATION PRACTICES AGAINST RISING DAMP

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Abstract

The restoration of architectural heritage from rising damp is a complex technical and scientific challenge. The paper illustrates a comprehensive approach to address this issue. It highlights critical information gaps and specific topics that need further investigation in the state of the art and current practices. The research methodology adopts a multidisciplinary and holistic approach to the restoration process with the integration of historical investigation, knowledge of building elements and materials, non-invasive diagnostics for identifying degradation phenomena, methods and materials for restoration, and long-term monitoring.

The research activity is part of a broader project aimed at establishing operational protocols with advanced technologies for the planned and preventive maintenance of architectural heritage. The outcome will be a digital platform, an open-access tool to support integrated building design and conservation, ensuring sustainable conservation practices to managing rising damp and related issues.

The paper focuses on the restoration processes of two significant case studies: the Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milano). The research results provide valuable insights into the effectiveness and durability of different intervention methods. Moreover, the critical analysis facilitates the choice of best practices for sustainable building heritage conservation.

Keywords

Restoration process, Rising damp, Infrared thermography, Church of San Gennaro in Capannori (Lucca), Church of San Giuseppe in Rosate (Milano).

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1. INTRODUCTION

Rising damp is a significant and increasingly recognized problem in the restoration and conservation of architectural heritage. In fact, humid conditions can seriously compromise masonry's structural and aesthetic integrity with irreversible damage. Despite the growing interest in this topic, some critical gaps still exist in the scientific and technical literature. The lack of standardized protocols for evaluating the effectiveness of intervention methods is one of the fundamental issues. Most of the works focus on individual case studies, which hinder the comparison between the different available techniques [1, 2]. The fragmentation of the current state of the art makes it difficult to establish a hierarchy of effectiveness between the different methods and to state generalizable conclusions. Moreover, a significant research gap exists in the long-term monitoring and durability of interventions.

Different methods and techniques against rising damp are available nowadays. There is a significant variability in their working, invasiveness, applicability, and effectiveness. Standard techniques include chemical barriers, physical barriers, active and passive electro-osmotic techniques, and inversion or neutralization of electromagnetic polarity [1, 3]. Table 1 summarizes the main methods and techniques currently used against rising damp, highlighting both advantages and disadvantages. Once rising damp is stopped, removing salt efflorescence, and using breathable plasters and finishes are essential treatments to allow for the proper evaporation of residual moisture and to prevent the formation of new salt deposits. A comprehensive intervention that integrates the practices mentioned above is required to ensure the long-term effectiveness and sustainable conservation of building heritage.

Despite extensive research on rising damp, documentation on the effectiveness of intervention methods remains incomplete and fragmented. The literature highlights the need for additional comparative and long-term studies to provide recommendations and best practices.

A multidisciplinary approach that considers all aspects of the building, from its history and typology to di-

Technology	Description	Advantages	Disadvantages
Physical barriers / Chemical barriers	Horizontal or vertical waterproof membranes installation / water reppellent resins and silicones injection	▪ Good initial effectiveness	▪ High invasiveness ▪ High costs ▪ Damage of structural integrity
Electrosmosis (active and passive)	Active: Use of electrical pulses to reverse the flow of water in capillaries through electrodes Passive: Exploit differences in natural potential	▪ Minimally invasive ▪ Adjustable electric field intensity	▪ Variable effectiveness ▪ Periodic maintenance
Reverse polarity	An alternating electric field tries to cancel the capillary force by reversing the movement of water	▪ Non-invasive ▪ Easy to install ▪ Low energy consumption	▪ Variable effectiveness ▪ Power supply
Electromagnetic fields	Uses electromagnetic fields generated by devices placed near or inside the walls to alter the surface tension of the water, reducing the ability of the water to rise through the capillaries	▪ Non-invasive ▪ Low operating costs	▪ Few scientific studies ▪ Complementary techniques
Pulsed frequency system	Devices that emit specific current pulses or frequencies to interfere with the natural capillary rising process of water	▪ Non-invasive ▪ Easy to install	▪ Variable effectiveness ▪ Power supply ▪ Continuous maintenance ▪ Few scientific studies
Drainage systems	Installation of drains to remove water from foundations	▪ Low hydrostatic foundation pressure ▪ Versatility of application	▪ High installation costs ▪ Invasive ▪ Not always applicable ▪ Not always effective
Dehumidifier plasters	Use of porous plasters to allow the moisture evaporation. These products don't resolve the cause of rising damp	▪ Ease of application	▪ Periodic replacement
Environmental dehumidification	Use of dehumidifiers to reduce indoor humidity	▪ Non-invasive ▪ Simple to implement	▪ Power supply ▪ Continuous maintenance

Tab. 1. *Main methods and techniques against rising damp.*

agnostic interventions, is required to tackle rising damp and develop an effective restoration protocol. In particular, diagnostics has a crucial role in identifying degradation phenomena and short and long-term monitoring of interventions.

This work aims to provide a holistic view of the current state of the art on rising damp management and identify issues requiring further investigation and implementation. The research investigation is focused on the critical analysis of two case studies belonging to listed building heritage: the Ancient Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milan). Site inspections during previous restorations revealed, in both buildings, widespread efflorescence, sub-efflorescence, and biological patinas, as well as slight detachment of plaster, peeling of paint films, alveolation, decohesion and crumbling of building surfaces. A comprehensive research methodology was adopted, combining historical and technical approaches, including the study of historical documents, literature review, and analysis of construction and material characteristics. This approach provided a deeper understanding of the structural and conservation challenges and the effectiveness of conservation solutions.

The investigation included detailed condition assessments and identification of structural problems using non-invasive diagnostic techniques, focusing on infrared thermography (IRT) to detect hidden defects such as moisture and material degradation that could affect structural stability. Passive infrared thermography (IRT) is applied in various fields, with various methodologies tailored to specific contexts. Active IRT is particularly useful in material characterization and stratigraphy of localized areas of historic buildings [4–6]. Its usefulness in building historical and evolutionary analysis is well documented, particularly for monitoring phenomena such as moisture in structures, although its application is often limited to specific areas [5, 7–10]. However, there is a need for a standardized procedure for thermographic analysis because the measurements are conducted using different and not comparable methodologies [6, 7, 11].

The literature highlights key factors for reliable thermographic analysis: analysis timing, understanding IRT principles, accurate calibration of thermal cameras, and use of digital and mathematical thermal models [4, 9, 11, 12]. The integration of IRT with 3D models, often supported by drones, to locate specific features during analysis is a promising emerging trend.

Research into the use of IRT for assessing material performance and quantifying moisture content is still evolving. However, simultaneous measurements and continuous surveys are suggested for best practice protocols and quantitative results.

Infrared thermography combined with other non-destructive techniques provides a comprehensive view of building conditions, promoting preventive conservation and continuous monitoring and the potential evolution towards 4D models [12–15].

Despite skepticism about the reliability of IR thermography, proper technical training of operators in both execution and data interpretation can provide qualitative information in real time. Moreover, the minimum requirements of the thermal camera must be a sensor of 320x240 pixels, a thermal resolution of 0.05°C, and an IFOV of 1.5mrad [4, 16].

This study is part of a more comprehensive research program to define operational protocols based on the best technologies currently available for the conservation, preventive, and planned maintenance of architectural heritage. The outcome of the research activities is the development of a digital platform, configured as an open knowledge tool, to support integrated design and the conservation of historic buildings.

The proposed operational protocols consider the entire restoration process, particularly for architectural heritage affected by rising damp, and include the use of CNT®-Domodry® technology to resolve the phenomenon. This innovative dehumidification system, patented by Domodry®, generates weak, impulsive electromagnetic waves suitably modulated within a defined frequency range and completely harmless [17–19]. Applying this technique against rising damp and verifying its effectiveness through case studies are parts of specific conservation recommendations for the architectural heritage according to the principles of restoration (compatibility, minimal intervention, reversibility, recognizability) and sustainability of the interventions.

2. CASE STUDIES

This study examines the Ancient Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milan), both of which have had CNT devices installed to control rising damp. Specifically, two devices were installed in San Gennaro in 2021 and one in San Giuseppe in 2016.

The Ancient Church of San Gennaro is of great historical and artistic importance. It is one of the most important examples of Romanesque religious architecture in the Lucca area for its rich decoration and the presence of a recently restored sculpture of an angel attributed to Leonardo Da Vinci. The church stands in the old center of the small town of Capannori, located on the border of the Lucca plain and the Valdinievole. The structure was built in the 12th century above the former construction dating back to the 9th century. The sandstone sack masonries are made with a local porous sandstone known as Matraia stone, named after the locality of the quarry about 12 km away from Capannori [20]. The church preserves the medieval three-nave plan and original decorations. The apse was modified in the 18th century, and a square bell tower was added in 1840 next to the north facade. The building has undergone numerous restorations over the years due to the widespread presence of rising damp and related degradation phenomena such as detachment and decohesion of surfaces.

The Church of San Giuseppe was built in the 18th century along the central urban axis of the town of Rosate. It is one of the remarkable examples of Mannerist Baroque architecture in the Province of Milan. The church has a central octagonal plan with a rectangular presbytery. It is built in brick masonry with decorative details made in gilded stucco and artfully crafted painted wooden doors. A dome with a central painted medallion and stucco relief covers the church. The presbytery, surrounded by polychrome marble balustrades, has a barrel-vaulted ceiling. The facades are entirely plastered. The main facade is characterized by a double order of pilasters and a stone entrance portal.

The first documented restoration occurred in 1940 and focused on consolidating the roof and internal masonry, which were severely damaged by rising damp. However, this restoration proved ineffective, and in 1963, further interventions were required on the masonry, including replastering. In June 1969, additional restoration work was conducted, and the plastic and painted decoration of the interiors was renewed by the painter Taragni [21].

The late restoration of the building was carried out between 2016 and 2017 following the collapse of the roof. This project involved stabilizing and repairing the roof and dome. In addition, due to the ongoing problem of rising damp, a more rigorous technical and scientific approach was adopted. The aim was to thoroughly assess the condition of the building and implement definitive solutions to the existing problems, optimizing the use of resources and minimizing future expenditure in terms of time and cost.

3. MATERIALS AND METHODS

The analytical process was carried out in several phases, starting with a thorough assessment of the condition of the buildings and the identification of pathologies using non-invasive diagnostic techniques. This included a preliminary microclimate assessment using a thermo-hygrometer for environmental parameters and a contact thermo-hygrometer for surface parameters.

Thermographic surveys were conducted using a “NecH2640” thermal camera to verify the presence of rising damp in the masonry of both case studies. This thermal camera fully complies with the recommended standards and ensures the results’ reliability thanks to its characteristics: geometric resolution of 640x480 pixels, thermal resolution of 0.03°C, and an IFOV of 0.6mrad. The monitoring has also been carried out for three years at San Gennaro Church and seven years at San Giuseppe Church, providing crucial data to evaluate the effectiveness and durability of the solutions implemented.

Hourly readings of relative humidity and indoor air temperature (24 data points per day) were recorded for one year in the Church of San Gennaro using Domodry® RH-T sensors (temperature range: -20°C to 60°C, accuracy: 0.3°C; RH range: 0-100%, accuracy: 2%; over 3 years of storage capacity). Two IDROSCAN® sensors (measuring range: 1500 to 2500 u.i., accuracy: 2 u.i.; over 3 years of storage capacity) were used over the same period to measure masonry moisture in “idroscan units” (u.i.) daily.

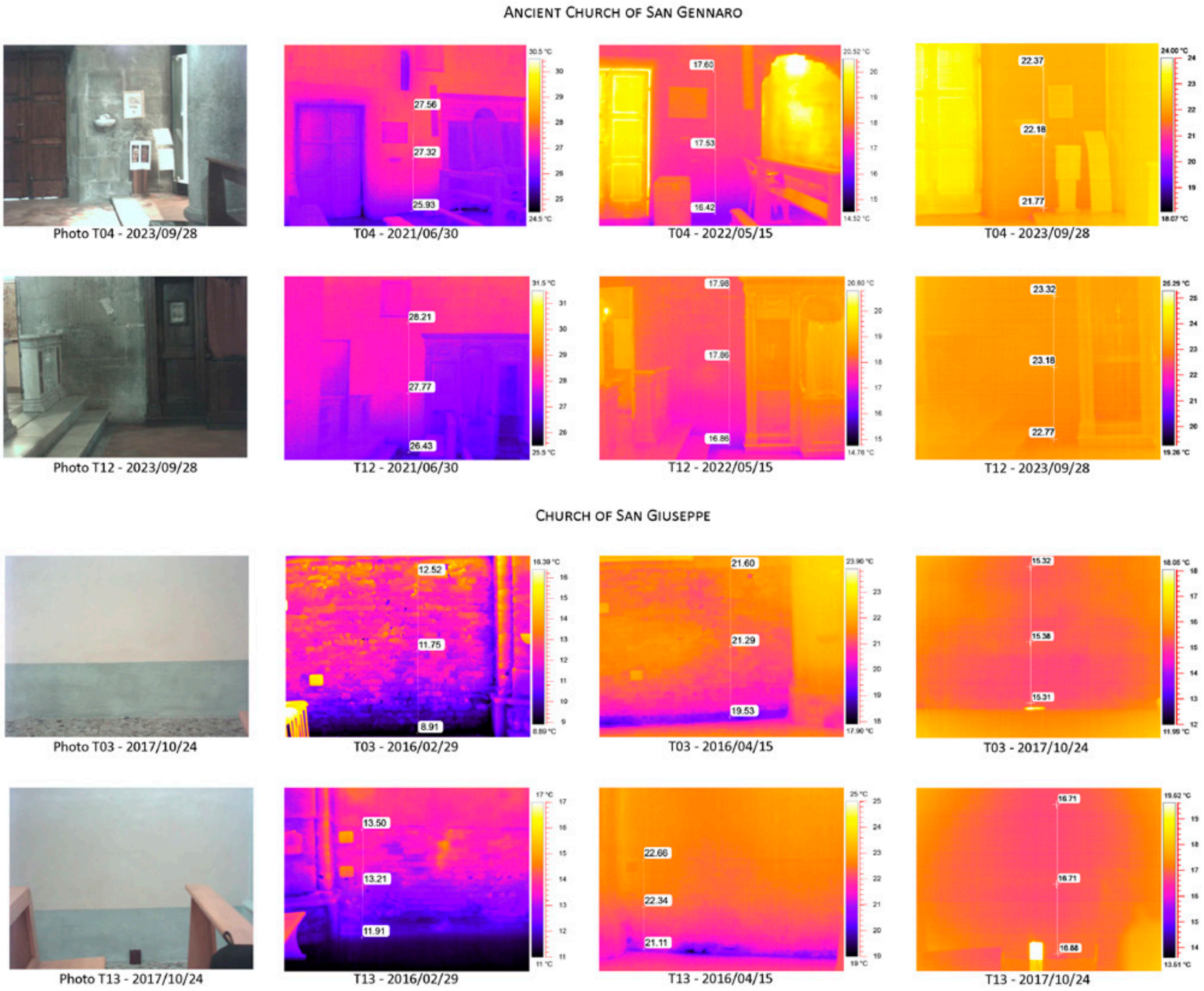

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Photo T13 - 2017/10/24 T13 - 2016/02/29 T13 - 2016/04/15 T13 - 2017/10/24

Fig. 1. *IR thermography with the indication of temperatures along the wall carried out during the diagnostic campaign.*

Data was stored on the CNT device or sensor and later downloaded by a technician or automatically via the Domodry Control Center when internet access was available.

The thermographic survey was conducted in the Church of San Giuseppe to control the effectiveness of the CNT system against rising damp. It also allowed the localization of thermal critical areas where sampling was performed for gravimetric analysis. Samples were taken at six critical points for a total of 16 samples. At each point, samples were taken at depths between 5cm (S) and 10 cm (P) from the outer surface and at heights of 50 cm (B), 100 cm (A) and 150 cm (AA) above the ground. Samples were taken with a low-speed drill to avoid overheating, per UNI 11085 "Natural and artificial stone materials - Determination of water content: weight method". The samples were placed in an airtight glass tube and weighed in the laboratory using a balance with an accuracy of 0.001g. The samples were dried up to obtain a constant mass at 105°C in an electrically heated laboratory oven with an accuracy of ±2°C.

Ancient Church of San Gennaro		
	Indoor	Outdoor
UR	49,70%	41,00%
T_{air}	25,8 °C	26,0 °C
T_{dew}	14,5 °C	11,7 °C
U_{sp}	10,21 g/kg	8,51 g/kg

Church of San Giuseppe		
	Indoor	Outdoor
UR	63,40%	79,10%
T_{air}	17,2 °C	11,6 °C
T_{dew}	10,3 °C	8,3 °C
U_{sp}	7,65 g/kg	6,79 g/kg

Tab. 2. *Environmental parameters during the preliminary IR surveys.*

4. RESULTS

Preliminary thermographic surveys (Fig. 1) and environmental analyses revealed the presence of rising damp in both case studies, which critically affects both pathological conditions and the indoor microclimate (Tab. 2).

Due to the widespread occurrence of the above-mentioned pathologies, the installation of CNT® devices was chosen to stop rising damp (Fig. 2). Thermographic tests were conducted at one-year intervals and then again two or more years after installation.

The Domodry® sensors installed in the Ancient Church of San Gennaro alongside the CNT system for continuous monitoring of wall moisture and environmental conditions provided essential data for real-time evaluation of the system's performance and optimization of intervention strategies to ensure complete and timely drying. The results showed a reduction in masonry moisture after the activation of the CNT devices, with an estimated timeline for complete evaporation of residual moisture by September 2023 (Fig. 3). Throughout the monitoring period, the indoor relative humidity generally remained below the recommended threshold of 50%, with occasional spikes above this level. The indoor temperature averaged between 18°C and 22°C, maintaining comfortable conditions. The dehumidification rate was slightly slower than expected, probably due to the significant wall thickness and high initial water content.

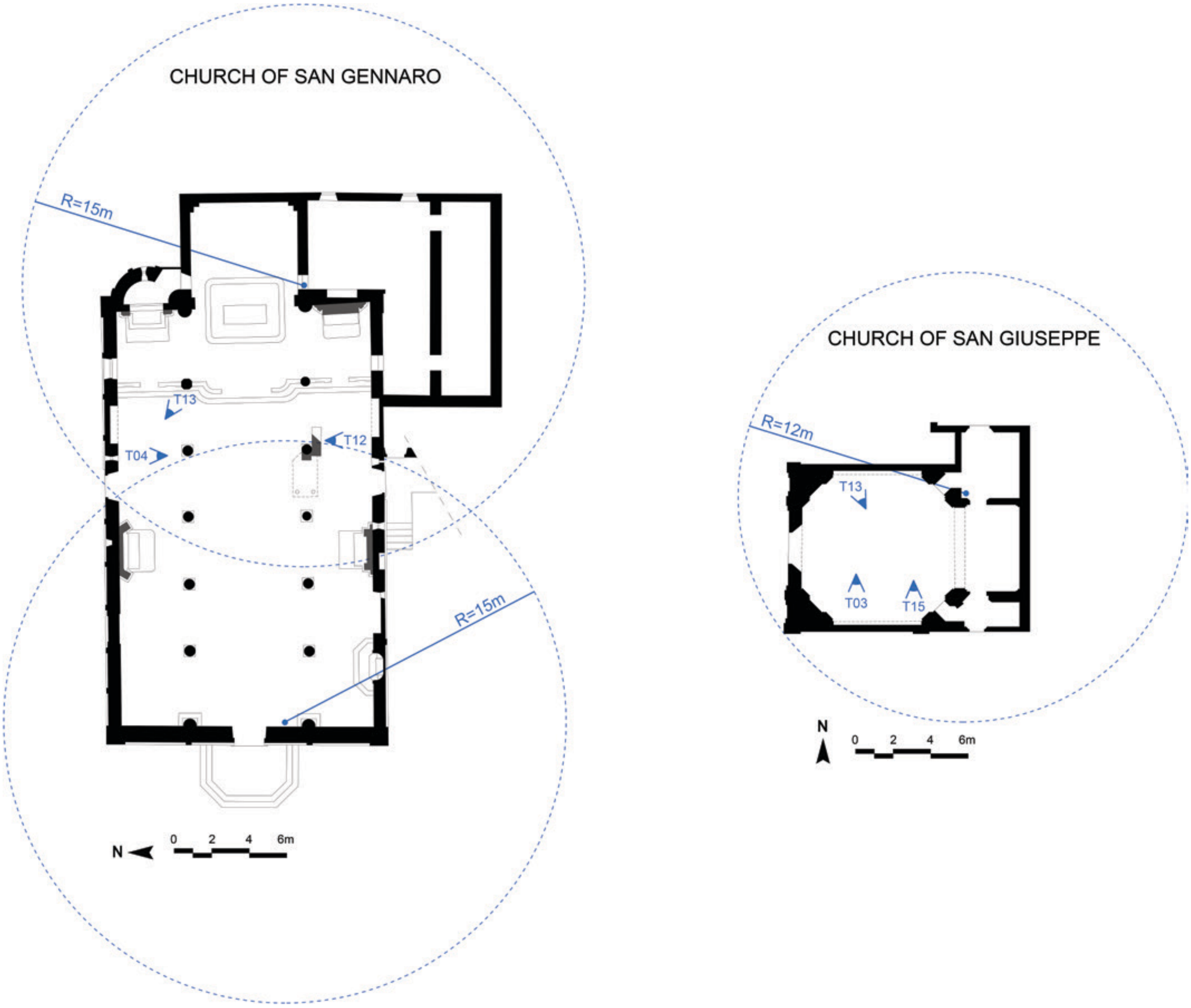

Fig. 2. *Localization in the two case studies of CNT devices with indication of their radius influence and viewpoints of thermographic analysis.*

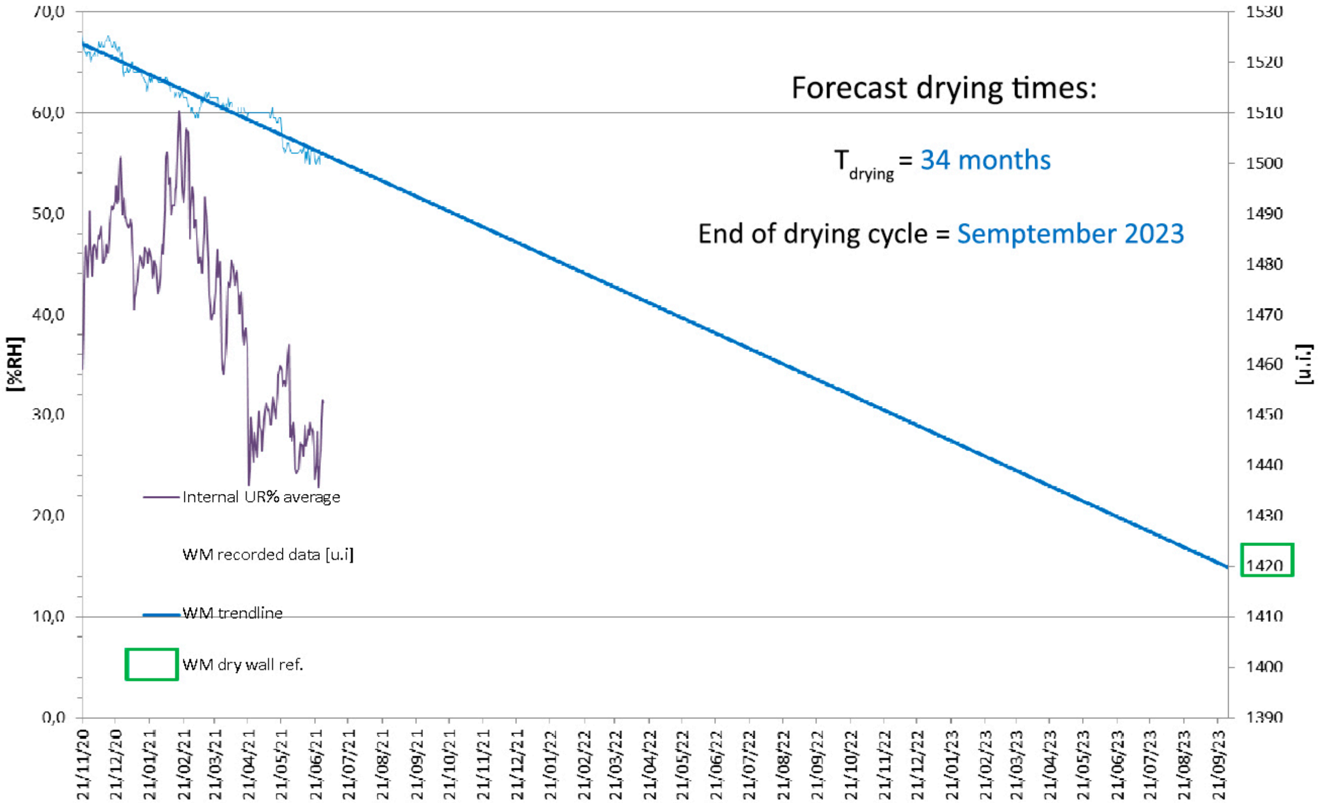

Fig. 3. *Wall humidity: Forecast drying times from 2020/11/21.*

The effectiveness of the CNT system was also validated by thermographic surveys (Fig. 1). At the time of installation of the system on 2020/11/20, it was impossible to carry out thermographic mapping due to unfavorable thermo-hygrometric conditions. The combination of high relative humidity and low temperatures would have reduced the rate of water evaporation, leading to an underestimation of wall moisture by thermography. Therefore, thermographic surveys were conducted seven months after installation and revealed anomalous thermal patterns in the walls, with a significant gradient in surface temperature distribution. The upper sections, approximately 1.2-1.5m above ground, showed average temperatures 2°C higher than those close to the ground, with peaks of up to 2.6°C. This thermal gradient indicated the presence of rising damp. During the inspection on 2022/05/10, the thermographic survey showed a reduction in the thermal anomalies along the vertical extent of the walls. This confirmed both the stopping and regression of the capillary rise phenomenon and the progress towards natural drying of the walls. Finally, during the final inspection on 2023/09/28, the thermographic analysis showed a substantial disappearance of thermal anomalies, and the walls showed no residual moisture and contained only physiological moisture levels.

In the Church of San Giuseppe, the effectiveness of water content evaporation was confirmed by the gravimetric tests conducted in three diagnostic campaigns: before the installation of CNT devices in 2015, in 2016, and in 2024. The tests (Figs. 4 and 5) showed that wall moisture levels were close to normal physiological levels for dry masonry, except for a slight hygroscopic moisture detected in the P1-AP area. It was also noted that surface samples from the plaster had a slightly higher water content than those from deeper within the masonry. Additionally, the S3-LP sample showed a moisture content of 7.84%, more than twice the value of 3.5% of the physiological humidity content. This anomalous data, confirmed by the results of the thermographic surveys, depends on localized infiltration.

The plaster applied during the last restoration of the Church of San Giuseppe showed whitish deposits and detachments due to efflorescence. The presence of hygroscopic salts was confirmed by thermographic surveys that highlighted colder areas in the form of “leopard spots” (Fig. 6). This drawback underlines the importance

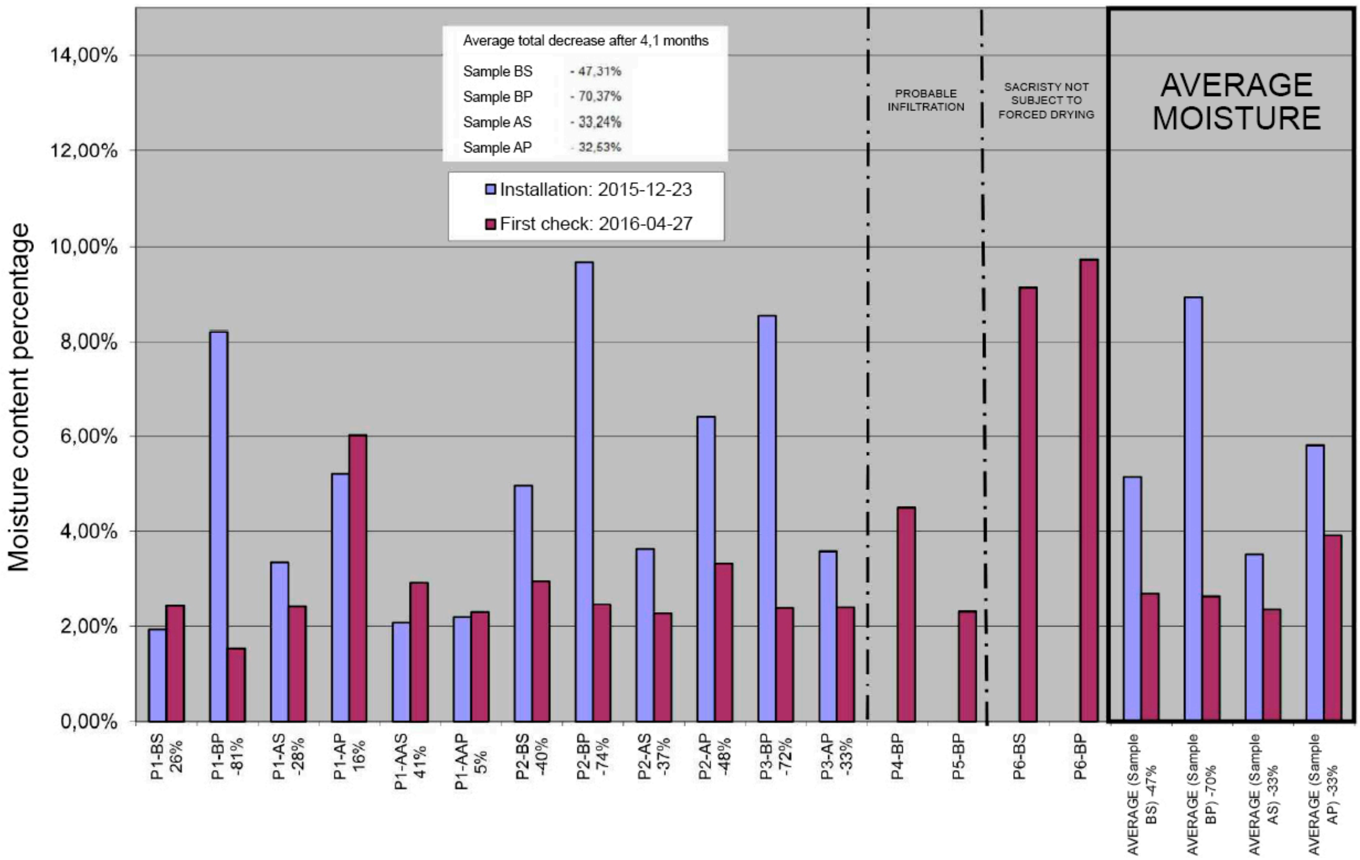

Fig. 4. *Graph of the measured humidity, samples of 2015 and 2016.*

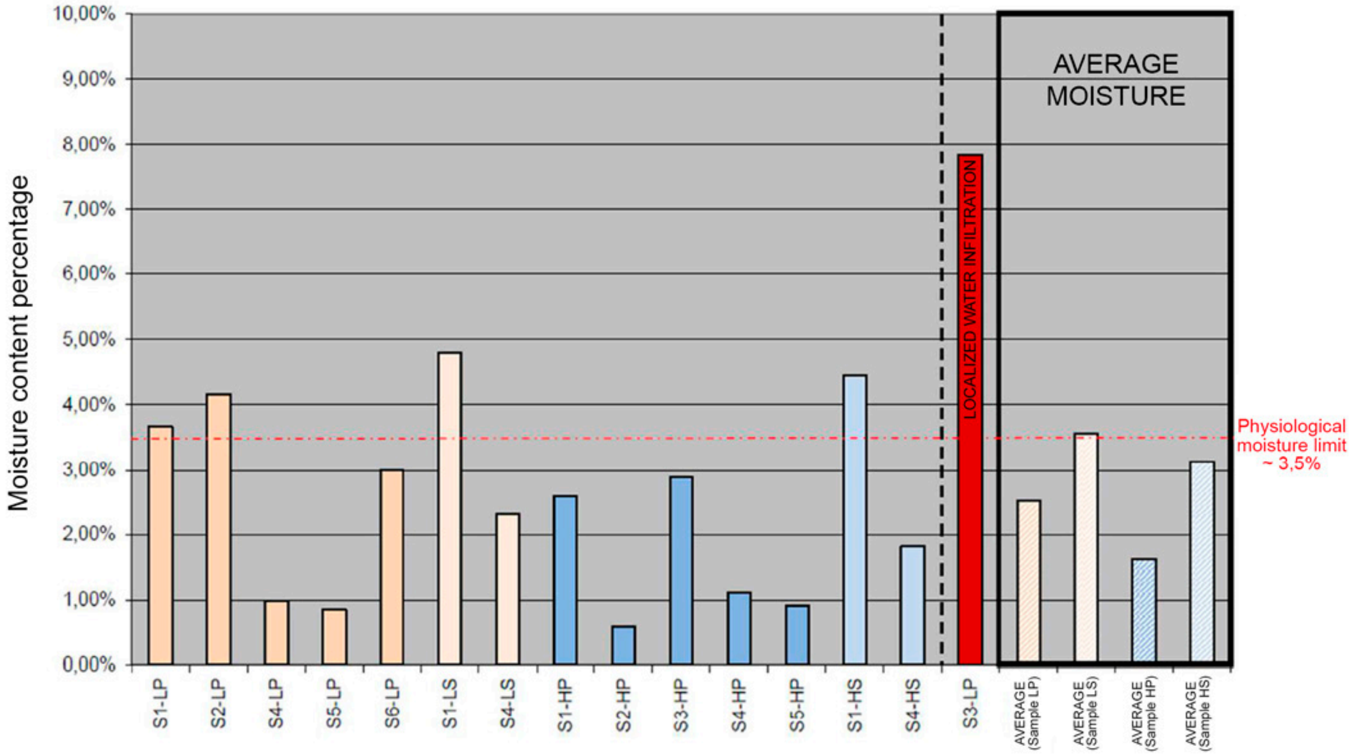

Fig. 5. *Graph of the measured humidity, samples of 2024.*

Fig. 6. *Monitoring of restoration in the Church of San Giuseppe, Rosate (Milano).*

of cleaning surfaces from hygroscopic salts before any other intervention in the restoration process.

The Church of San Gennaro case study presented a different scenario, characterized by an integrated and detailed approach to managing rising damp [22]. This case highlights the importance of targeted, sequential interventions for effective restoration of historic buildings.

A preliminary survey, using drones and 3D laser scanning, mapped areas of degradation and critical conditions to ensure safe and informed interventions. Prior to consolidation, chippings and damaged mortar were mechanically removed. Petrographic analysis using a polarizing optical microscope of original plaster and masonry stones allowed the choice of lime plaster. After the last restoration of the Church of San Gennaro, the only issue was the persistence of dark stains on the columns whose surfaces were not cleaned from hygroscopic salts (Fig. 7). Thermographic analysis confirmed that the stains were not caused by moisture. After an initial drying process by natural evaporation, the next step was the removal of hygroscopic salts using compresses using Japanese paper and sepiolite and subsequent washing

Fig. 7. *Monitoring of restoration in the Ancient Church of San Gennaro, Capannori (Lucca).*

with deionized water. This method of salt removal was chosen for its effectiveness and minimal impact, reducing the risk of damage to historic surfaces while ensuring thorough cleaning that preserves the original structure. The compresses were left in place long enough to absorb and remove the salts. This experience provides a model for the management of moisture and salts in other historic buildings and demonstrates the effectiveness of combining natural drying techniques with salt removal. Moreover, the salt removal showed that the stain may be due to a reaction between previous paint and moisture/salts, resulting in discoloration and flaking. Further analysis is underway to determine the type of paint used.

Preventive measures were also taken to prevent future external water infiltration, including the reconstruction of cornice edges and facade moldings. These architectural elements are essential for the properly drainage of rainwater, protecting the walls from erosion and preserving the exterior decoration of the monument.

5. DISCUSSION OF RESULTS

The investigations carried out in the two case studies contribute to the development of a protocol for best conservation practices, including each stage of the restoration process from the preliminary phase of building components and materials knowledge, the identification of pathological conditions up to the on-site verification of the effectiveness and durability of interventions.

A comprehensive diagnostic plan is a fundamental requirement of sustainable restoration. It allows us to assess and monitor the building's condition over time, optimizing the time and resources required by restoration. The diagnostic plan of building heritage must primarily include non-destructive qualitative and quantitative analyses (e.g., macroscopic observations, thermo-hygrometric parameters, IR thermography, colorimetric test, scotch tape test, water absorption test) [23]. Before any subsequent invasive testing, these diagnostic methods should be used (e.g., weight tests, optical microscopy, X-ray diffraction on powders, spectroscopy, and X-ray microtomography).

The research activities have also shown that, in most cases, invasive diagnostic techniques require small quantities of materials. Moreover, the sampling can be conducted on degraded or already detached parts of the building without compromising the building's state of preservation.

The design of restoration interventions requires a holistic view with a synergistic dialogue between different interdisciplinary competencies to overcome the current single-issue approach. Previous interventions on architectural heritage masonry surfaces have shown that rising damp is often an issue to the durability of interventions [24].

Therefore, the priority action in the restoration process must be stopping the rising damp using non-invasive and sustainable technologies, such as the CNT-Domodry. However, the use of devices against rising damp is a necessary but not sufficient measure to ensure the effectiveness of restoration [19]. Mechanical ventilation systems should also be installed to improve ventilation and air circulation, ensure the proper removal of residual masonry moisture, and avoid the formation of condensation and crystallization of hygroscopic salts.

Cleaning building surfaces is another compulsory requirement. It allows the removal of physical, chemical, and biological pathologies due to the presence of water in the masonry. Removing efflorescence and sub-efflorescence is essential for preventing the degradation of the finishing applied during the restoration. Figure 8 illustrates the detachment of the plaster applied during the last restoration of the Castle of San Basilio in Pisticci (Matera) caused by the presence of efflorescence, although rising damp was stopped [19].

In treating biodeterioration on stone surfaces, once the pathogens have been identified, attention must be paid to the possible presence of photoautotrophic and heterotrophic microorganisms, which must be eliminated simultaneously to prevent further degradation. To ensure sustainable and compatible interventions, natural-based products can be applied by packs, brushing, or spraying until saturation. These natural-based products can provide long-term efficacy without causing collateral damage to the substrate [24, 25].

The cleaning of masonry made in weak materials, such as calcarenite and Matraia stone, can be done with sorghum brushes or by cycles of spray washing with de-

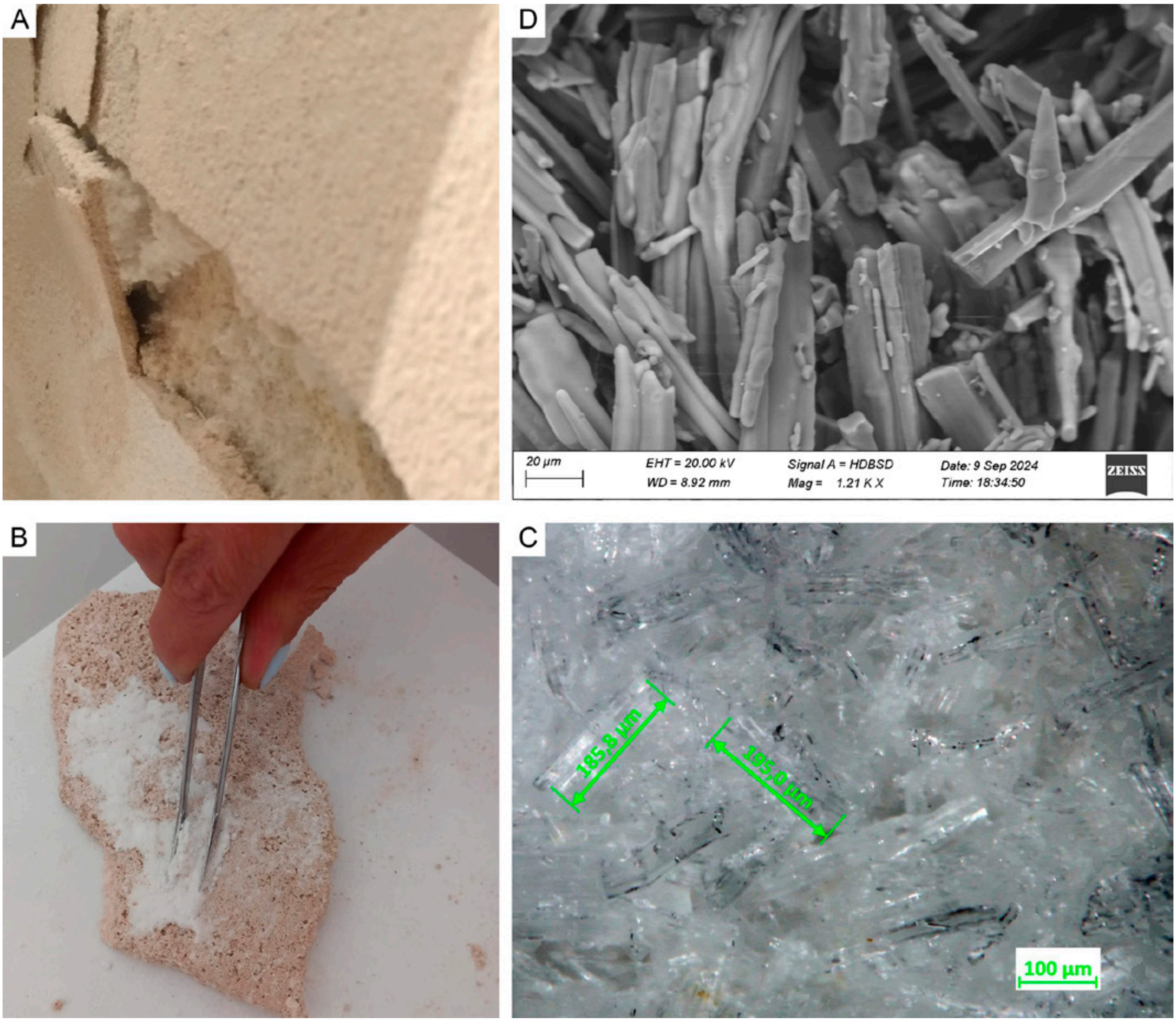

Fig. 8. *(A) Plaster detachment; (B) sampling of salts; (C) optical microscopy of saltpeter crystal; (D) Scanning Electron Microscopy (SEM) of saltpeter crystal.*

mineralized water, using a test brush for more stubborn incrustations. In any case, testing small, inconspicuous areas before proceeding with surface cleaning is advisable to avoid any abrasive effects.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

The research activities are part of a broader project to develop a digital protocol of best practices for architectural heritage conservation, focusing on preventive and predictive maintenance against rising damp. The findings of investigations highlight the critical role of IR thermal analysis in diagnostic and short- and long-term restoration monitoring.

The critical analysis of restorations has shown a widespread lack of preventive, planned maintenance. Current conservation practices often prioritize emergency actions for single-issue problems without adopting a multidisciplinary approach. The research results contribute to the development of guidelines for a conservation protocol that addresses all stages of the design process, from the preliminary study of materials and building components to the monitoring of the short and long-term effectiveness of interventions using non-invasive diagnostics.

The variability of methods and equipment for IR surveys can affect the comparability and reliability of results. Therefore, developing standardized protocols for thermography and other diagnostic techniques is essential to improve data comparability and diagnostic accuracy.

It is necessary to extend the case studies to a broader range of buildings, historical periods, and climatic conditions to validate and generalize the findings. Moreover, long-term monitoring allows the effectiveness and durability of the technologies and methods used, providing a more comprehensive insight into the suitability of these conservation techniques.

Future research could explore the integration of innovative technologies, such as predictive models based on AI and drones for continuous monitoring. These innovations could provide new tools for more accurate assessment and management of architectural heritage.

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Authors contribution

Conceptualization, G.B. and A.G.; methodology, G.B.; resources, G.B. and A.G.; data curation, G.B.; writing and editing, C.R.; review, G.B. and C.R.; supervision, A.G. All authors have read and agreed to the published version of the manuscript.

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